NONDESTRUCTIVE TESTING HANDBOOK

Second Edition

VOLUME 6
MAGNETIC PARTICLE TESTING

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NONDESTRUCTIVE TESTING

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PRESIDENT'S FOREWORD

Many different means exist to disseminate technical information: conferences, technical papers, personal contact, the classroom and handbooks. As the NDT industry's technical society, ASNT is directly involved in all of these.

This volume of the *Nondestructive Testing Handbook* is the sixth in ASNT's ten-volume series. Webster defines *encyclopedia* as "a work that contains information on all branches of knowledge or treats comprehensively a particular branch of knowledge." A handbook can be considered an encyclopedia on a single topic, in this case the technology of magnetic particle testing. This book represents the collected and organized efforts of many authorities who have generously made this contribution to the literature of nondestructive testing. Distribution of such information is critically important to the advancement of nondestructive testing throughout industry.

The magnetic particle method is much more than the high school physics horseshoe magnet and iron filings demonstration. It is a simple yet highly effective tool for the detection of surface and near surface discontinuities in ferromagnetic materials. In the general application, a magnetic field is applied to the test object. Discontinuities in the material force a portion of the field to bridge the anomaly, forming a magnetic leakage field. A powder of magnetic particles, either dry or in liquid suspension, is applied to the component and the leakage field attracts and holds the particles, forming a test indication.

Equipment used in the method ranges from a simple and inexpensive held-held yoke to large, wet horizontal systems capable of delivering thousands of amperes of electric current through the component or through a conducting coil surrounding the part. Test objects range in size from a sewing needle to the very largest casting, forging or weldment. Discontinuities only a few thousandths of an inch long can be detected.

This highly sensitive, versatile and inexpensive technique is very dependent on operator capabilities and even more dependent on the operator's attention and persistence. An inspector's visual survey of the test surface is still the best and most effective way to detect and interpret the indications formed by magnetic particles.

With rapidly advancing technology and the need for increased testing reliability, it is likely that automated systems will become increasingly accurate for specialized applications using advanced optical scanning systems with computerized data analysis. However, such automation will not eliminate the need for well trained and experienced magnetic particle inspectors.

A handbook on the magnetic particle test method should include information on the physics and theory of the technique, written in a style that is accessible to both the engineer and the technician. At the other end of the spectrum, it should also contain instructions on *how to do it* and, just as importantly, instructions on how *not* to do it. Where and when the method should be applied, including the materials that can be tested, and the structural configurations where its use would be an advantage, should be discussed. Capabilities and limitations must be clearly presented along with essential variables of the method and various techniques. Descriptions of equipment and its use, in general and specific testing situations, are required to aid inspectors in establishing their test procedures. Calibration guidelines are equally important. The qualifications of personnel to develop techniques, to prepare procedures, to perform the examinations and to interpret and evaluate test results should be clearly delineated. Pitfalls and potential problems should be presented so that the reader might anticipate and address them before they are encountered in the performance of a test.

In short, the handbook must provide the reader with most of the information needed (1) to determine that the magnetic particle method should be used; (2) to establish the techniques to apply it; and (3) to evaluate the test results. These goals have been accomplished in this book by the hard work and unselfish contributions of many volunteers who participated in preparing the text.

Several individuals merit special recognition. Technical editors Tom Schmidt and Kermit Skeie, volume coordinator Rod Stanley, and metric conversion reviewer Jan van den Andel have worked on this volume on their own time for more than four years and are directly responsible for its completion. Publication of this book has been accomplished with the direction and editorial coordination of Paul McIntire of the ASNT headquarters staff.

My personal thanks to all individuals, named and unnamed, who brought this project to its outstanding conclusion.

Robert Baker
ASNT President (1988-1989)

PREFACE

All of the *Nondestructive Testing Handbook* volumes are written as practical, instructional materials for NDT field technicians. To fully explain the techniques and to encourage accurate test results, the physics and mathematics of the technology are provided along with useful applications information. Each volume is written and technically edited for ASNT by *volunteers* who provide their expertise and donate their time to the project.

Within the *NDT Handbook* series, this book is the companion volume to *Electromagnetic Testing*, the text that covers eddy current, diverted flux and microwave tests. Both books were produced with the guidance of the Electrical and Magnetic Methods Committee of ASNT's Technical Council, and the volumes share many authors and reviewers.

Within ASNT, the Handbook Development Committee deserves special recognition for its work on the series. Organized under the Methods Division of ASNT's Technical Council, the Handbook Development Committee is directly responsible for production of the *Nondestructive Testing Handbook*'s second edition. As Handbook Development Director, Roderic Stanley has chaired this committee during the publication of two volumes and he, along with all of the committee members, made special effort to help complete this latest book.

Even though this material was prepared by the authors especially for *Magnetic Particle Testing*, some of the first drafts had an unexpected consistency, if not a kind of familiarity. It soon became clear that this occurred because of the high quality and availability of several early publications in the field — Carl Betz's *Principles of Magnetic Particle Testing* (1967) and F.B. Doane's *Principles of Magnaflux Inspection* (1940). The American Society for Nondestructive Testing gratefully acknowledges this debt and extends thanks to Magnaflux Corporation, Chicago, Illinois, in particular for access to its photographic archives.

In an effort to document nondestructive testing applications for an international audience and to acknowledge the differences in magnetic particle testing outside the United States, this book was written and reviewed by authorities from across the US and from Germany, United Kingdom, Japan, Holland and Canada. Much effort was made to reference international specifications, procedures and equipment whenever they differed from their American counterparts: In addition, as with all the second edition volumes, the International System of Units (SI) has been used throughout this text.

Providing multiple units of measure is a time-consuming task that affects all levels of book production, clerical and technical. Special recognition goes to Jan van den Andel of Westinghouse Canada for again undertaking this difficult job. He has supplied metric conversions for all of the books in the second edition, while at the same time serving as one of our most trustworthy and valued technical reviewers.

From among the publishing professionals who contributed to this project, ASNT extends its thanks to Hollis Humphries Black, who keyed all the text in this volume; Turner Wainwright Design, our technical drafting source; and Michael McGinn, art director for Lawhead Press. The quality of the finished volume is representative of their skills and the dedication of all the book's contributors.

Paul McIntire
Handbook Editor

ACKNOWLEDGMENTS

Magnetic Particle Testing, Volume 6 of the *Nondestructive Testing Handbook*'s second edition, is an effort by many volunteers to present a comprehensive guide to this important inspection technology. As originally outlined and in keeping with the objectives established by ASNT's Electrical and Magnetic Committee, the volume presents both theory *and* applications.

The three commentaries that follow were written to highlight the volume's content and intentions, and to suggest the book's place within the extensive literature of magnetic particle testing. More importantly, they also acknowledge the industry's debt to the volunteers who produced all of this text.

Purpose of this Nondestructive Testing Handbook

Many years ago, ASNT began what is probably its most significant contribution to the science of nondestructive testing, namely publication of the *Nondestructive Testing Handbook*. First published in 1959, the *NDT Handbook* aspired to be the encyclopedia which would include all the basic knowledge necessary for successful practice of nondestructive testing procedures. The first edition contained two volumes, edited by Dr. Robert C. McMaster.

Now, thirty years later, NDT has grown and matured tremendously. The sheer volume of knowledge has increased to the point where a separate book is necessary for each testing technique and a group effort is required to properly cover even one inspection method. Such a group has been laboring for five years to organize this volume and now the effort has come to fruition.

Organization of the Volume

The organizational group for this book consisted of Paul McIntire, Tom Schmidt, Kermit Skeie and Rod Stanley.

As an ASNT staff member and editor of the *NDT Handbook* series, McIntire is the one who produced all drafts from authors' copy, coordinated the peer review process, made the final edits and saw to all the details of book production.

Kermit Skeie and Tom Schmidt were the technical editors who devised the book's basic format, outlined its content, enlisted most of the authors, reviewed the manuscripts for technical accuracy and themselves contributed manuscripts.

In addition to his duties as chair of the Handbook Development Committee, Rod Stanley acted as the magnetic particle volume coordinator. In this role, Stanley motivated the book's contributing authors, served as the primary reviewer and was also a reliable contributor of extensive manuscript.

Volunteer Contributors

The organizers of this volume could not have accomplished their task alone. The actual text of this book was written by authors who are longtime experts in their fields, and who have voluntarily contributed their knowledge and time to this comprehensive effort. The editors wish to acknowledge and thank all those who contributed.

Future of the Magnetic Particle Method

The magnetic particle method is one of the oldest nondestructive tests. Some people think of it as *low tech* and on the way to obsolescence. As some of the chapters of this volume amply demonstrate, magnetic particle testing is a *complex* procedure and its proper use demands as much skill and scientific foundation as any other method.

And the method is far from obsolete. It provides a fast, overall test of the surface and near surface integrity of magnetizable materials unmatched by other techniques, and it visibly indicates discontinuities directly on the test surfaces, at their actual locations, and in nearly actual size.

There is, in fact, a kind of mutual dependence among all the nondestructive testing techniques. Common practice often includes a survey of new materials by the magnetic particle method to find general discontinuity locations for later detail testing by other methods. This author vividly remembers attending a meeting in 1954 where the prediction was made that the "obsolete magnetic particle method [would] soon be replaced by sophisticated electronic methods." As it turns out, that predictor was long ago replaced, but the test method has remained, increasing in use and value.

Use of the Nondestructive Testing Handbook

This volume details the magnetic particle test method in all its facets. All levels of technical ability are addressed. Principles are covered simply for the beginner, but subject matter is also covered in great depth for the more accomplished practitioner. Thus, the material presented here will serve as a basic source of information on the magnetic particle method for many years to come.

J. Thomas Schmidt
Volume technical editor

Role of this Nondestructive Testing Handbook

Development of Magnetic Particle Tests

The magnetic particle method has historically been based on empirical guidelines that are perpetuated because they appear to work. Usually, no attention is given to the adage that "we never know what we missed unless failure occurs."

With equipment, structures and products of all kinds being designed with a relatively low safety factor, more attention must be given to refining the magnetic particle method to make it more reliable — application of fracture mechanics demands predictable performance.

Need for Standardization of the Technique

Why would a practitioner of NDT, NDI or NDE need a book on magnetic particle testing? The method seems so simple in concept and has served so well for fifty years that nearly everyone knows all that is needed about the subject, right? If so, then why in the 1980s would a controlled study on the magnetic particle method result in a probability of detection less than 50 percent?

In the 1960s, a supervisor of NDT development in quality engineering stated that no funding was available for studies of magnetic particle testing because the test would soon be replaced by other methods. High strength materials would replace virtually all the ferromagnetic materials in use and the specifications on this old-line testing method were adequate and in place. Why then, nearly 10 years later, could qualified and certified inspectors find less than 60 percent of the known discontinuities in a monitored study? Why, more than 20 years later, was their process standard on magnetic particle testing rewritten? This volume of the *Nondestructive Testing Handbook* was designed to help answer such questions.

Goals of this Volume

For a long time, magnetic particle testing lacked the reference standards so common and essential to other NDT methods. Several such standards are described in detail in this book.

This volume also reveals some misconceptions about the magnetic particle method. One example is the often stated procedure that an effective magnetic field on a cylinder, produced with a current carrying conductor, is four times the diameter of the conductor. This can be neither theoretically nor practically supported. The fallacy was, in fact, first revealed by artificial discontinuity standards.

Data and techniques established elsewhere in the world have been largely ignored in the United States. This book has tried to expand the scope of previously published reference materials by acknowledging and quoting from a variety of international sources.

A major application for magnetic particle methods is the testing of piping and tubing, both new and used, by the petrochemical industries. Methods, theories and techniques for this application are included in this volume.

Finally, for those with specific needs (electromagnetic theory, safety or existing specifications, for example) much helpful and authoritative information is provided by this text.

This collection of data from dozens of authors could not be compiled or disseminated through a single channel other than a professional society such as ASNT. This book is a direct product of the Society's volunteer commitment and effort.

Kermit Skeie
Volume technical editor

Content of this Nondestructive Testing Handbook

Magnetic Testing.

Magnetic testing has been with us for very many years. Magnetic methods have been used, and continue to be used, throughout industry to test ferromagnetic components as diverse as bars, billets, railroad rails, pipe lines, cranes, auto parts, landing gear, ball bearings and even nuts and bolts. Objects are tested magnetically when new for conformance to specifications and are also tested during and after use to determine the object's ability to continue in service.

The actual techniques employed are often determined by the size and shape of the test object, and the suspected location of possible discontinuities. There is, however, a common thread that holds magnetic test methods together. This thread starts with the fact that the test object must be magnetized (in one or more directions, often at the same time), continues through the selection of the best possible sensor to detect the relevant test parameters and ends with the acceptance or rejection of the material in accordance with certain predetermined criteria.

Electromagnetic Testing

Methods for magnetizing test objects include permanent magnets and the use of electric current. Permanent magnet methods have been given a new lease on life with the introduction of rare earth magnets (neodymium iron and samarium cobalt). Electric current methods include the creation of an electromagnet (commonly termed a *yoke* which, stripped to its essentials, is a coil with a high permeability core), the use of air cored coils and threader bars, and the passage of current through the test object itself. All of these methods create magnetic flux in the tested material.

At this point, however, the specialized topic of magnetic particle testing breaks away from the general field of electromagnetic testing (covered in Volume 4 of the *Nondestructive Testing Handbook* series). *Electromagnetic testing* is a term that designates the entire subject of magnetic and electric fields and their interactions with materials, and so includes eddy current methods, magnetic flux leakage, microwave and thermoelectric methods. Magnetic particle testing turns out to be a branch of magnetic flux leakage inspection.

Coverage of this Volume

Historically, from the testing viewpoint, magnetic particle inspection has been considered a stand-alone method. In reality, what makes it so is its sensor: that collection of oddly shaped and sized highly permeable materials that we cause to pass through magnetic leakage fields from tight discontinuities in the hope that some of them might be held by the leakage field.

This book attempts to provide both the theory behind and the technology of this fascinating topic. It covers the discontinuities detected by the technique; methods for magnetizing materials; methods for testing whether materials might be sufficiently magnetized for the detection of certain types of discontinuities; and some of the codes and specifications that have evolved around the technique. Safety hazards are also addressed (try to take a black light onto an oil rig in the North Sea!) and a group of contributors have shared various industrial applications.

Readers are cautioned to keep an open mind when performing magnetic tests, especially in relation to the many specifications that have sprung up around the technology. What may work in a particular situation may not be addressed in specification documents or it may not be addressed correctly. As inspectors, our job is to detect and interpret discontinuity indications, not to be hide bound by documentation. We hope that this text provides enough stimulating material that its readers will be able to perform magnetic particle tests with a better knowledge of the technique and to try new versions of older methods with a deeper understanding of their foundations.

This material was gathered from a wide variety of sources and we have tried to include some of the less common techniques and some techniques that may be used in Europe but not in the United States. We have covered as many applications as possible and regret if we have not provided information that is specific to some inspection problems.

Lead Authors and Reviewers

Every Section of this Volume was assigned its own coordinator who in most cases served as the primary author. All of these individuals and the contributors they organized deserve special recognition. Each of those named below produced their part of this book as a volunteer — many on their own time with their own resources, in an effort to make the technology available to the widest possible audience.

Equally important is the large group of individuals who reviewed all the text in this volume for technical content. The peer reviewers are also listed below and they deserve much credit, for donating the time needed to refine these documents for presentation. Because of the reviewers, many changes and improvements were made possible, to extend the book's coverage and to maintain its continuity.

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Major contributors to individual chapters are listed alphabetically on the Section title page under the name of the primary author.

Origin and Use of the SI System

The SI system was designed so that all branches of science could use a single set of interrelated measurement units. These units are modified in specified ways to make them adaptable to the needs of individual disciplines. Without the SI system, this *Nondestructive Testing Handbook* volume could have contained a confusing mix of Imperial units, old cgs metric units and the units preferred by certain localities, industries or scientific specialties.

Use of the SI system also provides a mathematical advantage. In equations, SI units and their powers balance on each side of the equal sign. This provides a double-check of accuracy: an equation error will reveal itself not only through an imbalance but through the different units created by the imbalance.

SI Units for Magnetic Particle Testing

Specific units used in this volume are mainly those for magnetism, visible light and ultraviolet radiation. Originally, these units were developed by scientists using the cgs (centimeter gram second) metric system. With the introduction of SI, these quantities were rearranged into a series of base units (Table 1) and derived units (Table 2).

For magnetic theories, this meant the removal of intermediate units (such as the *unit pole*) and made possible a direct conversion from flux cut per second to voltage. The SI units include the weber (Wb), the tesla (T) and several derived units. Tesla is a large unit and is often used with the SI multipliers (Table 3). Listed below are the four basic units found in this text.

Magnetic field strength: expressed in *ampere per meter* ($A{\bullet}m^{-1}$). Was formerly measured in *oersted* (Oe), a nonexisting physical agent enabling analysis of complex magnetic field problems. One ampere per meter is equal to about 1.3×10^{-2} Oe.

Magnetic flux density: expressed in weber per square meter ($Wb{\bullet}m^{-2}$) or *tesla* (T) to indicate flux per unit area. Was formerly measured in *gauss* (G). One tesla is equal to 10^4 gauss.

Ultraviolet irradiance: expressed in *watts per square meter* ($W{\bullet}m^{-2}$). Was formerly measured in cgs metric units as *microwatts per square centimeter* ($\mu W{\bullet}cm^{-2}$). The units of measure used for the visible light range cannot be used for ultraviolet energy.

Visible light intensity: expressed as *lux* (lx). Was formerly measured in *footcandle* (ftc). One lux is equal to 0.1 footcandle.

TABLE 1. Base SI Units

Quantity	Unit Name	Unit Symbol
length	meter	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temperature	kelvin	K
amount of substance	mole	mol
luminous intensity	candela	cd
plane angle	radian	rad
solid angle	steradian	sr

TABLE 2. Derived SI Units

Quantity	Name	Symbol	Relation to Other SI Units
frequency	hertz	Hz	$1{\bullet}s^{-1}$
force	newton	N	$kg \times m{\bullet}s^{-2}$
pressure (stress)	pascal	Pa	$N{\bullet}m^{-2}$
energy (work)	joule	J	$N \times m$
power	watt	W	$J{\bullet}s^{-1}$
electric charge	coulomb	C	$A \times s$
electric potential	volt	V	$W{\bullet}A^{-1}$
capacitance	farad	F	$C{\bullet}V^{-1}$
electric resistance	ohm	Ω	$V{\bullet}A^{-1}$
conductance	siemens	S	$A{\bullet}V^{-1}$
magnetic flux	weber	Wb	$V \times s$
magnetic flux density	tesla	T	$Wb{\bullet}m^{-2}$
inductance	henry	H	$Wb{\bullet}A^{-1}$
temperature	degrees Celsius	°C	K − 273.15
luminous flux	lumen	lm	$cd \times sr$
illuminance	lux	lx	$lm{\bullet}m^{-2}$
radioactivity	becquerel	Bq	$1{\bullet}s^{-1}$
radiation absorbed dose	gray	Gy	$J{\bullet}kg^{-1}$
radiation dose equivalent	sievert	Sv	$J{\bullet}kg^{-1}$

SI Multipliers

Very large or very small units are expressed using the SI multipliers, prefixes that are usually of 10^3 intervals. The range covered in this text is shown in Table 3. These multipliers become a property of the SI unit. For example, a centimeter (cm) is 1/100 of a meter, and the volume unit, cubic centimeter (cm^3), is $(1/100)^3$ or 10^{-6} m^3. Units such as the centimeter, decimeter, decameter and hectometer are avoided in technical uses of the SI system because of their variance from the 10^3 interval.

Every effort has been made to include all necessary SI and conversion data in the text of this book. If questions remain, the reader is referred to the information available through national standards organizations and to the specialized information compiled by technical societies (see ASTM E-380, *Standard Metric Practice Guide*, for example).

Jan van den Andel
Westinghouse Canada

TABLE 3. SI Multipliers

Prefix	Symbol	Multiplier
tera	T	10^{12}
giga	G	10^{9}
mega	M	10^{6}
kilo	k	10^{3}
hecto	h	10^{2}
deca	da	10
deci	d	10^{-1}
centi	c	10^{-2}
milli	m	10^{-3}
micro	μ	10^{-6}
nano	n	10^{-9}
pico	p	10^{-12}

CONTENTS

SECTION 1

FUNDAMENTALS OF MAGNETIC PARTICLE TESTING

Bernie Boisvert, NDT consultant, Dayton, Ohio

PORTIONS OF THIS TEXT ADAPTED FROM *NONDESTRUCTIVE INSPECTION METHODS* (US AIR FORCE TO-33B-1-1)

PART 1

INTRODUCTION TO MAGNETIC PARTICLE TESTING

Capabilities and Limitations of Magnetic Particle Techniques

Magnetic particle testing can reveal surface discontinuities, including those too small or too tight to be seen with the unaided eye. Magnetic particle indications form on an object's surface above a discontinuity and show the location and approximate size of the discontinuity. Magnetic particle tests can also reveal discontinuities that are slightly below the surface.

There are limits on this ability to locate subsurface discontinuities. These are determined by the discontinuity's depth, its size, type and shape, and the strength of the applied field. In some cases, special techniques or equipment can improve the test's ability to detect subsurface discontinuities.

Magnetic particle testing cannot be used on nonmagnetic materials, including glass, ceramics, plastics or such common metals as aluminum, magnesium, copper and austenitic stainless steel alloys. In addition, there are certain positional limitations: a magnetic field is directional and for best results must be oriented perpendicular to the discontinuity. This generally requires two complete magnetizing operations to detect discontinuities parallel and perpendicular to the test object's axis. Objects with large cross sections require a very high current to generate a magnetic field adequate for magnetic particle tests. A final limitation is that a demagnetization procedure is usually required following the magnetic particle process.

This text provides an overview of the magnetic particle testing process and is introductory to the detailed treatments in subsequent sections. Topics covered here include: (1) basic steel and component production and some of the discontinuities produced; (2) the fundamental theory of magnetism, magnetic flux and types of magnetic fields; (3) principles of electrically induced magnetism and magnetizing current; (4) testing media and processes; and (5) basic principles and methods of demagnetization.

Such data can be helpful to managers, supervisors and personnel outside nondestructive testing who require general information on the magnetic particle testing process. It may also be helpful for introductory studies by individuals already using magnetic particle testing or those preparing for advanced training in the technique.

Principles of Magnetic Particle Testing

Magnetic particle testing is a nondestructive method of revealing surface and slightly subsurface discontinuities in magnetizable materials. It may be applied to raw materials such as billets, bars and shapes; during processes such as forming, machining, heat treating and electroplating; and in testing for service related discontinuities. Magnetic particle procedures cannot be used with nonmagnetizable materials such as aluminum or copper.

The testing method is based on the principle that magnetic flux in a magnetized object is locally distorted by the presence of a discontinuity. This distortion causes some of the magnetic field to exit and reenter the test object at the discontinuity. This phenomenon is called *magnetic flux leakage*. Flux leakage is capable of attracting finely divided particles of magnetic materials which in turn form an outline or indication of the discontinuity.

One of the objectives of magnetic particle testing is to detect discontinuities as early as possible in the processing sequence, thus avoiding the expenditure of effort on materials that will later be rejected. Practically every process, from the original production of metal from its ore to the last finishing operation, may introduce discontinuities. Magnetic particle testing can reveal many of these, preventing flawed components from entering service. Even though magnetic particle testing may be applied during and between processing operations, a final test is usually performed to ensure that all detrimental discontinuities have been detected.

The test itself consists of three basic operations: (1) establish a suitable magnetic flux in the test object; (2) apply magnetic particles in a dry powder or a liquid suspension; and (3) examine the test object under suitable lighting conditions, interpreting and evaluating the test indications.

PART 2

FABRICATION PROCESSES AND MAGNETIC PARTICLE TEST APPLICATIONS

There are several ways to classify magnetic particle testing applications. Most approaches involve the discontinuities of interest, but these classifications prove to be too specific or too general for practical application.

One broad classification method, which is also used in liquid penetrant testing, is based on discontinuity location: surface or subsurface. This classification procedure is useful for magnetic particle tests since the ability to find discontinuities of each type varies sharply. Beyond this use though, the location classification system is too broad for common use by magnetic particle test inspectors.

Another method of classifying test applications is by using the process in which they are applied: forging, casting, welding, heat treating, grinding and so on. These processes are also used to define discontinuity types: forging cracks, heat treat cracks or grinding cracks, for example. While this system is used extensively for describing discontinuities, it is too specific for all magnetic particle applications.

The most widely used classification system considers the origin of discontinuities in the stages of fabrication and service. These classes may be broadly categorized as follows.

1. *Primary production and processing tests*: this testing category is used to inspect the stages of processing from pouring and solidification of the ingot to production of basic shapes, including sheet, bar, pipe, tubing, forgings and castings. These tests are typically used to locate two discontinuity subgroups: (a) those formed during solidification are called *inherent discontinuities*; and (b) those formed during mill reduction are called *primary processing discontinuities*.
2. *Secondary processing* or *manufacturing and fabrication tests*: this testing category is used to inspect the results of processes that convert raw stock into finished components. Forming, machining, welding and heat treating discontinuities are detected with this kind of magnetic particle test.
3. *Service tests*: these test procedures are widely used for detecting over-stress and fatigue cracking. Magnetic particle tests are *not* used to detect corrosion, deformation or wear, three of the most common service induced problems.

Basic Ferromagnetic Materials Production

In the production of ferrous alloys, iron ore is converted to steel in one or more furnaces where it is melted, refined and alloying elements are added. While in the liquid state, the metal is poured into a mold and allowed to solidify into a shape typically called an *ingot*.

Ingots are quite large and must be formed into more manageable shapes by hot working through a series of rolls or mills. These semifinished shapes are called *blooms*, *billets* or *slabs*, depending on their size and shape. A bloom is an intermediate product, rectangular in shape with a width not more than twice its thickness and a cross-sectional area typically larger than 0.02 m^2 (36 $in.^2$). A billet can be round or square with a cross-sectional area from 1,600 mm^2 to 0.02 m^2 (2.5 to 36 $in.^2$). A slab is an intermediate shape between an ingot and a plate with a width at least twice its thickness.

Inherent Discontinuities

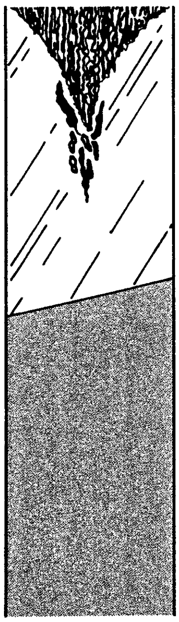
This group of discontinuities occurs during the initial melting and refining processes and during solidification from the molten state. Such discontinuities are present before rolling or forging is performed to produce intermediate shapes.

Pipe

When molten metal is poured into an ingot mold, solidification progresses gradually, starting at the bottom and sides of the mold and progressing upward and inward. The solidified metal is slightly smaller in volume than the liquid and there is progressive shrinkage during solidification. The last metal to solidify is at the top and center of the mold. Because of the shrinkage, there is typically insufficient liquid metal remaining to fill the mold and a depression or cavity is formed.

In addition, impurities such as oxides and entrapped gases tend to migrate to the center and top of a mold and may become embedded in the last portions to solidify. After solidification, the upper portion is cut off or cropped and

FIGURE 1. Cross section of an ingot showing shrinkage cavity at top center



discarded, removing most of the shrinkage cavity and impurities. However, if the cavity is deeper than normal or if the cropping is short, some of the unsound metal will show up in the intermediate shape as a void called *pipe*.

Figure 1 shows an ingot cross section illustrating the shrinkage cavity and impurities in the top center. Pipe is almost always centered in the semifinished shape and is undesirable for most purposes.

Nonmetallic Inclusions

All steel contains nonmetallic matter that mainly originates in deoxidizing materials added to the molten metal during the refining operation. These additives are easily oxidized metals such as aluminum, silicon, manganese and others. The oxides and sulphides of the metals make up the majority of nonmetallic inclusions. When finely divided and well distributed, these discontinuities are not objectionable.

However, sometimes the additives collect during solidification and form large clumps in an ingot. During primary processing these large clumps are rolled out into long discontinuities called *stringers*. In highly stressed components, stringers can act as nucleation points for fatigue cracking. In certain test objects, stringers are acceptable in limited amount. Government and industry specifications on steel cleanliness define the amount of inclusions or stringers that may be accepted.

The addition of lead or sulfur to molten steel is a common practice for the alloys known as *free machining steels*. These alloys contain a large number of nonmetallic inclusions that break or chip during machining operations. Magnetic particle tests of free machining alloys often indicate an alarming number of discontinuities that are not considered detrimental in service.

Blowholes

As molten steel is poured into an ingot and solidification commences, there is an evolution of gases. These gases rise through the liquid in the form of bubbles and many escape or migrate to the cropped portion of the ingot.

However, some gases can be trapped in the ingot, forming the discontinuities known as *blowholes*. Most blowholes are clean and will weld or fuse shut during primary and secondary rolling. Those near the surface may have an oxidized skin and will not fuse, appearing as seams in the rolled, forged or extruded product. Oxidized blowholes in the interior of slabs appear as laminations in plate products.

Ingot Cracks

Contraction of the metal during solidification and cooling of the ingot generates significant surface stresses and internal stresses which can result in cracking. If the cracks are internal and no air reaches them, they are usually welded shut during rolling and do not result in discontinuities. If they are open to the air or otherwise become oxidized, they will not seal but remain in the finished product.

During the rolling of an ingot into a billet, oxidized cracks form long seams. It is common practice to use magnetic particle tests of billets before additional processing. Such preprocessing tests permit the removal of seams by grinding, chipping or flame scarfing. If not removed before rolling or working, seams are further elongated in finished shapes and this may make the final product unsuitable for many applications.

Primary Processing Discontinuities

When steel ingots are worked down to shapes such as billets, slabs and forging blanks, some inherent discontinuities may remain in the finished product. In addition, rolling or forming operations may themselves introduce other discontinuities. The primary processes considered here include the hot working and cold working methods of producing shapes such as plate, bars, rod, wire, tubing and pipe.

Forging and casting are also included in this category because they typically require additional machining or other subsequent processing. All the primary processes have the potential for introducing discontinuities into clean metal.

Seams

Seams in bars, rod, pipe, wire and tubing are usually objectionable and make the product unsuitable for many applications. Seams can originate from ingot cracks and despite preprocessing tests, some cracks can be overlooked or incompletely removed.

Rolling and drawing operations can also produce seams in the finished product. If the reduction on any of the rolling passes is too great, an overfill may then produce a projection from the billet (see Fig. 2). This projection can be folded or lapped on subsequent passes, producing a long deep seam.

The reverse also occurs if the shape does not fill the rolls, resulting in a depression or surface groove. On subsequent rolling passes, this underfill produces a seam running the full length of the shape. Seams originating from overfilled rolls usually emerge at an acute angle to the surface. Seams caused by underfilled rolls are likely to be normal to or perpendicular to the surface.

Seams or die marks can be introduced by defective or dirty dies during drawing operations. Such seams are often fairly shallow and may not be objectionable, especially when subsequent machining removes the seam. Seams are always objectionable in components that experience repeated or cyclic stresses in service. These seams can nucleate fatigue cracks.

Laminations

Laminations in plate, sheet and strip are formed when blowholes or internal cracks are not welded shut during rolling, but are flattened and enlarged. Laminations are large and potentially troublesome areas of horizontal discontinuity.

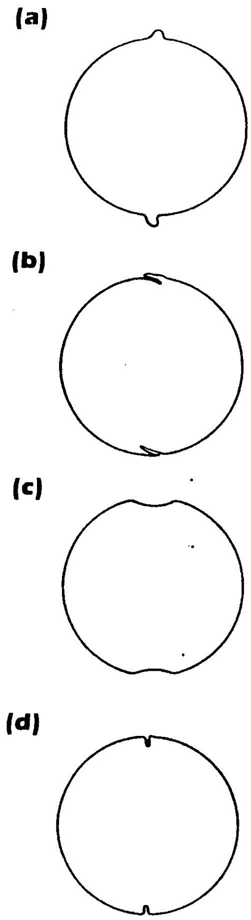
Magnetic particle testing detects lamination only when it reaches and breaks the edges of a plate. Laminations that are completely internal to the test object typically lie parallel to its surface and cannot be detected by magnetic particle procedures.

Cupping

Cupping occurs during drawing or extruding operations when the interior of the shape does not flow as rapidly as the surface. The result is a series of internal ruptures that are serious whenever they occur (see Fig. 3).

Cupping can be detected by the magnetic particle method only when it is severe and approaches the surface.

FIGURE 2. Formation of seams and laps: (a) overfill produces excess metal squeezed out of rolls; (b) a lap results when the projection is folded over and forced back into the bar's surface during a subsequent pass; (c) underfill results when there is not enough metal to fill the rolls; and (d) a seam in the finished bar occurs when underfill is squeezed tight on a subsequent rolling pass



Cooling Cracks

Bar stock is hot rolled and then placed on a bed or cooling table and allowed to reach room temperature. During cooling, thermal stresses may be set up by uneven rates of temperature change within the material. These stresses can be sufficient for generating cracks (see Fig. 4).

FIGURE 3. Cupping formed during drawing or extruding

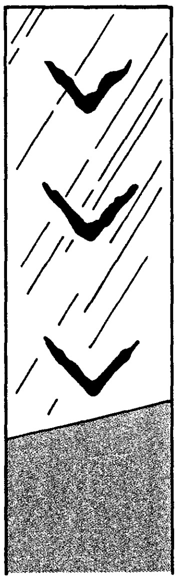
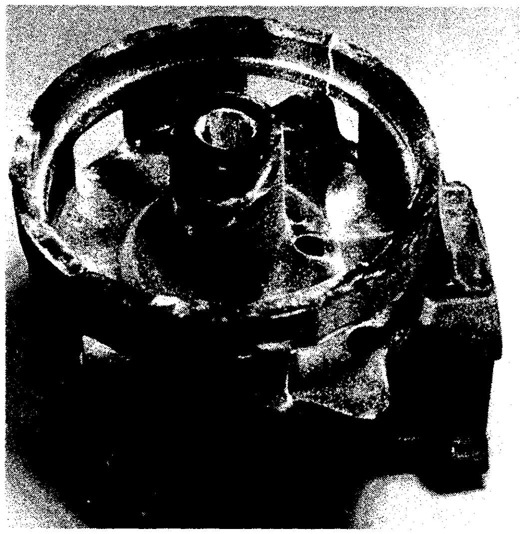


FIGURE 4. Cooling cracks indicated with fluorescent magnetic particles



Cooling cracks are generally longitudinal but because they tend to curve around the object shape, they are not necessarily straight. Such cracks may be long and often vary in depth along their length. Magnetic particle indications of cooling cracks therefore can vary in intensity (heavier where the crack is deepest).

Forging Discontinuities

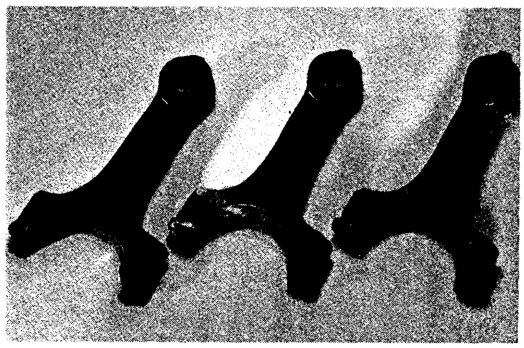
Forgings are produced from an ingot, a billet or forging blank that is heated to the plastic flow temperature and then pressed or hammered between dies into the desired shape. This hot working process can produce a number of discontinuities, some of which are described below.

Flakes

Flakes are internal ruptures that some believe are caused by cooling too rapidly. Another theory is that flakes are caused by the release of hydrogen gas during cooling.

Flakes usually occur in fairly heavy sections and some alloys are more susceptible than others. These ruptures are usually well below the surface, typically more than half way between the surface and the center. Because of their positioning, flakes are not detectable by magnetic particle techniques unless machining brings the discontinuity close to the surface.

FIGURE 5. Forging laps in piston rods



Forging Bursts

When steel is worked at improper temperatures, it can crack or rupture. Reducing a cross section too rapidly can also cause forging bursts or severe cracking.

Forging bursts may be internal or surface anomalies. When at or near the surface, they can be detected by the magnetic particle method. Internal bursts are not generally detected with magnetic particles unless machining brings them near the surface.

Forging Laps

During the forging operation, there are several factors that can cause the surface of the object to fold or lap. Because this is a surface phenomenon exposed to air, laps are oxidized and do not weld when squeezed into the object (see Fig. 5).

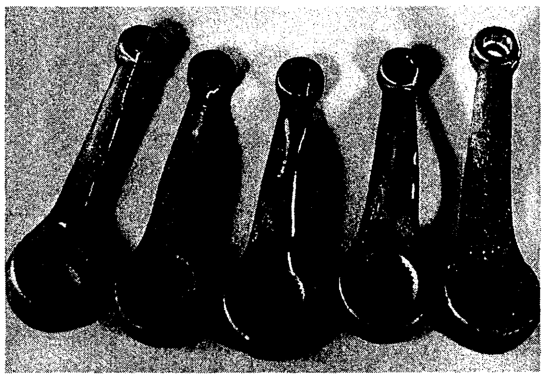
Forging laps are difficult to detect by any nondestructive testing method. They lie at only slight angles to the surface and may be fairly shallow. Forging laps are almost always objectionable since they serve as fatigue crack nucleation points.

Flash Line Tears

As the dies close in the final stage of the forging process, a small amount of metal is extruded between the dies. This extruded metal is called *flash* and must be removed by trimming.

If the trimming is not done or not done properly, cracks or tears can occur along the flash line (see Fig. 6). Flash line tears are reliably detected by magnetic particle testing.

FIGURE 6. Flash lines and laps in forgings



Casting Discontinuities

Castings are produced by pouring molten metal into molds. The combination of high temperatures, complex shapes, liquid metal flow and problematic mold materials can cause a number of discontinuities peculiar to castings. Some of these are described below.

Cold Shuts

Cold shuts originate during pouring of the metal when a portion of the molten liquid solidifies prior to joining with the remaining liquid. The presence of an oxidized surface, even though it is liquid or near liquid, prevents fusion when two surfaces meet. This condition can result from splashing, interrupted pouring or the meeting of two streams of metal coming from different directions.

Cold shuts can be shallow skin effects or can extend quite deeply into the casting. Shallow cold shuts called *scabs* can be removed by grinding. Deep cold shuts cannot be repaired.

Hot Tears and Shrinkage Cracks

Hot tears are surface cracks that occur during cooling after the metal has solidified. They are caused by thermal stresses generated during uneven cooling. Hot tears usually originate at abrupt changes in cross section where thin sections cool more rapidly than adjacent heavier masses.

Shrinkage cracks are also surface cracks that occur after the metal cools. They are caused by the contraction or reduction in volume that the casting experiences during solidification.

Weldment Discontinuities

Welding can be considered a localized casting process that involves the melting of both base and filler metal. Welds are subject to the same type of discontinuities as castings but on a slightly different scale. In addition, other discontinuities may be formed as a result of improper welding practices. Some of the discontinuities peculiar to weldments are described below.

Lack of Fusion and Lack of Penetration

Failure to melt the base metal results in a void between the base and filler materials. This lack of fusion can be detected by magnetic particle methods if it is close enough to the weld surface.

With lack of penetration, only a thin layer of the base metal has been melted. Magnetic particle testing does not generally detect lack of penetration.

Heat Affected Zone Cracks and Crater Cracks

Cracks in the base metal adjacent to the weld bead can be caused by the thermal stresses of both melting and cooling. Such cracks are usually parallel to the weld bead. Heat affected zone cracking is easily detected by magnetic particle testing.

Cracks in the weld bead caused by stresses from solidification or uneven cooling are called *crater cracks*. Cracks caused by solidification usually occur in the final weld puddle. Cracks caused by uneven cooling occur in the thin portion at the junction of two beads. Magnetic particle testing is widely used to detect crater cracks.

Manufacturing and Fabrication Discontinuities

This classification includes discontinuities associated with various finishing operations after the material has been rough formed by rolling, forging, casting or welding. Processes such as machining, heat treating or grinding may introduce discontinuities, some of which are described below.

Machining Tears

Machining tears occur if a tool bit drags metal from the surface rather than cutting it. The primary cause of this is improperly shaped or dull cutting edges on the bit.

Soft or ductile metals such as low carbon steel are more susceptible to machining tears than harder medium carbon and high carbon steels. Machining tears are surface discontinuities and are reliably detected by the magnetic particle method.

Heat Treating Cracks

When steels are heated and quenched (or otherwise heat treated) to produce properties for strength or wear, cracking may occur if the operation is not suited to the material or the shape of the object. The most common sort of such cracking is *quench cracking*, which occurs when the metal is heated above the critical transition point and is then rapidly cooled by immersing it in a cold medium such as water, oil or air.

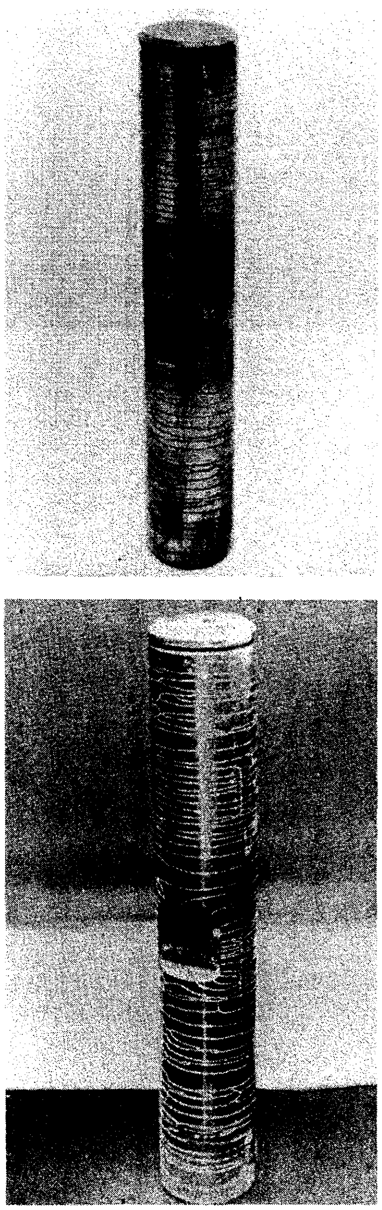
Cracks are likely to occur at locations where the object changes shape from a thin to a thick cross section, at fillets or notches. The edges of keyways and roots of splines or threads are also susceptible to quench cracking.

Cracks can also originate if the metal is heated too rapidly, causing uneven expansion at changes of cross section. In addition, rapidly increasing heat can cause cracking at corners, where heat is absorbed from three surfaces and is therefore absorbed much more rapidly than by the body of the object. Corner cracking can also occur during quenching because of the thermal stresses of uneven cooling.

FIGURE 7. Grinding cracks indicated with: (a) visible magnetic particles; and (b) fluorescent magnetic particles

(a)

(b)



Straightening and Grinding Cracks

The uneven stresses caused by heat treating frequently result in distortion or warping and the metal forms must be straightened into their intended shape. If the distortion is too great or the objects are very hard, cracking can occur during the straightening operation.

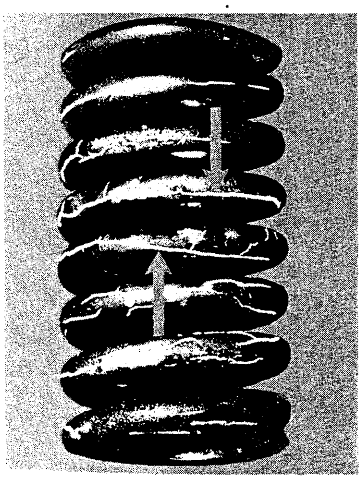
Surface cracks can also occur in hardened objects during improper grinding operations. Such thermal cracks are created by stresses from localized overheating of the surface under the grinding wheel. Overheating can be caused by using the wrong grinding wheel, a dull or glazed wheel, insufficient or poor coolant, feeding too rapidly or cutting too heavily. Grinding cracks are especially detrimental since they are perpendicular to the object surface and have sharp edges that propagate under repeated or cyclic loading (see Fig. 7).

Another type of discontinuity that may occur during grinding is cracking caused by residual stresses. Hardened objects may retain stresses that are not high enough to cause cracking. During grinding, localized heating added to entrapped stresses can cause surface ruptures. The resulting cracks are usually more severe and extensive than typical grinding cracks.

Plating, Pickling and Etching Cracks

Hardened surfaces are susceptible to cracking from electroplating, acid pickling or etching processes. There are several mechanisms that cause this cracking.

FIGURE 8. Treating with acid weakens the surface metal, allowing the release of a spring's internal stresses through surface cracks



Acid pickling can weaken surface fibers of the metal, allowing internal stresses from the quenching operation to be relieved by crack formation (see Fig. 8). Another cracking mechanism is the interstitial absorption of hydrogen released by the acid etching or electrodeposition process (Fig. 9). Absorption of nascent hydrogen adds to the internal stresses of the object and subsequently may cause cracking. This mechanism, called *hydrogen embrittlement*, can result in cracking during the etching or plating operation or at some later time when additional service stresses are applied.

Service Discontinuities

The remaining category of discontinuities are those formed after fabrication processes are complete and the object has been placed in service. The objective of magnetic particle testing during processing is to detect and eliminate harmful discontinuities and to place into service objects that are free of discontinuities. Even when this is fully accomplished, discontinuities can occur from service conditions. Some discontinuities such as deformation and wear are not detected by the magnetic particle test, but the technique is useful for indicating the discontinuities listed below.

Overstress Cracking

All materials have load limits (called *ultimate strength*) and when service stressing exceeds this limit, cracking occurs. Usually the failure is completed by surface fracture of the object. In this case, the crack is easy to detect and magnetic particle testing is not required.

FIGURE 9. Hydrogen or pickling cracks on steel spring

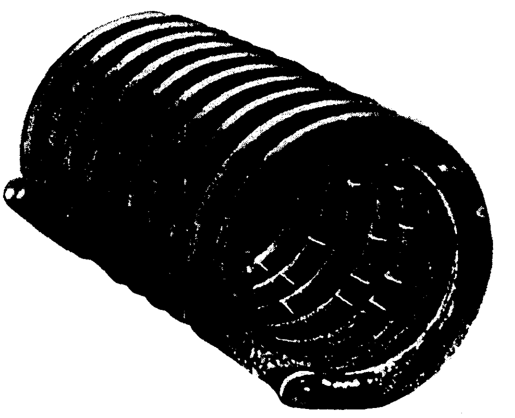
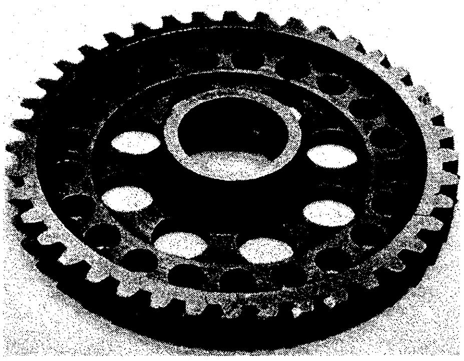
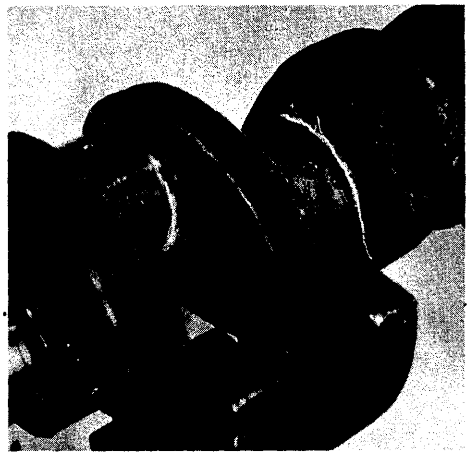


FIGURE 10. Fatigue cracking in manufactured components: (a) gear tooth roots; (b) automobile crankshaft; and (c) aircraft component

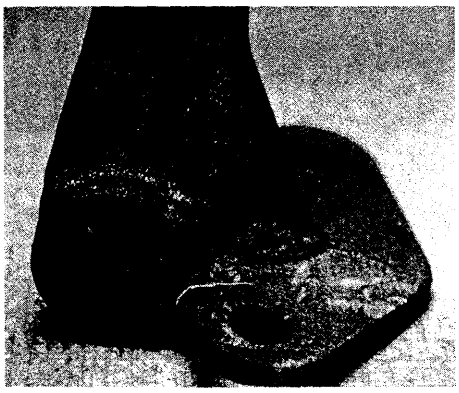
(a)



(b)



(c)



There are instances where surfaces do not visibly separate and magnetic particle testing is needed to detect and locate the cracking.

Fatigue Cracking

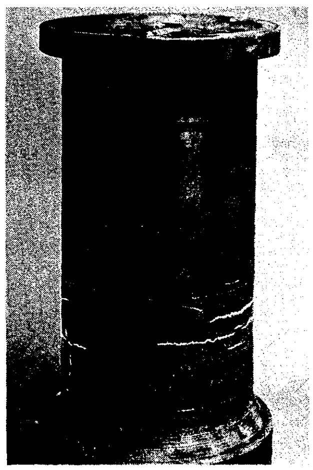
Objects subjected to repeated alternating or fluctuating stresses above a specific level eventually develop a crack (see Fig. 10). The crack continues to grow until the object fractures. The stress level at which fatigue cracks develop is called the *fatigue strength* of the material and is well below the ultimate strength of the material. There is an inverse relationship between the number of stress applications (cycles) and the stress level necessary to initiate cracking: low cycles and high stress produce the same results as high cycles and low stress.

Another factor contributing to fatigue cracking is the presence of surface anomalies such as copper penetration (see Fig. 11) sharp radii, nicks and tool marks. These act as stress risers and lower both the number of cycles and the stress level needed to initiate cracking. Fatigue cracking typically occurs at the surface and is reliably detected by magnetic particle testing.

Corrosion

Magnetic particle procedures are not used to detect surface corrosion or pitting. However, there are secondary discontinuities that can be revealed by the magnetic particle method. .When objects are under sustained stress, either

FIGURE 11. Fatigue crack from copper penetration on a journal



internal or external, and are at the same time exposed to a corrosive atmosphere, a particular kind of cracking results. Known as *stress corrosion cracking*, this discontinuity is easily detected by magnetic particle testing.

Another occurrence related to corrosion is pitting. Pitting itself does not usually produce magnetic particle indications (in some applications, sharp edged pits can hold particles). Pitting can serve as a stress riser and often nucleates fatigue cracks. Fatigue cracks originating at corrosion pits are reliably detected by the magnetic particle method.

PART 3
MAGNETIC FIELD THEORY

Magnetic Domains

Materials that can be magnetized possess atoms that group into submicroscopic regions called *magnetic domains*. These domains have a positive and negative polarity at opposite ends. If the material is not magnetized, the domains are randomly oriented, usually parallel with the crystalline axes of the material.

When the material is subjected to a magnetic field, the domains orient or align themselves parallel with the external magnetic field. The material then acts as a magnet. Figure 12 illustrates the domain alignment in nonmagnetized and magnetized material.

Magnetic Poles

A magnet has the property of attracting ferromagnetic materials. The ability to attract or (repel) is not uniform over the surface of a magnet but is concentrated at localized areas called *poles*. In every magnet, there are two or more poles with opposite polarities. These poles are attracted to the Earth's magnetic poles and therefore are called *north* and *south poles*.

FIGURE 12. Orientation of magnetic domains: (a) in a nonmagnetized material; and (b) in a magnetized material

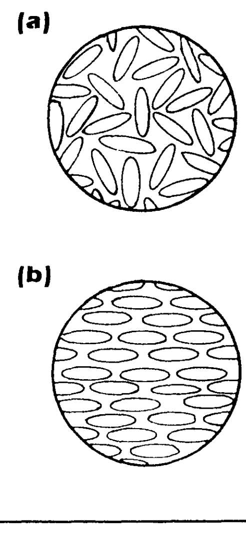


Figure 13 can be duplicated by placing a sheet of paper over a bar magnet and sprinkling iron particles on the paper. It shows the magnetic field leaving and entering the ends or poles of the magnet. This characteristic pattern illustrates the term *lines of force* used to describe a magnetic flux field. There are a number of important properties associated with lines of force.

1. They form continuous loops which are never broken but must complete themselves through some path.
2. They do not cross one another.
3. They are considered to have direction, leaving from the north pole, traveling through air to the south pole where they reenter the magnet and return through the magnet to the north pole.
4. Their density decreases with increasing distance from the poles.
5. They seek the path of least magnetic resistance or reluctance in completing their loop.

When a bar magnet is broken into two or more pieces, new magnetic poles are formed. The opposing poles attract one another as shown in Fig. 14.

FIGURE 13. Magnetic field surrounding a bar magnet

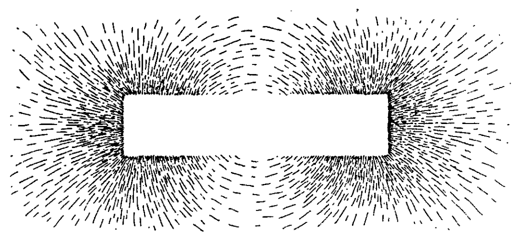
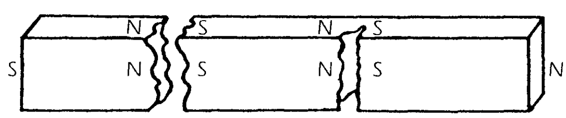


FIGURE 14. Broken bar magnet illustrating locations of newly formed magnetic poles



If the center piece in Fig. 14 is reversed so that similar poles are adjacent, the lines of force repel one magnet from the other. If one of the bars is small enough, the lines of force can cause it to rotate so that unlike poles are again adjacent. This illustrates the most basic rule of magnetism: unlike poles attract and like poles repel.

Types of Magnetic Materials

All materials are affected to some degree by magnetic fields. Matter is made up of atoms with a positively charged nucleus surrounded by a field or cloud of negatively charged electrons. The electron field is in continual motion, spinning around the nucleus. When the material is subjected to a magnetic field, the electron orbits are distorted to some degree. The amount of this distortion (or the corresponding change in magnetic characteristics) when subjected to an external magnetic field provides a means of classifying materials into three groups: diamagnetic, paramagnetic or ferromagnetic.

Diamagnetic Materials

The term diamagnetic refers to a substance whose magnetic permeability is slightly less than that of a vacuum. When placed in a strong magnetic field their induced magnetism is in a direction opposite to that of iron. Diamagnetic materials include mercury, gold, bismuth and zinc.

Paramagnetic Materials

Paramagnetic denotes a substance whose permeability is slightly greater than that of air or unity. When such materials are placed in a strong magnetic field, there is a slight alignment of the electron spin in the direction of the magnetic flux flow. This alignment exists only as long as the paramagnetic material is in the external magnetic field.

Aluminum, platinum, copper and wood are paramagnetic materials.

Ferromagnetic Materials

Ferromagnetic substances have a permeability that is much greater than that of air. When placed in an external magnetic field, the magnetic domains align parallel with the external field and remain aligned for some period of time after removal from the field.

This continued alignment after removal from the external field is called *retentivity* and can be an important property in some magnetic particle testing procedures.

Some examples of ferromagnetic materials are iron, cobalt, nickel and gadolinium.

Sources of Magnetism

Permanent Magnets

Permanent magnets are produced by heat treating specially formulated alloys in a strong magnetic field. During the heat treating process, the magnetic domains become aligned and remain aligned after removal of the external field. Permanent magnets are essential to modern technology, including applications such as magnetos, direct current motors, telephones, loud speakers and many electric instruments.

Common examples of permanent magnetic materials include alloys of aluminum, nickel and cobalt (alnico); copper, nickel and cobalt (cunico); copper, nickel and iron (cunife); and cobalt and molybdenum (comol).

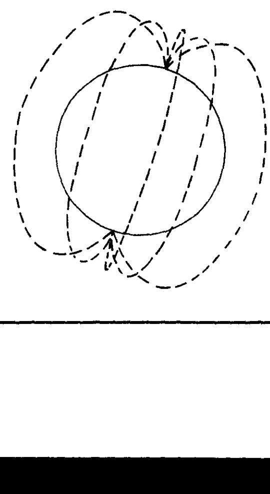
Magnetic Field of the Earth

The planet Earth is itself a huge magnet, with north and south poles slightly displaced from the Earth's axis. This displacement results in a slight deviation between geographic north and magnetic north.

As a magnet, the Earth is surrounded by magnetic lines of force as shown in Fig. 15. These lines of force make up what is sometimes called the *earth field* and they can cause problems in both magnetizing and demagnetizing of ferromagnetic test objects. The earth field is weak, on the order of 0.03 mT (0.3 G).

Movement of ferromagnetic objects through the earth field can induce slight magnetization. This is a problem in aircraft where magnetized components can affect the compasses used in navigation. Similarly, demagnetizing can be difficult if certain objects, usually long shafts, are not oriented in an east-west direction during the demagnetization process.

FIGURE 15. Magnetic field of the Earth



Mechanically Induced Magnetism

Cold working of some ferromagnetic materials, either by forming operations or during service, can magnetize the objects. When mechanically induced magnetization occurs as a result of forming operations, it can be removed by subjecting the magnetized object to a routine demagnetization process.

It can be difficult to remove mechanically induced magnetization resulting from cold working. Disassembly is usually impractical and demagnetization must be accomplished using portable yokes or cable coils. The operation is complicated when other ferromagnetic components are near the magnetized object: the demagnetizing operation can magnetize adjacent objects and a sequence of demagnetizing operations must then be performed.

PART 4
MAGNETIC FLUX AND FLUX LEAKAGE

Circular Magnetic Fields

The most familiar type of magnet is the horseshoe shape shown in Fig. 16a. It contains both a north and south pole with the lines of magnetic flux leaving the north pole and traveling through air to reenter the magnet at the south pole. Ferromagnetic materials are only attracted and held at or between the poles of a horseshoe magnet.

If the ends of such a magnet are bent so that they are closer together (see Fig. 16b), the poles still exist and the magnetic flux still leaves and reenters at the poles. However, the lines of force are closer together and more dense. The number of lines of flux per unit area is called *magnetic flux density*.

If the magnetic flux density is high enough, ferromagnetic particles are strongly attracted and can even bridge the physical gap between poles that are close enough together. The area where the flux lines leave the pole, travel through air and reenter the magnet is called a *magnetic flux leakage field*.

When the ends of a magnet are bent together and the poles are fused to form a ring (see Fig. 16c), the magnet no longer attracts or holds ferromagnetic materials (there are no magnetic poles and no flux leakage field). The magnetic flux lines still exist but they are completely contained within the magnet. In this condition, the magnet is said to contain a circular magnetic field or to be *circularly magnetized*.

If a crack crosses the magnetic flux lines in a circularly magnetized object, north and south poles are immediately created on either side of the discontinuity. This forces a portion of the magnetic flux into the surrounding air, creating a flux leakage field that attracts magnetic particles (see Fig. 16d) and forms a crack indication.

Longitudinal Magnetization

If a horseshoe magnet is straightened, a bar magnet is formed with north and south poles (see Fig. 17a). Magnetic flux flows through the magnet and exits or enters at the poles. Ferromagnetic materials are attracted only to the poles and such an object is said to have a longitudinal field or to be *longitudinally magnetized*.

If these magnetic flux lines are interrupted by a discontinuity, additional north and south poles are formed on either side of the interruption (see Fig. 17b). Such secondary poles and their associated flux leakage fields can attract magnetic particles. Even if the discontinuity is a very narrow crack, it can still create magnetic poles (see Fig. 17c) that hold magnetic materials (the magnetic flux leakage field is still finite).

Magnetic Field Strength

The amount of distortion or the strength of a flux leakage field from a discontinuity depends on several factors: (1) the

FIGURE 16. Horseshoe magnet illustrating the fundamental properties of magnetism: (a) direction of magnetic flux; (b) magnetic flux in air around poles; moving poles close together raises the magnetic flux density; (c) fusing the poles forms a circularly magnetized object; and (d) a discontinuity in a circularly magnetized object and its resulting flux leakage field

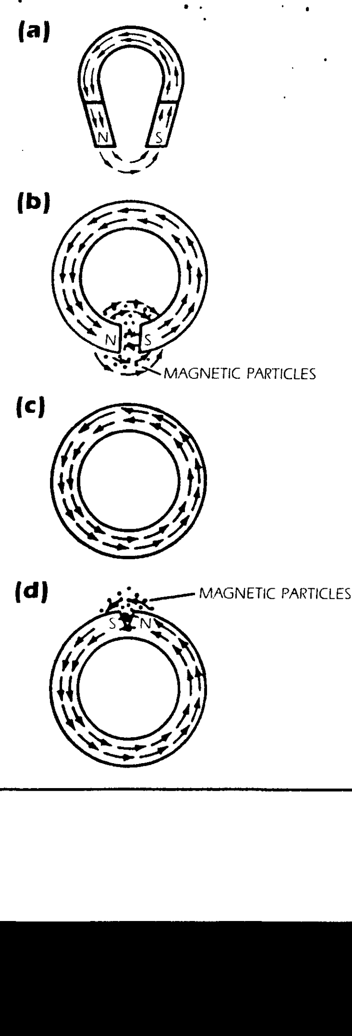


FIGURE 17. Bar magnet illustrating longitudinal magnetization: (a) horseshoe magnet straightened into a bar magnet with north and south poles; (b) bar magnet containing a machined slot and corresponding flux leakage field; and (c) a crack in a longitudinally magnetized object produces poles that attract and hold magnetic particles

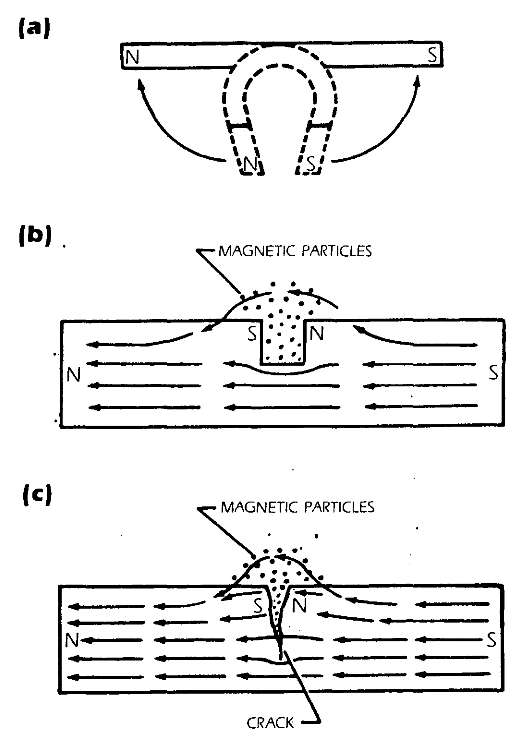


FIGURE 18. Slot or keyway on the reverse side of a magnetized bar

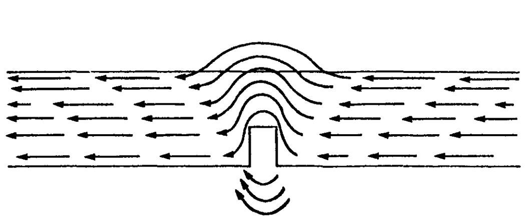
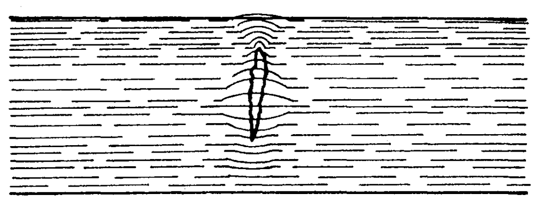


FIGURE 19. Internal or midwall discontinuity in a magnetized test object; there may or may not be magnetic flux leakage, depending on the value of the flux in the object



number of magnetic flux lines; (2) the depth of the discontinuity; and (3) the width of the discontinuity's air gap at the surface (the distance between the magnetic poles).

The strength of the leakage field directly determines the number of magnetic particles that can be attracted to form a test indication. The greater the leakage field strength, the denser the indication, so long as the magnetic flux leakage field is highly curved.

Subsurface Discontinuities

A slot such as a keyway on the backside of an object creates new magnetic poles that distort the internal flux flow. If the slot is close enough to the surface, some magnetic flux lines may be forced to exit and reenter the magnetized object at the surface. The resulting leakage field can form a magnetic particle test indication.

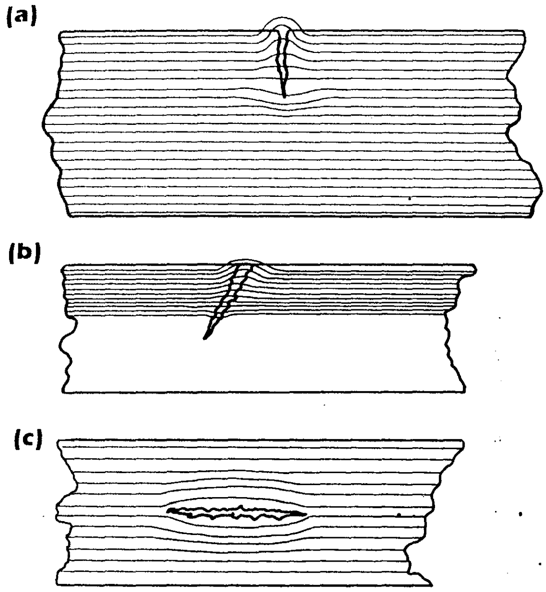
The size and strength of the indication depends on: (1) the proximity of the slot to the top surface; (2) the size and orientation of the slot; and (3) the intensity and distribution of the magnetic flux field. A similar effect occurs if the discontinuity is completely internal to the object. Figure 18 is an illustration of a keyway on the far side of a bar and Fig. 19 illustrates a midwall discontinuity.

Effect of Discontinuity Orientation

The orientation of a discontinuity in a magnetized object is a major factor in the strength of the leakage field that is formed. This applies to both surface and internal discontinuities. The strongest leakage field is formed when the discontinuity is perpendicular to the magnetic flux flow. If the discontinuity is not perpendicular, the strength of the leakage field is reduced and disappears entirely when the discontinuity is parallel to the magnetic flux flow.

Figure 20 illustrates the effect of discontinuity orientation on the strength of the magnetic leakage field.

FIGURE 20. Flux leakage fields from discontinuities with different orientations: (a) perpendicular to the magnetic flux; (b) at 45 degrees angle to the magnetic flux; and (c) parallel to the magnetic flux



Formation of Indications

When magnetic particles collect at a flux leakage site, they produce an indication that is visible to the unaided eye under the proper lighting conditions. The formation of indications depends the magnetic flux lines' characteristics, including that they (1) form continuous loops; (2) do not cross each other; (3) decrease in intensity with distance from the surface; and (4) repel each other.

When a ferromagnetic particle is placed in a magnetic field, it is drawn toward the magnetic source. As it gets closer to a pole, more flux lines flow through it. This concentrates the flux lines through the low reluctance ferromagnetic path rather than the high reluctance air path. It is this preferential action which causes particles to begin collecting at leakage fields and to subsequently form discontinuity indications.

PART 5
ELECTRICALLY INDUCED MAGNETISM

Circular Magnetization

When an electric current flows through a conductor such as a copper bar or wire, a magnetic field is formed around the conductor (see Fig. 21a). The direction of the magnetic lines of force is always 90 degrees from the direction of current flow. When the conductor has a uniform shape, the flux density or number of lines of force per unit area, is uniform along the length of the conductor and it uniformly decreases as the distance from the conductor increases.

Because a ferromagnetic object is, in effect, a large conductor, electric current flowing through the object forms a magnetic field in the same manner as the copper conductor. This magnetic field is known as *circumferential magnetization* because the magnetic flux lines form complete loops within the object (see Fig. 21b).

A characteristic of circumferential magnetic fields is that the magnetic flux lines form complete loops without magnetic poles. Because magnetic particles are only attracted to and held where the flux lines exit and enter the object surface, indications do not occur unless a discontinuity crosses the flux lines. The resulting accumulation of magnetic particles forms an outline of the discontinuity over its exact location.

FIGURE 21. Magnetic field generated around: (a) a conductor carrying an electric current; and (b) a ferromagnetic test object used as a conductor

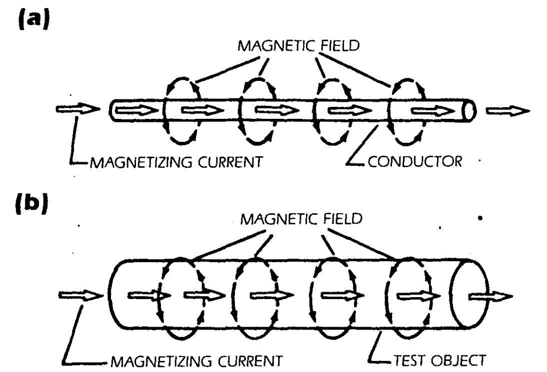
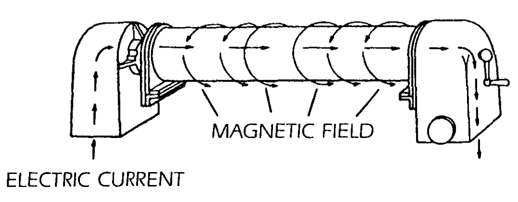


FIGURE 22. Inducing a circumferential magnetic field in an object used as a conductor

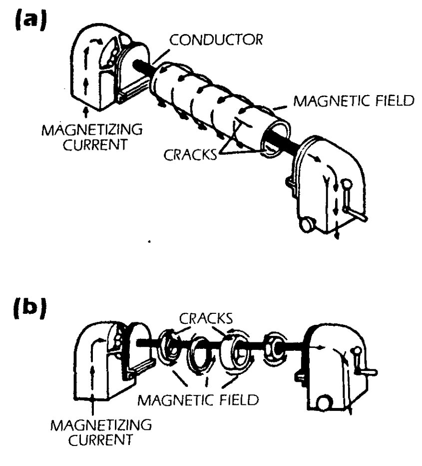


Inducing Circular Magnetization in a Test Object

Figure 22 illustrates a method for inducing a circular field using a magnetic particle testing unit. The test object is clamped between the contact plates so that electric current passes through it.

When tubes are tested by passing a current through them, the magnetic flux rises toward the outside surface,

FIGURE 23. Inducing a circumferential magnetic field using an internal conductor for: (a) a tube with inside and outside surface discontinuities; and (b) multiple ring shapes with cracking on the inside and outside surfaces



with negligible flux on the inside surface. The inside surface is often equally important when testing for discontinuities. Since a magnetic field surrounds a conductor, it is possible to induce a satisfactory field in the tube by inserting a copper bar or some other conductor through the component and passing the current through the bar.

This method is called *internal conductor magnetization* (see Fig. 23).

Magnetic Field Direction

The direction of the magnetic lines of force is always at right angles to the direction of the magnetizing current.

An easy way to determine the direction of the magnetic flux is to imagine the conductor held in your right hand with the thumb extended in the direction of the electric current flow. Your clenched fingers then point in the direction of the magnetic flux flow. This is known as the *right hand rule* and is illustrated in Fig. 24.

FIGURE 24. The right hand rule indicates the direction of magnetic flux flow based on the direction the magnetizing current

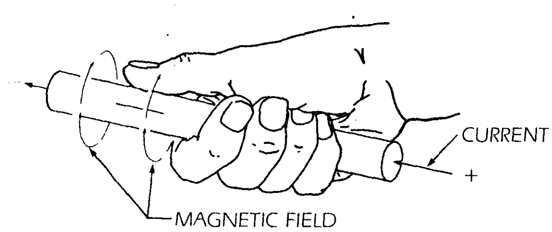
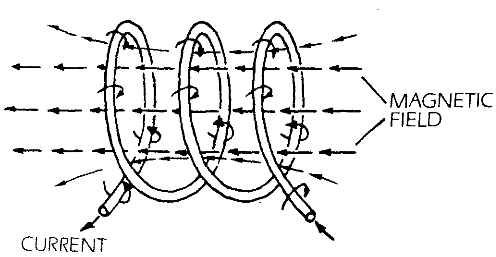


FIGURE 25. Formation of a longitudinal magnetic field using a coiled conductor



Longitudinal Magnetization

Electric current can be used to induce longitudinal fields in ferromagnetic materials. The magnetic field around a conductor is oriented in a lengthwise direction by forming the conductor into a coil (see Fig. 25). Application of the right hand rule shows that the magnetic field at any point within the coil is in a lengthwise direction.

When a ferromagnetic object is placed inside a coil carrying an electric current (see Fig. 26), the magnetic flux lines concentrate themselves in a longitudinal direction. An object that has been longitudinally magnetized is characterized by poles close to each end.

When a longitudinally magnetized object contains a transverse discontinuity, a leakage field is produced that attracts magnetic particles and forms an indication. Figure 27 illustrates a typical coil found on magnetic particle test systems used to locate transverse discontinuities.

FIGURE 26. Test object containing a longitudinal magnetic field induced by a coil

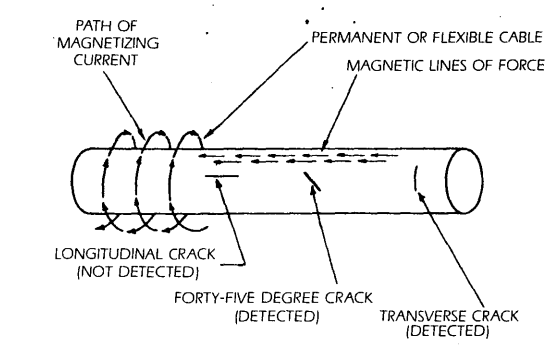
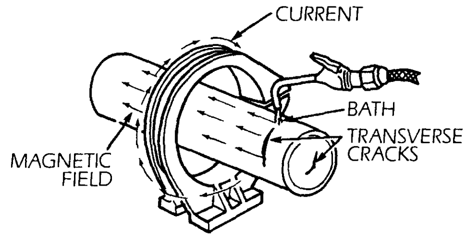


FIGURE 27. Formation of a transverse discontinuity indication during longitudinal magnetization



Multidirectional Magnetization

When testing for discontinuities in different directions, it is standard practice to perform two tests, one with circular magnetization and the other with longitudinal. Two or more fields in different directions can be imposed on an object sequentially and in rapid succession.

When this is done, magnetic particle indications are formed when discontinuities are favorably oriented to the direction of any field. Such indications persist as long as the rapid alternations of current continue.

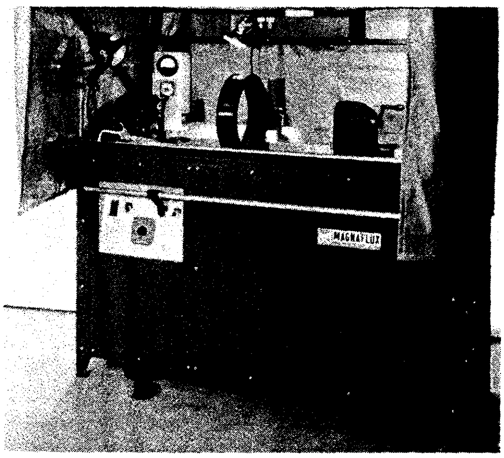
PART 6
MAGNETIC PARTICLE TEST SYSTEMS

Stationary Magnetic Particle Test Systems

Wet method horizontal magnetic particle test systems typically consist of (1) a high current, low voltage magnetizing source; (2) head stock and tail stock for holding test objects and providing electrical contact for circumferential magnetization; (3) a movable coil for longitudinal magnetization; and (4) a particle suspension tank with an agitation system.

The basic components, along with magnetizing control indicators and ampere meters, are enclosed within a table top structural frame. Systems are available in a large number of sizes from a 25 mm (1 in.) contact plate opening up to systems that are 6 m (20 ft) long. Manufacturer's provide alternating current, direct current or a combination of the two. Maximum magnetizing current output is available from 1,000 A to 10 kA. Figure 28 shows a typical stationary or wet horizontal unit.

FIGURE 28. Typical wet horizontal magnetic particle test system



Power Packs

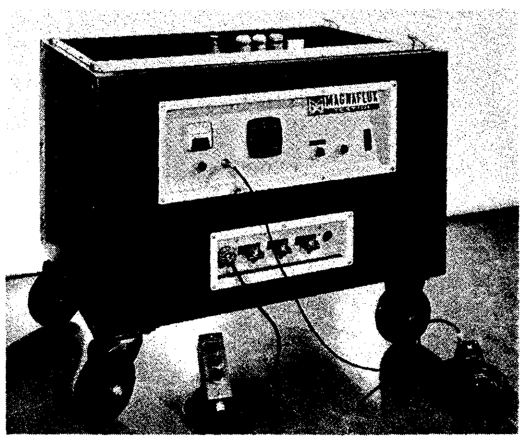
Power packs are the electrical sources needed to produce high amperage, low voltage magnetizing current. They are used to magnetize test objects such as castings and forgings that are too large to be placed in a stationary testing unit. The size and weight of power packs prevent moving them and test objects are accordingly transported to the test site. The rating or current output of commercial power packs varies widely but is typically from 6 to 20 kA of magnetizing current.

The current is applied by ancillary cable wraps, formed coils, clamps and prods. Most power pack units incorporate an adjustable current control, one or two ammeters and an automatic shot duration timer.

Mobile and Portable Testing Units

There are many applications where it is not possible to bring the test object to the magnetic particle system. Mobile

FIGURE 29. Typical mobile magnetic particle test system



units are one type of equipment that can be transported to the test site and still provide relatively high magnetizing currents (see Fig. 29). Traditional mobile units may be considered small versions of the power pack systems. While some mobile units have a magnetizing current output of 6 kA, most are limited by size considerations to between 3 and 4 kA. Transportability is also improved by restricting the types of magnetizing current to alternating current and half-wave direct current. Magnetizing current is applied to the test object by cable wraps, formed coils, prods and clamps. Oil field portable magnetizing units can reach 15 kA by capacitor discharge through internal conductors or cable wraps.

FIGURE 30. Portable magnetic particle testing system with fixed distance prod assembly

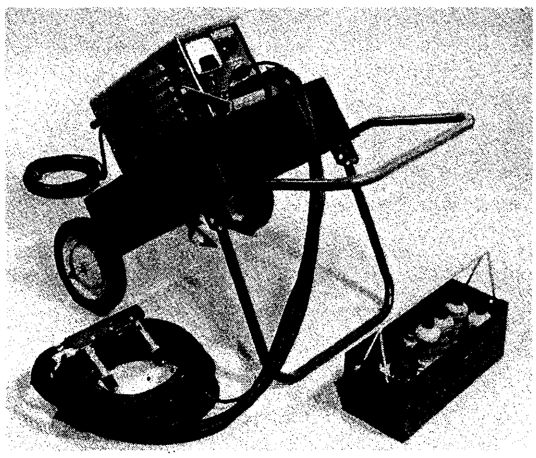
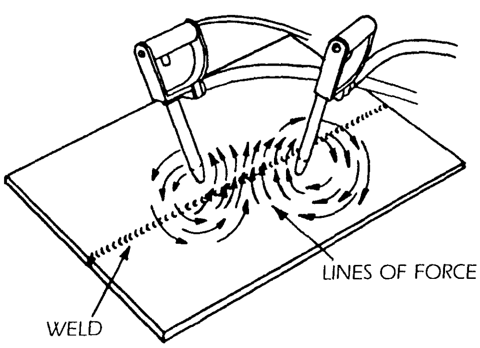


FIGURE 31. Circular magnetic field generated around magnetizing prods



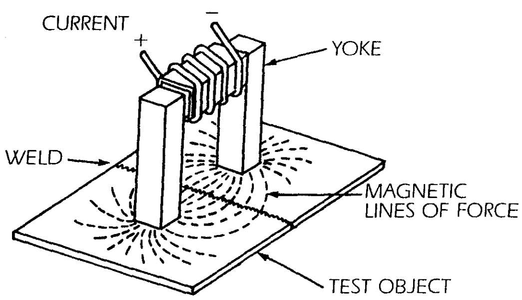
The term *portable equipment* refers to compact, light weight units that can be hand carried to the test site (see Fig. 30). Some portable units are mounted on wheeled carts to facilitate portability. Like stationary and mobile equipment, portable units come in a variety of sizes, shapes, weights and amperage outputs. The most common method of applying current with a portable unit is with prods or clamps. However, cable wraps and formed coils are also used in many applications. Reduced weight and size are achieved by omitting the step down transformer needed for demagnetization.

Prods and Yokes

Prods are magnetization accessories that can be used with stationary, power pack, mobile and portable units. They typically consist of a pair of copper bars 12 to 20 mm (0.5 to

FIGURE 32. Hand probe or yoke with a preformed coil assembly

FIGURE 33. Longitudinal magnetic field generated by a yoke



0.75 in.) in diameter with handles and connecting cables. One of the prods has a trigger to remotely activate the magnetizing current from the unit's mainframe. Prods set up a circular magnetic field that diminishes in intensity as the distance between prods increases (see Fig. 31).

Yokes are often cable connected to a mobile or portable unit that provides the magnetizing current. A yoke designed with a self-contained magnetizing source is often called a *hand probe*. Hand probes contain small transformers that generate low voltage and high current (see Fig. 32). Yokes usually contain a magnetizing coil with a core of laminated transformer iron. Attached to the core are legs which may either be fixed or articulated. When magnetizing current is applied to the coil, a longitudinal magnetic field is created in the core and transmitted to the legs. When coupled to a test object, a longitudinal magnetic field is generated between the poles as shown in Fig. 33.

Yokes are often specified by their lifting ability or the surface field they create midway between their poles, as measured with a gaussmeter.

PART 7

FERROMAGNETIC MATERIAL CHARACTERISTICS

Magnetic Flux and Units of Measure

A magnetic field is made up of flux lines within and surrounding a magnetized object or a conductor carrying an electric current. The term *magnetic flux* is used when referring to all of the lines of flux in a given area. Flux per unit area is called *magnetic flux density* (the number of lines of flux passing transversely through a unit area).

There can be some confusion about the units of measure used to define these magnetic quantities. The unit of magnetic flux was originally called a *maxwell* with one maxwell being one line of flux. The unit of flux density was the *gauss* with one gauss equal to one maxwell per square centimeter. In 1930, the International Electrotechnical Commission redefined and renamed the gauss as an *oersted*, or the intensity of a magnetic field in which a unit magnetic pole experiences a force of one dyne.[1]

In 1960, the International Organization for Standardization released ISO 1000: *The International System of Units (SI)*. This document standardizes the metric units for magnetic flux. Flux intensity is measured using the *weber* (Wb) with one weber equal to 10^8 lines of flux. The flux density unit is the *tesla* (T) or one weber per square meter. One weber per square millimeter (or one tesla) is equal to 10,000 gauss.

Magnetic Hysteresis

All ferromagnetic materials have certain magnetic properties that are specific to that material. Most of these properties are described by a magnetic hysteresis curve. The data for the hysteresis curve are collected by placing a bar of ferromagnetic material in a coil and applying an alternating current. By increasing the magnetizing field strength H in small increments and measuring the flux density B at each increment, the relationship between magnetic field strength and flux density can be plotted.

The relationship between magnetic field strength and flux density is not linear for ferromagnetic materials. A specific change in H may produce a smaller or larger change in B as shown in Fig. 34, the initial curve for an unmagnetized piece of steel. Starting at point O (zero magnetic field strength and zero magnetic flux) and increasing H in small increments, the flux density in the material increases quite rapidly at first, then gradually slows until point A is reached. At point A, the material becomes magnetically saturated. Beyond the *saturation point*, increases in magnetic field strength do not increase the flux density in the material. In diagrams of full hysteresis loops, the curve OA is often drawn as a dashed line since it occurs only during the initial magnetization of an unmagnetized material. It is referred to as the *virgin curve* of the material.

When the magnetic field strength is reduced to zero (point B in Fig. 34b), the flux density slowly decreases. It lags the field strength and does not reach zero. The amount of flux density remaining in the material (line OB) is called *residual magnetism* or *remanence*. The ability of ferromagnetic materials to retain a certain amount of magnetism is called *retentivity*.

Removal of residual magnetism requires the application of a magnetic field strength in an opposite or negative direction (see Fig. 34c). When the magnetic field strength is first reversed and only a small amount is applied, the flux density slowly decreases. As additional reverse field strength is applied, the rate of reduction in flux density (line BC) increases until it is almost a straight line (point C) where B equals zero.

The amount of magnetic field strength necessary to reduce the flux density to zero is called *coercive force*. Coercive force is a factor in demagnetization and is also very important in eddy current testing of ferromagnetic materials.

As the reversed magnetic field strength is increased beyond point C, the magnetic flux changes its polarity and initially increases quite rapidly. It then gradually slows until point D is reached (Fig. 34d). This is the reverse polarity saturation point and additional magnetic field strength will not produce an increase in flux density.

When the reversed magnetic field strength is reduced to zero (point E in Fig. 34e) the flux density again lags the magnetic field strength, leaving residual magnetism in the material (line OE). The flux densities of the residual magnetism from the straight and reversed polarities are equal (line OB is equal to line OE).

Removal of the reversed polarity residual magnetism requires application of magnetic field strength in the original direction. Flux density drops to zero at point F in

FIGURE 34. Hysteresis data for unmagnetized steel: (a) virgin curve of a hysteresis loop; (b) hysteresis loop showing residual magnetism; (c) hysteresis loop showing coercive force; (d) hysteresis loop showing reverse saturation point; (e) hysteresis loop showing reverse residual magnetism; and (f) complete hysteresis loop

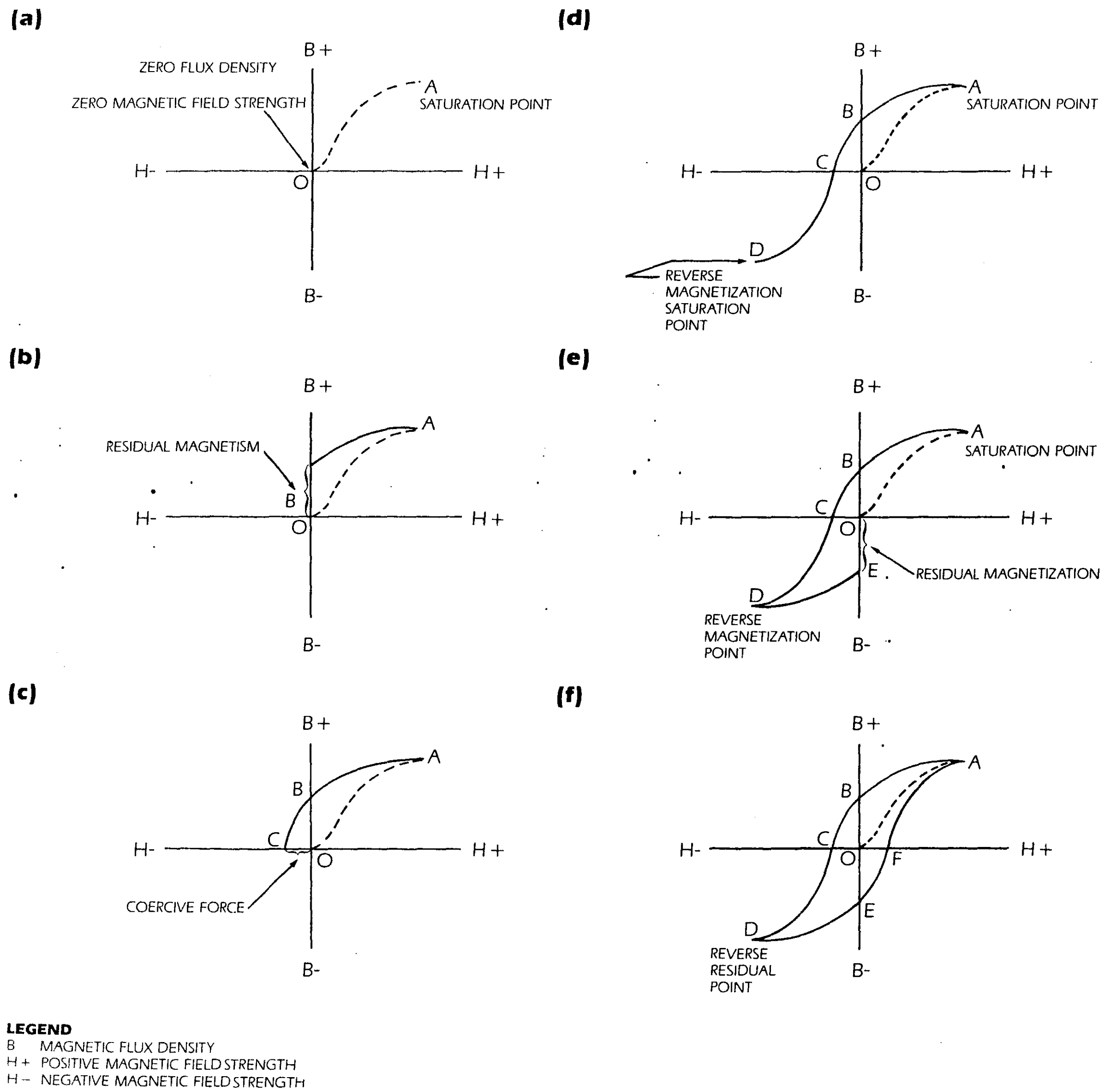


Fig. 34f with the application of coercive force *OF*. Continuing to increase the field strength results in the magnetic polarity changing back to its original direction. This completes the hysteresis loop *ABCDEF* (note that the curve *CDEF* is a mirror image of curve *ABCF*).

Magnetic Permeability

One of the most important properties of magnetic materials is *permeability*. Permeability can be thought of as the ease with which materials can be magnetized. More specifically, permeability is the ratio between the flux density and the magnetic field strength (*B* divided by *H*). Figure 35a is the virgin curve of a high permeability material and Fig. 35b is the curve of a low permeability material.

The reciprocal of permeability is *reluctance*, defined as the resistance of a material to changes in magnetic field strength.

Magnetic properties and hysteresis loops vary widely between materials and material conditions. They are affected by chemical composition, microstructure and grain size. Figure 36a is a hysteresis loop for hardened steel and the loop is typical of a material with low permeability, high reluctance, high retentivity and high residual magnetism that requires high coercive force for removal. Figure 36b is the hysteresis loop for an annealed low carbon steel. It is typical of a material with high permeability, low reluctance, low retentivity and low residual magnetism that requires a low coercive force for removal.

FIGURE 35. Magnetic permeability curves: (a) high permeability virgin curve; and (b) low permeability virgin curve

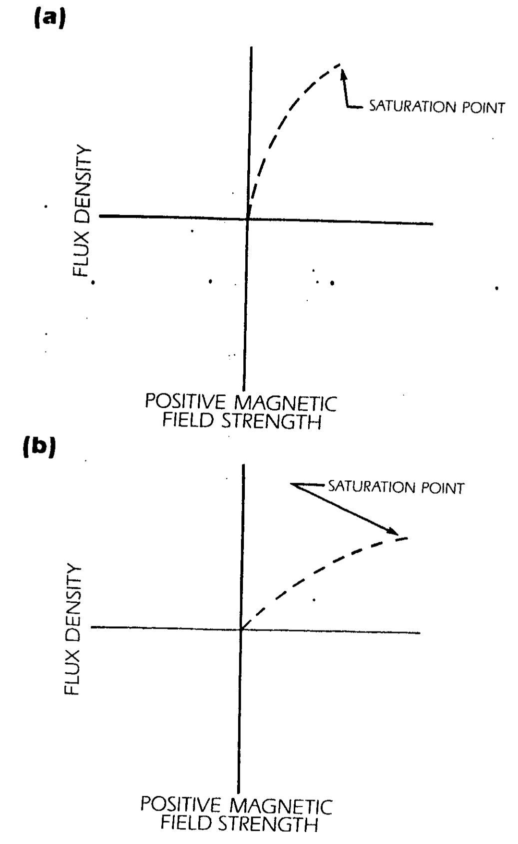
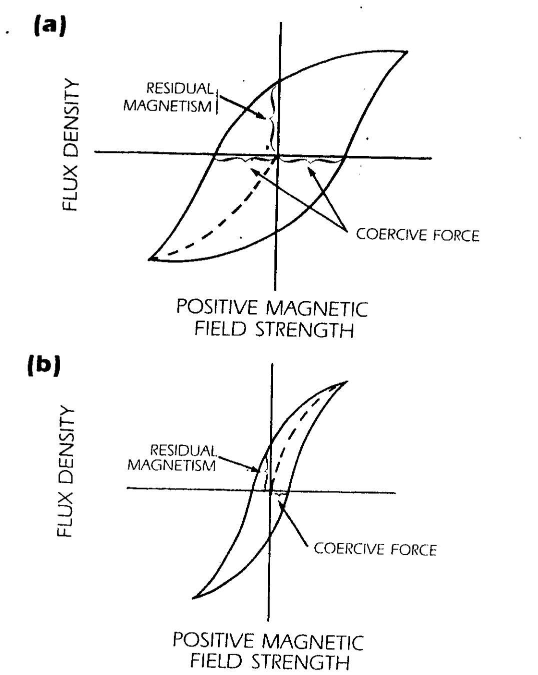


FIGURE 36. Hysteresis loops: (a) hardened steel hysteresis loop; and (b) annealled low carbon steel hysteresis loop



PART 8
TYPES OF MAGNETIZING CURRENT

In the very early days of magnetic particle testing, it was believed that the most desirable current for magnetization was direct current provided by storage batteries.

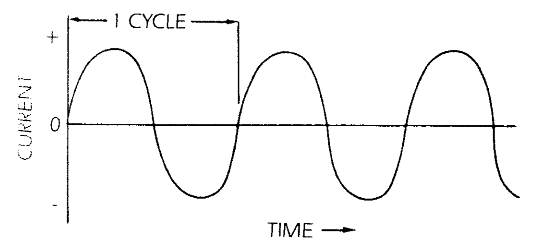
As knowledge of the magnetic particle process expanded and electrical circuitry continued to advance, many types of magnetizing currents became available: alternating current, half-wave direct current and full-wave direct current. The terms half-wave rectified direct current and full-wave rectified direct current are used for alternating current rectified to produce half-wave and full-wave direct current.

Alternating Current

Alternating current is useful in many applications because it is commercially available in voltages ranging from 110 to 440 V. Electrical circuitry to produce alternating magnetizing current is simple and relatively inexpensive because it only requires transforming commercial power into low voltage, high amperage magnetizing current.

In the United States and some other countries, alternating current alternates sixty times in a second. Many other countries have standardized fifty alternations per second. The alternations are called *cycles*. One *hertz* (Hz) equals one cycle per second and 60 Hz is sixty cycles per second. Figure 37 shows the waveform of alternating current. In one cycle, the current flows from zero to a maximum positive value and then drops back to zero. At zero, it reverses direction and goes to a maximum negative peak and returns to zero. The curve is symmetrical with the positive and negative lobes being mirror images.

FIGURE 37. Waveform of alternating current



Use of Alternating Current in Magnetic Particle Tests

There are three primary advantages to using alternating current as a magnetizing source. First, the current reversal causes an inductive effect that concentrates the magnetizing flux at the object surface (called the *skin effect*) and it provides enhanced indications of surface discontinuities. Magnetic fields produced by alternating current are also much easier to remove during demagnetization. A third advantage is that the pulsing effect of the flux caused by the current reversals agitates the particles applied to the test object surface. This agitation increases particle mobility, allowing more particles to collect at flux leakage points, and increases the size and visibility of discontinuity indications.

Concentration of the flux at the test object surface also can be a disadvantage because most subsurface discontinuities are not detected. Another disadvantage is that some specifications do not allow the use of alternating current on plated components when the coating thickness exceeds 0.08 mm (0.003 in.). The flux in a test object may not be at peak value, depending on where within the magnetizing cycle the current is turned off.

Half-Wave Direct Current

When single-phase alternating current is passed through a simple rectifier, the reversed flow of current is blocked or clipped. This produces a series of current pulses that start at zero, reach a maximum point, drop back to zero and then pause until the next positive cycle begins. The result is a varying current that flows only in one direction. Figure 38 shows the waveform for half-wave direct current.

Half-wave direct current has penetrating power comparable to single-phase full-wave direct current. Half-wave current has a flux density of zero at the center of a test object and the density increases until it reaches a maximum at the object surface. The pulsing effect of the rectified wave produces maximum mobility for the magnetic particles; dry method tests are enhanced by this effect. Another distinct advantage of half-wave direct current is the simplicity of its electrical components. It can be easily combined with portable and mobile alternating current equipment for weld, construction and casting tests.

One of the disadvantages of half-wave magnetization is the problem in demagnetization: the current does not reverse so it cannot be used for demagnetizing. Alternating current can be used to remove some residual magnetism but the skin effect of alternating current and the deeper penetration of half-wave direct current cause incomplete demagnetization.

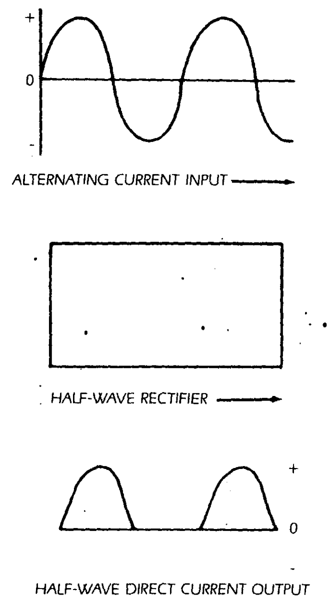
Full-Wave Direct Current

It is possible for electrical circuitry to not only block (or rectify) the negative flowing current, but to invert it so that the number of positive pulses is doubled. Figure 39 shows the waveform of single-phase full-wave rectified alternating current. The resulting current is usually called *single-phase full-wave direct current*

Single-phase full-wave direct current has essentially the same penetrating ability as three-phase full-wave direct current. The current fluctuation causes a skin effect that is not significant. It is also possible to incorporate switching devices in the circuitry that reverse the current flow. This permits built-in reversing direct current demagnetization. Because of its simpler components, the initial cost of single-phase full-wave direct current equipment is much less than that of three-phase full-wave equipment.

One disadvantage of single-phase units is the input power requirement. Single-phase equipment requires 1.73 times more input current than three-phase units. This becomes very significant at higher magnetizing currents where input values can exceed 600 A.

FIGURE 38. Half-wave direct current waveform



Three-Phase Full-Wave Direct Current

Commercial electric power, especially at 220 and 440 V, is provided as three-phase alternating current with each phase providing part of the total current. Figure 40 shows the waveform of three-phase alternating current. Three-phase full-wave magnetic particle equipment rectifies all three alternating current phases and inverts the negative flow to a positive direction, producing a nearly flat line direct current magnetizing current. Figure 41 shows the waveform of three-phase full-wave direct current.

FIGURE 40. Waveform of three-phase alternating current

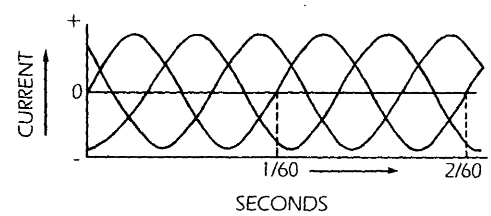


FIGURE 39. Single-phase full-wave direct current waveform

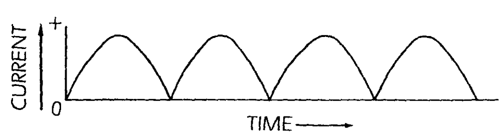
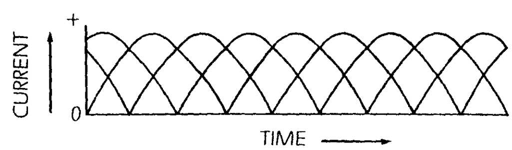


FIGURE 41. Three-phase full-wave direct current waveform



Three-phase full-wave direct current has all of the advantages of single-phase full-wave direct current plus some additional benefits. The current draw on the power line is spread over three phases, reducing the demand by nearly half. The demand on the line is also balanced, with each leg providing a portion of the current (single-phase pulls all of the current from one leg, resulting in an unbalanced line). Many power companies charge a higher rate to customers with unbalanced, high current requirements. The three-phase design also permits incorporating a *quick break* circuit that improves the formation of indications at the ends of longitudinally magnetized test objects.

PART 9
DEMAGNETIZATION PROCEDURES

Objects that have been magnetic particle tested retain some magnetism. The amount of residual magnetism depends on the material and its condition. Low carbon steel in the annealed condition retains little or no magnetism while hardened alloy steels retain strong magnetic fields for long periods of time.

Reducing or removing residual magnetism is not a direct function of the intensity of the retained magnetic field but is a direct function of the coercive force of the material. There are materials with high retentivity and low coercive force. The ease of demagnetization depends on the magnetic properties or hysteresis curve of the material.

Justification for Demagnetizing

There are several ways that an object can be magnetized: induced magnetization from earth fields; use of a magnetic chuck or plate during machining; mechanically induced magnetization; and magnetic particle testing. Demagnetization is required for the following reasons, despite the source of the magnetization.

1. A magnetized object can affect the accuracy and function of some instruments and meters. A common occurrence in aircraft is the induced magnetization resulting from traversing through the Earth's magnetic field.
2. Removal of the magnetic particle media following testing is necessary because residual particles can cause problems during subsequent operations such as machining and surface coating. Retained particles can also cause excessive wear on moving components in assemblies. Demagnetization is necessary because flux leakage can retain particles despite a typical cleaning process.
3. Machining of magnetized objects is objectionable because chips and shavings may adhere to the surface, disrupting the surface finish and dulling the cutting tool.
4. Magnetized objects attract and retain metallic debris during handling and cleaning prior to the application of surface coatings. The entrapped metal particles create serious imperfections in painted or plated surfaces.
5. Demagnetization is required when objects are to be electric arc welded. A residual magnetic field can cause the arc to deflect or wander. Arc deflection (called *arc blow*) is a particular problem in automated welding systems that do not compensate for a shift in arc.
6. Demagnetization may be required when remagnetizing in another direction, if the second magnetizing field intensity is less than the original. If the second magnetic field strength does not equal or exceed the initial field strength, the initial magnetic field remains dominant.

Reasons for Not Demagnetizing

Although demagnetization is generally required, there are occasions when it is not necessary. Demagnetization is not required when the test objects have very low retentivity (such materials are demagnetized when the magnetic field strength is removed). On some occasions, the residual magnetic field is such that it does not affect the function of the object nor its service life. Occasionally, the test object is magnetic particle tested a second time, with equal or greater magnetic field strength in another direction.

Demagnetization is not necessary when test objects are subjected to external magnetic fields such as clamping with a magnetic chuck during machining or hoisting with an electromagnetic crane. Finally, there is no need for demagnetization if the test object is exposed to a subsequent heating above the Curie point (the temperature where magnetic domains become random and the material becomes unmagnetized).

Methods of Demagnetization

Curie Point Heating

All ferromagnetic materials containing magnetic flux can be demagnetized by heating to a specific temperature and allowing the material to cool in the absence of an external magnetic flux. The temperature at which the material changes from ferromagnetic to paramagnetic is called the *Curie point*. This temperature varies widely depending on alloy composition. For example, the Curie point for nickel containing 1 percent silicon is 320 °C (608 °F) while the Curie point for nickel containing 5 percent silicon is 45 °C (113 °F). The Curie point for ferrous alloys ranges from about 650 to 870 °C (1,200 to 1,600 °F).

The transition from ferromagnetic to paramagnetic at the Curie point reverses on cooling and the material becomes ferromagnetic in an unmagnetized condition. Some X-ray diffraction studies show that this transition is not a crystalline structure transformation but a rearrangement of magnetic domains. Demagnetization by heating through the Curie point is the most thorough demagnetization possible but because of its expense it is not commonly used.

Electromagnetic Demagnetization

There are several techniques for demagnetizing an object using electromagnetic energy. All of these techniques subject a magnetized object to a magnetic force that is continually reversing its direction and gradually decreasing in intensity.

In Fig. 42, the top curve illustrates the magnetic field strength used to generate the flux intensity curve below. As the current diminishes in value with each reversal, the hysteresis curve traces an increasingly smaller path. The bottom curve illustrates the decreasing residual flux intensity in the object, indicated by the shrinking hysteresis loops. The magnetizing current and flux intensity curves are plotted against time. When the current reaches zero, the residual magnetism approaches zero.

Successful demagnetization depends on several requirements. First, the magnetic field strength at the start of the demagnetizing cycle must be high enough to overcome the coercive force and to reverse the direction of the residual field. This is accomplished by demagnetizing at a slightly higher current than that used in the magnetizing cycle. The second requirement is that, in each successive cycle, the reduction of magnetic field strength must be small enough that the reverse magnetic field strength exceeds the coercive force and reverses the flux direction from the previous reversal. This requires a number of cycles, depending on the permeability of the material. Ten to thirty reversals are often required.

Alternating Current Demagnetization

A common method of demagnetizing small objects is by passing them through a coil carrying alternating current (see Fig. 43). The objects are moved into the coil while the

FIGURE 42. Demagnetization hysteresis loops with current and flux intensity curves

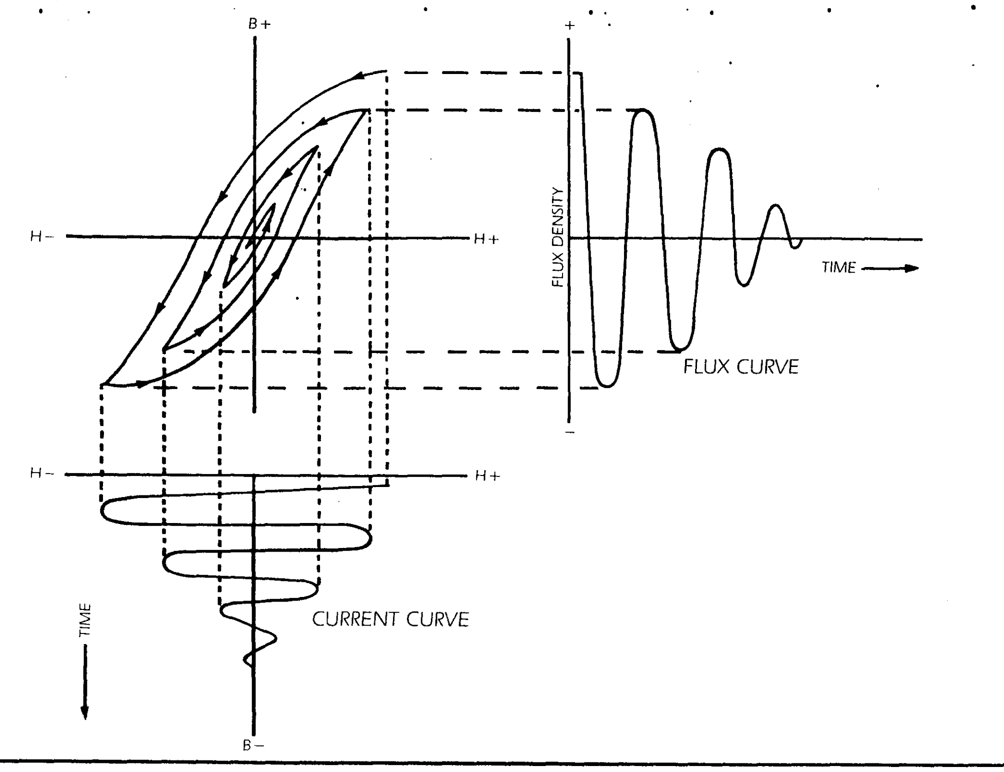
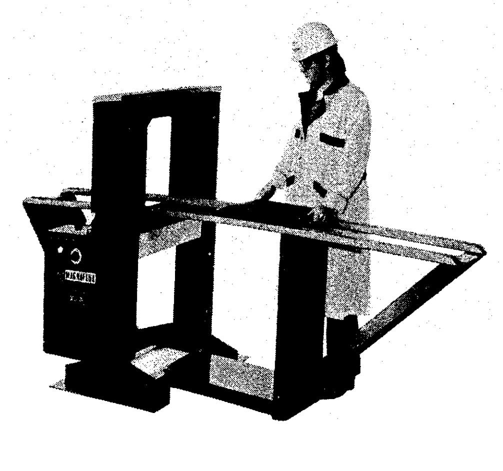


FIGURE 43. Alternating current coil demagnetizing unit with rail assembly



current is flowing for exposure to the maximum magnetic flux. The objects are then slowly and axially withdrawn some distance from the coil. Because flux intensity decreases with distance from its source, this procedure serves to reduce the magnetic field strength. To ensure that the flux is reduced to a minimum level, the objects should be withdrawn to a distance at least twice the coil diameter.

Alternating current demagnetization can also be accomplished by placing the object in the coil and gradually reducing the current to zero. Some coils and some magnetic particle system designs have built-in circuitry for current reduction. When decaying alternating current is available on wet horizontal units, the current can be applied directly to the object through the headstock and tailstock instead of passing the object through the coil. This is more effective than the coil technique for long, circularly magnetized objects.

There are some limitations to alternating current demagnetization. Most important is the fact that alternating current concentrates the magnetic flux at the object surface. Large test objects are not effectively demagnetized by the alternating current method because of its skin effect.

This lack of penetration also prohibits demagnetization of a number of small objects piled in a basket (the alternating current skin effect demagnetizes only the outside surface of objects on the outer layer). Quantities of small objects can be demagnetized with alternating current techniques only by placing them in a well separated single layer with their long dimensions parallel to the axis of the coil.

Direct Current Demagnetization

The principle of demagnetizing with direct current is identical to that of alternating current demagnetization. The magnetic field strength or current must be sequentially reversed and gradually reduced. One of the advantages of reversing direct current demagnetization is the deep penetration that is possible.

Because reversing the direction of direct current is done through electrical circuits, it is possible to control the rate of reversal. The most commonly used reversal rate is one cycle per second or a frequency of 1 Hz. This produces the optimum depth of penetration, permitting the demagnetization of large test objects. Direct current demagnetization often reduces the residual field to a value lower than is possible with alternating current. In practice, the test object is placed within the coil where it remains until the demagnetization cycle is complete.

Yoke Demagnetization

Yokes or probes are often used for demagnetization when portability is required. Either alternating current or reversing direct current can be used, depending on the available power supply. Pulsating half-wave direct current found in many self-contained power yokes cannot be used unless the unit also contains a current reversing circuit. Demagnetization is accomplished by passing objects through the poles of the yoke and withdrawing them while the current is flowing.

Yokes can also be used to demagnetize local areas on large objects. The poles are placed on the surface to be demagnetized, moved in a circular pattern, and then slowly withdrawn while the yoke is energized. When demagnetizing small areas on a large object, care must be exercised to avoid magnetizing adjacent areas.

Demagnetization Practices

There are practical limits to the demagnetization process. These limits are controlled by the equipment, the size and material of the object, and the Earth's magnetic field. Generally, the practical limit of demagnetization occurs at a point where a residual field remains but at a level that does interfere or complicate the intended function of the object in service.

Longitudinal, residual magnetic fields are usually measured with a field meter. Some meters read relative units and are useful for comparison purposes only; other meters read directly in tesla or gauss. The greatest flux leakage in a longitudinally magnetized object is at the ends or corners of the object. These are the best places to check for the effectiveness of demagnetization. Note that *when the read-*

ings are in relative units there may be differences between the readings of different manufacturer's field meters.

The magnetic field of a circularly magnetized object is completely contained within the object and there are no flux leakage points, except at discontinuities. Therefore, field strength meters cannot indicate residual magnetism of a circularly magnetized object. A common practice is to perform longitudinal magnetization as the last step in a two-step operation or to remagnetize in a longitudinal direction before demagnetization. This procedure allows the use of a field meter to check the effectiveness of demagnetization.

The Earth's magnetic field is in a north-south direction and can cause problems when demagnetizing objects with a high length-to-diameter ratio. When low residual fields are required, these problems can be reduced by placing the demagnetizing unit's coil axis in an east-west direction.

PART 10

MEDIA AND PROCESSES IN MAGNETIC PARTICLE TESTING

The formation of reliably visible discontinuity indications is essential to the magnetic particle testing method. An important factor in the formation and visibility of indications is the use of the proper magnetic particles to obtain the best indication from a particular discontinuity under the given conditions. Selection of the *wrong* particles can result in (1) failure to form indications; (2) the formation of indications too faint for detection; or (3) a distorted pattern over the discontinuity and the resulting misinterpretations.

In magnetic particle tests, there are two classes of media that define the method: dry and wet. Dry method particles are applied without the addition of a carrier vehicle. Wet method particles are used as a suspension in a liquid vehicle. The liquid vehicle may be water or a light petroleum distillate such as kerosene.

Magnetic particles are also categorized by the type of pigment bonded to them to improve visibility. Visible particles are colored to produce a good contrast with the test surface under white or visible light. Fluorescent particles are coated with pigments that fluoresce when exposed to ultraviolet light. A third pigment category includes particles coated with a material that is both color contrasting under visible light and fluorescent when exposed to ultraviolet light.

Magnetic Particle Properties

The media used in magnetic particle testing consist of finely divided ferromagnetic oxides. The particles can be irregularly shaped, spheroidal, flakes, or acicular (elongated). The properties of different materials, shapes and types vary widely and some are discussed below.

Magnetic Permeability

Magnetic particles should have the highest possible permeability and the lowest possible retentivity. This allows their attraction only to low level leakage fields emanating from discontinuities. As the particles become magnetized, they then attract additional particles to bridge and outline the discontinuity, thus forming a visible indication.

Magnetic permeability alone does not produce a highly sensitive particle material. For example, iron based dry powders have a higher permeability than the oxides used in wet method suspensions. Yet a typical dry powder does not produce indications of extremely fine surface fatigue cracks that are easily detected with wet method suspensions. High permeability is desirable but is no more important than size, shape or the other critical properties. All of these characteristics are interrelated and must occur in appropriate ranges in order for high permeability to be of value.

Coercive Force

Materials used in dry method powders and wet method suspensions should have a low coercive force and low retentivity. If these properties are high in dry powders, the particle can become magnetized during manufacture or during their first use, making them small, strong permanent magnets. Such particles have an increased tendency to magnetically adhere to the test surface where they first touch it. This reduces their mobility and produces a high background, reducing contrast and masking relevant discontinuity indications.

When wet method particles have a high coercive force, they are also easily magnetized, producing the same high level of background. Magnetized particles are attracted to any ferromagnetic material in the testing system (bath tank, plumbing system or rails) and this causes an extensive loss of particles from the suspension. Particle depletion creates process control problems and requires frequent additions of new particles to the bath.

Another disadvantage of magnetically retentive wet method particles is their tendency to clump, quickly forming large clusters on the test object surface. These clumps have low mobility and do not migrate to leakage fields. This causes distorted or obscured indications in heavy, coarse grained backgrounds.

While the emphasis is on low coercive force and low retentivity, there is an advantage to certain levels of coercive force and retentivity. Low residual magnetization in dry particles appears to increase their sensitivity to diffuse, low level leakage fields formed by discontinuities lying below the surface. It is suspected that the small amount of polarity established in elongated particles assists in lining them into strings when attracted by weak leakage fields. This is similar to the effect of a compass needle swinging in the Earth's comparatively weak magnetic field.

Wet method particles are also enhanced by some coercive force and residual magnetism. Very fine wet method particles begin to collect at discontinuities as soon as they are applied to the test object surface. If the particles remain fine and separate, their migration through the vehicle is very slow because of their small magnetic field strength, small size and their small mass in a high viscosity vehicle. Indications build up very slowly under these conditions, taking as long as ten seconds.

Strongly magnetized particles form clusters and adhere to the test object surface as soon as bath agitation stops. Particles with low magnetic field strength cluster more slowly while indications are forming. The leakage field at the discontinuity draws the particles toward it and the clusters are constantly enlarging due to agglomeration. At the same time, the clusters sweep up nearby fine particles as they move toward the discontinuity.

Effects of Particle Size

The size and shape of magnetic particles play an important role in how they behave when subjected to a weak magnetic field such as that from a discontinuity. Large, heavy particles are not likely to be attracted and held by a weak leakage field as they move over the object surface. However, very small particles may adhere by friction to the surface where there is no leakage field and thus form an objectionable background.

Dry Powder Particles

Within limits, sensitivity to very fine discontinuities typically increases as particle size decreases. Extremely small particles, on the order of a few micrometers, behave like dust. They settle and adhere to the object surface even though it may be very smooth. Extremely fine particles are very sensitive to low level leakage fields but are not desirable for production tests because of intense backgrounds that obscure or mask relevant indications.

Large particles are not as sensitive to fine discontinuities. However, in applications where it is desired to detect large discontinuities, powders containing only large particles may be used.

Most commercial dry powders are a carefully controlled mixture of particles containing a range of sizes. The smaller sized particles provide sensitivity and mobility while larger sized particles serve two purposes. They assist in building up indications at larger discontinuities and help reduce background by a sort of sweeping action, brushing finer particles from the test object surface. A balanced mixture containing a range of sizes provides sensitivity for both fine and large discontinuities, without disruptive backgrounds.

Wet Method Visible Particles

Particles used in a liquid suspension are usually much smaller than those used in dry powders. Typically, the particles for wet method testing range from 1 to 25 μm while dry powder ranges from 100 to 1,000 μm. The upper limit of particle size in most wet method visible materials is 20 to 25 μm (0.0008 to 0.001 in.).

Larger particles are difficult to hold in suspension. Even 20 μm particles tend to settle out of suspension rapidly and are stranded as the suspension drains off the test object. Stranded particles often line up in drainage lines that could be confused with discontinuity indications.

Wet Method Fluorescent Particles

Particles treated with a fluorescent dye or some of the visible pigments differ in size and behavior from black or red (uncoated) visible particles. Fluorescent particles must be compounded and structured to prevent separation of the dye and magnetic material during use. A mixture of loose pigment and undyed magnetic material produces a dense background and poorly formed indications. In addition, the undyed magnetic particles may be attracted and held at leakage fields but their lack of contrasting color makes them difficult to see.

Producing fluorescent magnetic particles involves bonding pigment around each magnetic particle. The bonding must resist the solvent action of petroleum vehicles and the abrasive action occurring in pumping and agitation systems. Some manufacturers encapsulate the bonded dye particle in a layer of resin. Particles built up synthetically are larger than the minimum sized visible particles and such powders have much fewer very fine or small particles. As a result of their processing, fluorescent particles have a definite size range that is maintained throughout the suspension's service cycle.

Effect of Particle Shape

The magnetic materials used in magnetic particle testing are available in a variety of shapes: spheres, elongated needles or rods and flakes. The shape of the particles has a bearing on how they form indications. When exposed to an external magnetic field, all particles tend to align along the flux lines. This tendency is much stronger with elongated particles such as the needle or rod shapes. Elongated shapes develop internal north-south poles more reliably than spheroid or globe shaped particles, because they have a smaller internal demagnetization field.

Because of the attraction of opposite poles, the north and south poles of these small magnets arrange the particles into strings. The result is the formation of stronger patterns in weaker flux leakage fields, as these magnetically formed strings of particles bridge the discontinuity. The superior effectiveness of elongated shapes over globular shapes is particularly noticeable in the detection of wide, shallow discontinuities and subsurface discontinuities. The leakage fields at such discontinuities are weaker and more diffuse. The formation of particle strings based on internal poles makes stronger indications in such cases.

The disadvantage of elongated particles is their tendency to mat and form clusters that mask indications. Particle mobility is greatly enhanced by a spheroid or globular shape.

Dry Powder Shapes

The superiority of elongated particles in diffuse magnetic fields holds true for dry powder testing. However, there is another effect that must be considered. Dry powders are often applied to object surfaces by releasing them out of mechanical or manual blowers. It is essential that the particles be dispersed as a uniform cloud that settles evenly over the object surface. Magnetic powder containing only elongated particles tends to become mechanically linked in its container and is then expelled in uneven clumps.

When a powder behaves in this manner, testing becomes very slow and it is difficult to obtain a smooth application over the test object surface. Powders made of spherical particles flow evenly and smoothly under the same conditions. A dry powder must have free flowing properties for ease of application, yet must also have an optimum shape for the greatest sensitivity in forming strong indications over weak leakage fields. These two conflicting requirements can be met by selectively blending particles of different shapes.

A specific proportion of elongated particles must be present for sensitivity and enough globular particles must be added to permit smooth and uniform application.

Wet Method Particle Shapes

The performance of particles suspended in a liquid vehicle is not as shape dependent as dry particles. The suspending liquid is much denser and more viscous than air and this slows the movement of particles through the liquid so that they accumulate more reliably at discontinuities.

Because of this slower movement, wet method particles form minute elongated aggregates. Even unfavorable shapes align magnetically into elongated aggregates under the influence of local, low level leakage fields. In suspension, the particles are kept dispersed by mechanical agitation until they flow over the surface of the magnetized object. There is no need to add certain shapes to improve the dispersion of the particles.

Visibility and Contrast

Visibility and contrast are properties that must be considered when selecting a magnetic particle material for a specific testing application. Magnetic properties, size and shape may all be favorable for producing the best indication, but if an indication is formed and the inspector cannot see it, then the test procedure has failed.

Visibility and contrast are enhanced by choosing a particle color that is easy to see against the test object surface. The natural color of metallic powders is silver-gray. The colors of iron oxides commonly used in wet method powders are black or red. Manufacturers bond pigments to the particles to produce a wide selection of other colors: white, black, red, blue and yellow, all with comparable magnetic properties.

The white or yellow colors provide good contrast against mill surface objects. They are not effective against the silver-gray of grit blasted or chemically etched surfaces or against bright, polished machine ground surfaces. For those applications, black, red or blue is used. The choice of color depends on the surfaces of the test objects and the prevailing test site lighting.

The ability to bond fluorescent dyes to magnetic powders has produced a particle material that provides the best possible visibility and contrast under proper lighting conditions. When test objects are examined in ultraviolet light, it is difficult *not* to see the light emitted by a few particles collected at a discontinuity.

Fluorescent particles are magnetically less sensitive than visible particles but the reduction in magnetic retentivity is more than offset by the increase in visibility and contrast.

Visibility and contrast of fluorescent particles are directly related to the darkness of the testing site. In a totally darkened area, even a small amount of ultraviolet energy activates fluorescent dye to emit a noticeable amount of visible light. When the test site is partially darkened, the amount of required ultraviolet energy increases dramatically yet the emitted visible light is only barely noticeable.

Most military and commercial specifications require the test site to be darkened to 20 lux (lx) or 2 footcandles (ftc) or less, with a minimum ultraviolet intensity of 1,000 microwatts per square centimeter ($\mu W \cdot cm^{-2}$) at the test object surface.

Particle Mobility

When magnetic particles are applied to the surface of a magnetized object, the particles must move and collect at the leakage field of a discontinuity in order to form a visible indication. Any interference with this movement has an effect on the sensitivity of the test. Conditions promoting or interfering with particle mobility are different for dry and wet method particles.

Dry Powder Mobility

Dry particles should be applied in a way that permits them to reach the magnetized object surface in a uniform cloud with minimum motion. When this is properly done, the particles come under the influence of leakage fields while suspended in air and are then said to possess three-dimensional mobility. This condition can be approximated on surfaces that are vertical or overhead.

When particles are applied to horizontal surfaces, they settle directly onto the surface and do not have mobility in three dimensions. Some extension of mobility can be achieved by tapping or vibrating the test object, agitating the particles and allowing them to move toward leakage fields. Alternating current and half-wave rectified alternating current (pulsed direct current) can give particles excellent mobility when compared to direct current magnetization.

Wet Method Particle Mobility

The suspension of particles in a liquid vehicle allows mobility for the particles in two dimensions when the suspension flows over the test object surface and in three dimensions when the test object is immersed in a magnetic particle bath.

Wet method particles have a tendency to settle out of the suspension either in the tank of the test system or on the test object surface short of the discontinuity. To be effective, wet method particles must move with the vehicle and must reach every surface that the vehicle contacts. The settling rate of particles is directly proportional: (1) to their dimensions; and (2) to the difference between their density and the lower density of the liquid vehicle. Their settling rate is inversely proportional to the liquid's viscosity. As a result, the mobility of wet method particles is never ideal and must be balanced against the other factors important to wet method test results.

Media Selection

The choice between dry method and wet method techniques is influenced principally by the following considerations.

1. Type of discontinuity (surface or subsurface): for subsurface discontinuities, dry powder is usually more sensitive.
2. Size of surface discontinuity: wet method particles are usually best for fine or broad, shallow discontinuities.
3. Convenience: dry powder with portable half-wave equipment is easy to use for tests on site or in the field. Wet method particles packaged in aerosol spray cans are also effective for field spot tests.

The dry powder technique is superior for locating subsurface discontinuities, mainly because of the high permeability and favorable elongated shape of the particles. Alternating current with dry powder is excellent for surface cracks that are not too fine but this combination is of little value for cracks lying wholly beneath the surface.

When the requirement is to find extremely fine surface cracks, the wet method is superior, regardless of the magnetizing current in use. In some cases, direct current is considered advantageous because it also provides some indications of subsurface discontinuities. The wet method also offers the advantage of complete coverage of the object surface and good coverage of test objects with irregular shapes.

Visible or Fluorescent Particles

The decision between visible particles and fluorescent particles depends on convenience and equipment. Testing with visible particles can be accomplished under common shop lighting while fluorescent particles require a darkened area and an ultraviolet light source.

Both wet method visible and wet method fluorescent tests have about the same sensitivity, but under proper lighting conditions fluorescent indications are much easier to see.

Magnetic Particle Testing Processes

A test object may be magnetized first and particles applied after the magnetizing current has been stopped (called the *residual method*) or the object may be covered with particles while the magnetizing current is present (known as the *continuous method*). With test objects that have high magnetic retentivity, a combination of the residual and continuous methods is sometimes used.

Residual Test Method

In the residual method, the test object is magnetized, the magnetizing current is stopped and then the magnetic particles are applied. This method can only be used on materials having sufficient magnetic remanence. The residual magnetic field must be strong enough to produce discontinuity leakage fields sufficient for producing visible test indications. As a rule, the residual method is most reliable for detection of surface discontinuities.

Hard materials with high remanence are usually low in permeability, so higher than usual magnetizing currents may be necessary to obtain an adequate level of residual magnetism. This difference between hard steels and soft steels is usually not critical if only surface discontinuities are to be detected.

Either dry or wet method particle application can be used in the residual method. With the wet method, the magnetized test object may be immersed in an agitated bath of suspended magnetic particles or it may be flooded with particle suspension in a curtain spray.

In the immersion technique, the strength of discontinuity indications is directly affected by the object's dwell time in the bath. By leaving the object in the bath for extended periods, leakage fields have time enough to attract and hold the maximum number of particles, even at fine discontinuities. If the test object has high retentivity, longer dwell time increases the sensitivity over that of the wet continuous method. Note that the location of the discontinuity on the object during immersion affects the accumulation of particles. Indications are strongest on upper horizontal surfaces and weaker on vertical or lower horizontal surfaces.

Care must be exercised when removing the test object from the bath or particle spray. Rapid movement can literally wash off indications held by weak discontinuity leakage fields.

Continuous Test Method

When a magnetizing current is applied to a ferromagnetic test object, the magnetic field rises to a maximum. Its value is derived from the magnetic field strength and the magnetic permeability of the test object. When the magnetizing current is removed, the residual magnetic field in the object is always less than the field produced while the magnetizing current was applied. The amount of difference depends on the *B-H* curve of the material. For these reasons, the continuous method, for any specific value of magnetizing current, is always more sensitive than the residual method.

Continuous magnetization is the only method possible for use on low carbon steels or iron having little retentivity. It is frequently used with alternating current on these materials because of the excellent mobility produced by alternating current.

With the wet method, the surface of the test object is flooded with particle suspension. The bath application and the magnetizing current are simultaneously stopped. The magnetic field strength continues to affect particles in the bath as it drains.

The wet continuous method requires more operator attention than the residual method. If bath application continues, even momentarily, after the current is stopped, particles held by a discontinuity leakage field can be washed away. If there is a pause between stopping the bath application and applying the magnetizing current, the suspension can drain off the test object leaving insufficient particles for producing discontinuity indications. Careless handling of the bath and current sequence can seriously hinder the production of reliable test results.

The highest possible sensitivity for very fine discontinuities is typically achieved by the following sequence: (1) immerse the test object in the bath; (2) pass magnetizing current through the object for a short time during immersion; (3) maintain the current during removal from the bath; (4) maintain the current during drainage of the suspension from the test object; and (5) stop the magnetizing current.

Conclusion

Magnetic particle tests are effective nondestructive procedures for locating material discontinuities in ferromagnetic objects of all sizes and configurations. It is a flexible technique that can be performed under a variety of conditions, using a broad range of supplementary components.

Application of the magnetic particle method is deceptively simple — good test results can sometimes be produced with little more than practical experience. In fact, the development of the technique was almost entirely empirical rather than theoretical.

However, the method is founded on the complex principles of electromagnetics and the magnetic interactions of at least three materials simultaneously. In addition, there is the critical consideration of the operator's ability to qualitatively and quantitatively evaluate the results of the inspection. This volume of the *Nondestructive Testing Handbook* provides many details on practical applications of the magnetic particle technique, while at the same time discussing its important theoretical foundations.

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SECTION 2

GLOSSARY FOR MAGNETIC PARTICLE TESTING

Calvin McKee, NDT consultant, Wayne, Pennsylvania

For the purpose of consistency within the magnetic particle testing industry, the definitions here were taken from existing documents whenever ever possible. Almost all the definitions have been slightly altered from their source documents in order to reflect current terminology and to maintain the style of the *Nondestructive Testing Handbook* series. This glossary was prepared for educational purposes and no other intention should be assumed.

A

acceptance standard: A specimen test object similar to the product to be tested, containing natural or artificial discontinuities that are well defined and similar in size to or extent of the maximum acceptable in the product.[2]

alternating current: An electric current that reverses the direction of its flow at regular intervals.

alternating current field: The active magnetic field produced around a conductor by an alternating current flowing in the conductor.

alternating current magnetization: Magnetization by a magnetic field that is generated when alternating current is flowing.[4]

ampere: A unit of electric current. Abbreviated *A* or *amp*.

ampere per meter: The magnetic field strength in air at the center of a single-turn circular coil having a diameter of one meter, through which a current of one ampere is flowing. Abbreviated $A{\bullet}m^{-1}$ or *A/m*.[4]

ampere turns: The product of the number of turns of a coil and the current in amperes flowing through the coil.[5]

arc: A luminous high temperature discharge produced when an electric current flows across a gaseous gap.[4]

arc strikes: Localized burn damage to an object from the arc caused by breaking an energized electric circuit. Also called *arc burns*.[5]

arcing: Current flow through a gap, often accompanied by intense heat and light.[1]

articulated pole pieces: On a magnetizing yoke, independently adjustable magnetic elements enabling the magnetization of irregular test object profiles.

artificial discontinuity: A manufactured material anomaly. See *acceptance standard* and *reference standard*.

artificial flaw standard: See *acceptance standard*.

B

background: In magnetic particle testing, the appearance of the surface against which test indications are viewed.[5]

bath: See *suspension*.

bearding: See *furring*.

Berthold penetrameter: A magnetic flux indicator containing an artificial discontinuity in the shape of a cross, mounted below an adjustable cover plate.[4]

black light: Electromagnetic radiation in the near ultraviolet range with wavelengths from 320 to 400 nm (3,200 to 4,000 Å).[5]

black light filter: A filter that transmits near ultraviolet radiation from while absorbing other wavelengths.[5]

C

capacitor discharge method: A single-shot magnetization method using discharge from a bank of capacitors. A means by which electrical current is built up and stored until a sufficient level is achieved to provide a predetermined magnetic field in a test object, usually saturation.

carrier fluid: The liquid vehicle in which fluorescent or nonfluorescent magnetic particles are suspended for ease of application. See *vehicle*.[5]

central conductor: An electric conductor passed through the opening in a part with an aperture, or through a hole in a test object, for the purpose of creating a circular magnetic field in the object.[3]

circular magnetic field: The magnetic field surrounding an electrical conductor (test object) when a current is passed longitudinally through the conductor.[5]

circular magnetization: The magnetization in an object resulting from current passed longitudinally through the object itself or through an inserted central conductor.[5]

circumferential magnetization: See *circular magnetization*.

coercive force: The reverse magnetic field strength needed to reduce bulk magnetism to zero.

coil method: A method of magnetization in which all or a portion of the object is encircled by a current-carrying coil.[5]

coil shot: A technique of producing longitudinal magnetization by passing electric current through a coil encircling the test object.[3]

coil technique: See *coil method*.

conditioning agent: An additive to water suspensions that imparts specific properties such as proper wetting, particle dispersion or corrosion resistance.[5]

contact head: Electrode assembly used to clamp and support an object to facilitate passage of electric current through the object for circular magnetization.[5]

contact method: See *current flow technique*.

contact pad: Replaceable metal pad, usually made of lead or copper braid, placed on electrodes to give good electrical contact, thereby preventing damage such as arc strikes to the test object.[5]

continuous technique: A sequence where magnetic particles are applied to the test object while the magnetizing force is present.[4]

Curie point: The temperature at which ferromagnetic materials can no longer be magnetized by outside forces and at which they lose residual magnetism (between 650 and 870 °C for most metals).[5]

current flow technique: A means of magnetizing by passing current through an object using prods or contact heads. The current may be alternating current or rectified alternating current.[5]

current induction technique: A means of magnetization in which a circulating current is induced in a ring component by the influence of a fluctuating magnetic field.[5]

D

dark adaptation: The adjustment of the eye over time to reduced illumination, including increased retinal sensitivity, dilation of the pupil and other reflex physical changes.[5]

defect: A discontinuity whose size, shape, orientation or location make it detrimental to the useful service of the test object or which exceeds the accept/reject criteria of an applicable specification.[1]

demagnetization: The reduction of residual magnetism to an acceptable level.[5]

demagnetizing coil: A coil of conductive material carrying alternating current used for demagnetization.[4]

diamagnetic material: A material with magnetic permeability less than 1.

direct contact magnetization: See *current flow technique.*

direct current: An electric current flowing continually in one direction through a conductor.[1]

direct current field: A residual magnetic field or an active magnetic field produced by direct current flowing in a conductor.[1]

discontinuity: A change in the physical structure or configuration of an object. May be intentional or unintentional.[5]

domain: A saturated macroscopic substructure in ferromagnetic materials where the elementary particles (electron spins) are aligned in one direction by interatomic forces. A domain would be a saturated permanent magnet.[3]

dry method: A magnetic particle testing method in which the ferromagnetic particles are applied in a dry powder form.[5]

dry powder: Finely divided ferromagnetic particles selected and prepared for magnetic particle testing.[3]

E

electrode: A conductor by means of which a current passes into or out of a test object.[4]

electromagnet: A soft iron core surrounded by a coil of wire that temporarily becomes a magnet when an electric current flows through the wire.[5]

encircling coil: See *coil method.*

evaluation: The process of determining the magnitude and significance of a discontinuity causing a test indication, after it has been interpreted as being relevant.

examination: The process of testing materials, interpreting and evaluating test indications to determine if the test object meets specified acceptance criteria.

examination medium: A powder or suspension of magnetic particles applied to a magnetized test surface to determine the presence or absence of surface or slightly subsurface discontinuities.[5]

F

false indication: An indication that may be interpreted as being caused by a discontinuity but located where no discontinuity exists.

ferromagnetic material: A material that exhibits the phenomena of magnetic hysteresis and magnetic saturation and whose magnetic permeability is dependent on the magnetizing field strength.

field flow technique: See *magnetic flow technique.*

fill-factor: In the coil method of magnetization, the ratio of the cross-sectional area of the object within the coil to the cross-sectional area of the coil.[4]

flash magnetization: Magnetization by a current flow of brief duration.[5] See *capacitor discharge method.*

flash point: The lowest temperature at which vapors above a volatile, combustible substance ignite in air when exposed to flame.[5]

flaw: See *defect.*

fluorescence: The emission by a substance of visible radiation as a result of and only during the absorption of ultraviolet energy.

fluorescent magnetic particle testing: The process using finely divided ferromagnetic particles that fluoresce when exposed to ultraviolet light (320 to 400 nm).[1]

flux density: See *magnetic flux density.*

flux indicator: A small device, generally a metal strip or disk, containing artificial discontinuities. Used to determine when correct magnetizing conditions or magnetic field direction have been achieved.

flux leakage field: The magnetic field that leaves or enters the surface of an object.[5]

flux leakage method: A method for the detection and analysis of a discontinuity using the flux that leaves a magnetically saturated, or nearly saturated, test object at a discontinuity.[2]

flux lines: See *lines of force.*

fluxmeter: An electronic device for measuring magnetic flux.

full-wave direct current: A single-phase or three-phase alternating current rectified to produce direct current characteristics of penetration and flow.

furring: Build up or bristling of magnetic particles resulting from excessive magnetization of the test object.[5]

G

gauss: A unit of magnetic flux density or magnetic induction. Magnetic field strength B is measured in gauss abbreviated (*G*). One gauss is one line of magnetic flux per square centimeter of area.[3] See *tesla*.

gaussmeter: A magnetometer using gauss to register field strength.

H

half-wave current: A unidirectional rectified single-phase alternating current that produces a pulsating unidirectional field.[5]

Hall effect: A potential difference developed across a conductor at right angles to the direction of both the magnetic field and the electric current. Produced when a current flows along a rectangular conductor subjected to a transverse magnetic field.[4]

heads: The clamping contacts on stationary magnetic particle systems.[3]

head shot: A short pulse of magnetizing current passed through an object or a central conductor while clamped between the head contacts of a magnetizing unit, generating circular magnetization of the object. Duration of the current is usually less than one second.[3]

horseshoe magnet: A bar magnet bent into the shape of a horseshoe so that the two poles are adjacent. Usually the term applies to a permanent magnet.[3]

hysteresis: (1) The lagging of the magnetic effect when the magnetizing force acting on a ferromagnetic body is changed. (2) The phenomenon exhibited by a magnetic system wherein its state is influenced by its previous history.

hysteresis loop: A curve showing flux density B plotted as a function of magnetizing force H as the magnetizing force is increased to the saturation point in both the negative and positive directions sequentially. The curve forms a characteristic S shaped loop. Intercepts of the loop with the B-H axis and the points of minimum and maximum magnetizing force define important magnetic characteristics of a material.[3]

I

indication: A magnetic particle accumulation that serves as evidence of a field leakage and requires interpretation to determine its significance.[5]

induced magnetization: A magnetic field generated in an object when no direct electrical contact is made.[5]

induced current technique: See *current induction technique*.

inductance: The magnetism produced in a ferromagnetic body by some outside magnetizing force.[3]

inherent fluorescence: Fluorescence that is an intrinsic characteristic of a material.[5]

inspection: See *examination*.

inspection medium: See *examination medium*.

internal conductor: See *central conductor*.

interpretation: The determination of a magnetic particle indication's source and relevancy.[5]

K

keeper: Ferromagnetic material placed across the poles of a permanent magnet to complete the magnetic circuit and prevent loss of magnetism.[4]

L

laminated pole pieces: See *articulated pole pieces*.

leakage field: See *flux leakage field*.

leeches: Permanent or electromagnets attached to electrodes carrying magnetizing current, to provide strong electrode contact.[5]

lifting power: The ability of a magnet to lift a piece of ferritic steel by magnetic attraction alone.[4]

lines of force: A conceptual representation of magnetic flux based on the line pattern produced when iron filings are sprinkled on paper laid over a permanent magnet.[5]

longitudinal magnetic field: A magnetic field wherein the flux lines traverse the component in a direction that is essentially parallel with its longitudinal axis.[5]

longitudinal magnetization: Magnetization in which the flux lines traverse the component in a direction essentially parallel to its longitudinal axis.[4]

M

magnetic circuit: The closed path followed by any group of magnetic flux lines.[4]

magnetic field: Within and surrounding a magnetized object, the space in which the magnetic force is exerted.[3]

magnetic field indicator: A device used to locate or determine the relative intensity of a flux leakage field emanating from an object.[5]

magnetic field leakage: See *flux leakage field*.

magnetic field strength: The measured intensity of a magnetic field at a specific point. Expressed in amperes per meter or oersted.

magnetic flow technique: When a test object or a portion of it closes the magnetic circuit of an electromagnet. The resulting field is longitudinal in direction.

magnetic flux: The total number of lines of force existing in a magnetic circuit.[4]

magnetic flux density: The normal magnetic flux per unit area. Expressed in tesla or gauss.[4]

magnetic flux leakage: See *flux leakage field*.

magnetic hysteresis: See *hysteresis*.

magnetic leakage field: See *flux leakage field*.

magnetic particle test: A nondestructive test method utilizing magnetic leakage fields and suitable indicating materials to disclose surface and near surface discontinuities.[5]

magnetic particle test system: Equipment providing the electric current and magnetic flux necessary for magnetic particle discontinuity detection. Provides facilities for holding components of varying dimensions and for adjusting and reading the magnetizing current.[4]

magnetic particles: Finely divided ferromagnetic material capable of being individually magnetized and attracted to flux leakage fields.[5]

magnetic permeability: See *permeability*.

magnetic pole: One of two sites on a magnet that generates magnetic fields. Flux leakage sites on an object.[5]

magnetic powder: Magnetic particles in dry or powder form with size and shape suitable for discontinuity detection.[4]

magnetic rubber: A specially formulated testing medium containing magnetic particles. Used to obtain replica castings of component surfaces with discontinuities being reproduced within the replica. A suitable magnetizing technique causes the migration of magnetic particles within the medium to the position of the discontinuity.[4]

magnetic saturation: In a specific material, the degree of magnetization where an increase in H produces no further increase in magnetization.

magnetic writing: A nonrelevant indication sometimes caused when the surface of a magnetized object comes in contact with another piece of ferromagnetic material or a current carrying cable.[5]

magnetism: The ability of a magnet to attract or repel another magnet or to attract a ferromagnetic material. A force field surrounding conductors carrying electric current.[1]

magnetization: The process by which elementary magnetic domains of a material are aligned predominantly in one direction.

magnetizing current: The electric current passed through or adjacent to an object that gives rise to a designated magnetic field.

magnetizing force: The magnetizing field strength applied to ferromagnetic material to produce magnetism.[5]

magnetometer: A device for measuring the strength of magnets or magnetic fields.[1]

multidirectional magnetization: Two or more magnetic fields in different directions imposed on a test object sequentially and in rapid succession.[4]

N

near surface discontinuity: A discontinuity not open to but located near the surface of a test object. Produces broad, fuzzy, lightly held dry particle indications.[5]

nonrelevant indication: A test indication produced by an acceptable discontinuity or by spurious effects such as magnetic writing, changes in section or the boundary between materials of different magnetic properties.[4]

O

oersted: The cgs unit of magnetic field strength. Replaced by the SI system's ampere per meter.[4]

overall magnetization: Magnetizing a complete object with a single energizing cycle.[5]

P

parallel magnetization: A magnetic field induced in magnetizable material placed parallel to a conductor carrying an electric current.[3] Not a recommended practice for magnetic particle testing.

paramagnetic material: A material with magnetic permeability slightly greater than 1.

permanent magnet: An object possessing the ability to retain an applied magnetic field for a long period of time after the active power of the field has been removed.[3]

permeability: (1) The ease with which a material can become magnetized. (2) The ratio of flux density to magnetizing force (B/H).[1]

pole: See *magnetic pole*.

powder: See *dry powder*.

powder blower: A compressed air device used to apply dry magnetic particles over the surface of a test object.[5]

prod magnetization: See *current flow technique*.

prods: Handheld electrodes for transmitting magnetizing current from a generating source to a test object.[4]

pulse magnetization: Direct or indirect application of a high field intensity, usually by the capacitor discharge method.

Q

quick break: A sudden interruption of magnetizing current.[5] Used in magnetic particle tests for materials with high residual longitudinal magnetism and limited to three-phase full-wave rectified alternating current.

R

rectified alternating current: A unidirectional electric current obtained by rectifying alternating current without the deliberate addition of smoothing to remove the inherent ripples.[4]

reference standard: A specimen containing controlled artificial or natural discontinuities. Used for verifying the accuracy of discontinuity detection processes or equipment.[4]

relevant indication: An indication caused by a condition or a type of discontinuity that requires evaluation.[5]

remanent magnetism: See *residual magnetic field*.[3]

residual magnetic field: The field remaining in a ferromagnetic material after the magnetizing force is reduced to zero.[3]

residual technique: Ferromagnetic particles are applied to a test object after the magnetizing force has been discontinued.

retentivity: A material's property of retaining to a greater or lesser degree some residual magnetism.[3]

ring standard: See *test ring*.

S

saturation level: See *magnetic saturation*.

sensitivity: The degree of capability of a magnetic particle test to indicate surface or near surface discontinuities in ferromagnetic materials.[5]

settling test: A procedure used to determine the concentration of particles in a magnetic particle bath.

shot: A short energizing cycle in a magnetic particle test.[5]

skin effect: The phenomenon that causes the magnetization produced by alternating current to be contained near the surface of a ferromagnetic object.[5]

slurry: A free-flowing pumpable suspension of a fine solid in a liquid.

subsurface discontinuity: See *near surface discontinuity*.

suspension: A two-phase system comprising finely divided magnetic particles dispersed in a vehicle, often a liquid petroleum distillate.[5] See *vehicle*.

swinging field: See *multidirectional magnetization*.

T

tesla: The Systeme Internationale unit of measure for magnetic flux density. One tesla is equivalent to 10^4 gauss.

test piece: See *reference standard*.

test ring: A ring specimen typically made of tool steel, containing artificial subsurface discontinuities used to evaluate and compare the performance and sensitivity of magnetic particles.[5]

through-coil method: See *coil method*.

true continuous method: Test technique in which magnetizing current is applied before application of magnetic particles and is maintained without interruption throughout the examination.[5]

toroidal field: An induced magnetic field occurring in a ring test object when current is induced. See *current induction technique*.

U

ultraviolet light: Electromagnetic radiation with wavelengths between 200 and 400 nm (2,000 and 4,000 Å). The range of wavelengths used for fluorescent nondestructive testing is typically between 320 and 400 nm. Shorter wavelengths are very hazardous. See *black light*.

V

vehicle: A liquid medium for the suspension of magnetic particles, often a light petroleum distillate or conditioned water. See *carrier fluid*.[5]

visible light: Radiant energy generated in the 400 to 700 nm (4,000 to 7,000 Å) wavelength range.[5]

W

wet method: A testing technique in which the magnetic particles are applied as a suspension in a liquid vehicle.[5]

wet slurry technique: A magnetic particle test in which the particles are suspended in high viscosity vehicle.[5]

Y

yoke: A *U* shaped magnet that induces a field in the area of the test object that lies between its poles. Yokes may be permanent magnets, alternating current electromagnets or direct current electromagnets.

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SECTION 3

A HISTORY OF MAGNETIC PARTICLE TESTING

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PART 1

ORIGINS OF THE MAGNETIC PARTICLE INDUSTRY

The *Nondestructive Testing Handbook* is edited to avoid using commercial wording — product names and trademarks are deleted as a matter of policy. Because the history of magnetic particle testing in the United States is so closely linked with the inventors' corporation, generic text was not always possible in this history.

The chapter focuses on the magnetic particle industry's origins in America, but important research and applications were occurring at the same time in other countries, particularly in Germany and Japan.

The 1920s: Era of Discovery

Magnetic flux leakage testing had its beginnings in the 1800s. In 1868, a British engineering publication reported that discontinuities were being located in gun barrels using a magnetic compass to register the flux.[1] In 1876, A. Hering obtained US patent 185,647 for a test method using a compass needle to detect discontinuities in rails.

Magnetic particle testing began in the twentieth century and its development is the focus of this discussion.

Hoke's Patent

After World War I in 1918, Major William E. Hoke (US Army, on assignment to the Bureau of Standards) was working on development of precision gage blocks as measurement standards. Hoke observed that metallic particles from hard steel parts being ground on a magnetic chuck sometimes formed patterns on the face of the part, patterns that frequently corresponded to cracks in the part's surface.

This alert observation marked the birth of magnetic particle testing (essentially, Hoke had recognized the basis for longitudinal magnetization). He applied for a patent which was issued in 1922 but made no attempt to commercialize the idea.

Contribution of Alfred de Forest

In the 1920s, Alfred Victor de Forest (Fig. 1a) was a research engineer, a consultant and a teacher at the Massachusetts Institute of Technology. The study of metals and their performance dominated his professional life. In 1928, de Forest was asked by Spang Chalfant Company to investigate the cause of failure in some of its oil well drill pipe. His work on this project resulted in the magnetic particle testing method in use today.

Alfred de Forest recognized the possibilities of the method if it could be perfected to detect cracks in any direction. This meant that the direction of the magnetic field in the object could not be left to chance, neither could it be only longitudinal. The only means of magnetizing previously known were external magnets or coils carrying current. Alfred de Forest used a system that passed magnetizing current directly through the test object.

This was the first recorded use of circular magnetization, the method now so widely used. He also conceived of using magnetic powders with controlled size, shape and magnetic properties, essential for consistent and reliable results. Conflicts with Major Hoke's original patent were worked out the year de Forest met F.B. Doane (Fig. 1b), of Pittsburgh Testing Laboratories. That year, 1929, the partnership of A.V. de Forest Associates was formed. In 1934, the company became Magnaflux Corporation.

In 1967, Carl Betz (Fig. 1c) wrote that de Forest and Doane were individuals "who had the vision to see the value of a new idea and the courage and faith to devote their lives to making this vision become a reality."[2] A.V. de Forest was involved with magnetic particle testing until his death in 1945. Doane remained active in the industry until his death in 1963.

The 1930s: Years of Development

Test System Development

In the early 1930s, de Forest and Doane showed great enthusiasm for their practical testing method. They set up a small laboratory and shop in Doane's basement and began making powder (*dust*, as it was then called). The pair produced a variety of particles, making it possible to inspect both smooth and rough surfaces, machined parts, castings or welds. The particles could be used for detecting discontinuities of various widths and depths, and for detecting both surface and some subsurface discontinuities. These first particles were dry powders.

The wet method (liquid suspension) technique was added in 1935. At the Wright Aeronautical Company in Paterson, New Jersey, black magnetic oxide was suspended in a light

FIGURE 1. Pioneers of the magnetic particle testing technique: (a) A.V. de Forest, one of the method's inventors; (b) F.B. Doane, coinventor of the magnetic particle method; and (c) Carl Betz, magnetic particle authority and author

(a)
(b)
(c)

petroleum product similar to kerosene. At the same time, the General Electric Company in Schenectady, New York began using finely ground mill scale suspended in light oil.

In 1936, a German patent was issued to F. Unger and R.S. Hilpert who suggested that magnetic particles could be suspended in water with wetting agents and rust inhibitors added. About two years later, there were important German developments in other areas of research. Based on a desire to establish standardized magnetic particle test sensitivities, a magnetic test gage was developed at the Reichs Roentgenstelle at Berlin-Dahlem. With few modifications, the gage is the same type now known as the Berthold field gage.[3]

In the United States, magnetic particle testing was introduced by Doane and de Forest to the Army Air Corps at Wright Field in Dayton, Ohio and to the Navy at the Naval Aircraft Factory in Philadelphia, Pennsylvania. The test method was soon being used in suppliers' plants as well as aircraft repair centers. The original cracked sample used for demonstrating the effectiveness of magnetic particle testing is shown in Fig. 2. The reaction of those who saw the particles attracted to the invisible cracks in his permanently magnetized sample continually intrigued de Forest.[4]

In the early 1930s, an experimental magnetizing fixture was first used to demonstrate the magnetic particle technique (see Fig. 3). Figure 4 shows an assembly of electrical components like those built for early applications. This system employed alternating current for magnetizing and was used to test tool steel bars. Figure 5 shows a unit used in the aircraft industry in the 1930s; it provided circular and longitudinal magnetization from storage battery power.

Early Inspection Applications

Hamilton Standard Company was among the first to use the magnetic particle technique to inspect aircraft propellers. Pratt and Whitney, producer of aircraft engines, soon followed. The first airlines to use the method were American Airlines and United Airlines. Both the Army and the Navy

FIGURE 2. Test object used by A.V. de Forest to demonstrate the magnetic particle technique

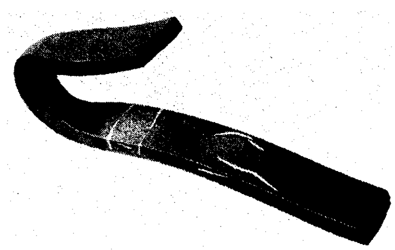


FIGURE 3. Experimental magnetic particle testing equipment used by F.B. Doane in 1930

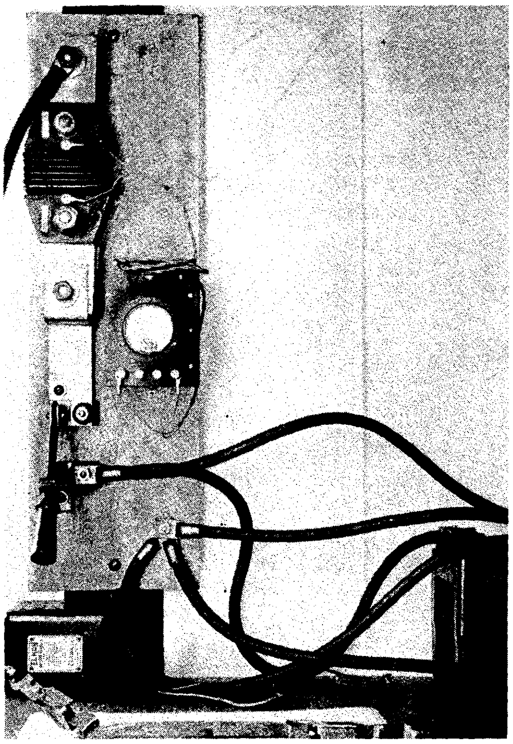


FIGURE 4. Alternating current magnetizing assembly (1933)

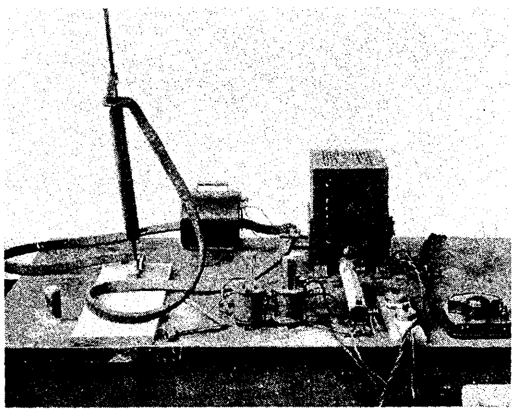


FIGURE 5. Storage battery unit used by the aircraft industry from 1932 to 1940

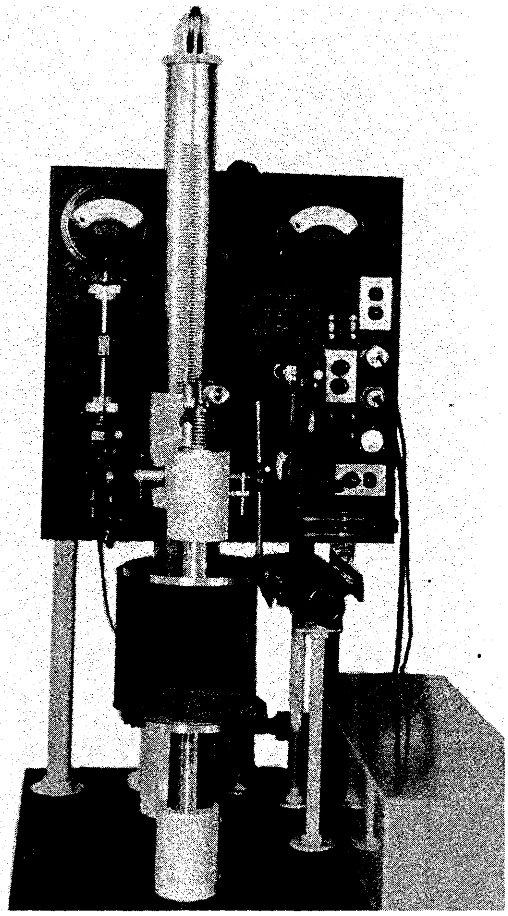
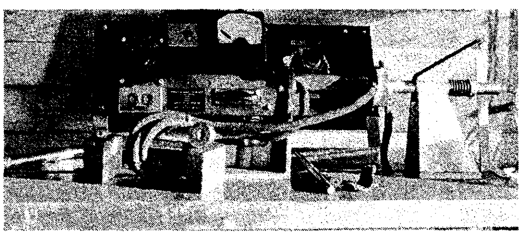


FIGURE 6. Magnetic particle testing system first used at the Indianapolis Motor Speedway (1936)

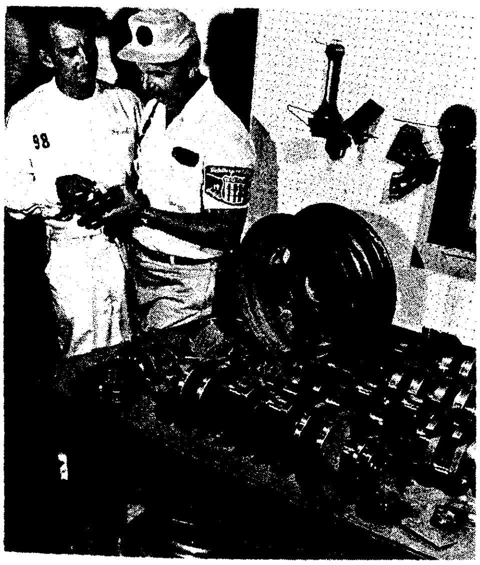


recognized the value of the technique for locating fatigue cracks in engine parts, propellers and other highly stressed parts during periodic overhaul.

The railroads were also early users of magnetic particle techniques, mainly for the location of fatigue cracks in axles and motion parts of steam locomotives. The automotive industry became interested and by the end of the 1930s, magnetic particle systems were being used in metallurgical laboratories and in some receiving inspection departments on an experimental basis. The Greyhound Bus Company began its use of the method for the location of fatigue cracks in engine parts at overhaul. Early users also included steam power plants who began scheduling the testing method during maintenance of turbines, boilers and piping welds.

During this same time, the merchant steel mills were restricting spending because of the Great Depression and had not yet begun using magnetic particle tests. However, the method was accepted by the specialty steel producers, those who made tool steel. This steel was more expensive and top quality was demanded. Seams in tool steel bars generally resulted in cracked tools, punches or dies. The labor cost of machining tools was high and specialty mills were often held responsible. Tool steel and alloy steel producers were among the early advocates of magnetic particle techniques.

FIGURE 7. Racing driver Parnelli Jones and inspector supervisor Ed Oclon reviewing parts with discontinuities at Indianapolis Motor Speedway



In Germany as well, the magnetic particle test method was developing parallel with welding techniques and their use on steel structures. Magnetic particle techniques were used to locate cracks and to detect misalignments of plate edges. Alternating current prods and direct current yokes were reported to produce the best results.

Another early user was the Indianapolis Motor Speedway. In 1936, magnetic particle testing was made mandatory there for all steering parts. In that same year, more than 50 percent of the parts presented for testing were rejected. In 1948, Wilbur Shaw, president of the Speedway, stated that the magnetic particle testing method had contributed more to their safety record than any other single factor. He confirmed that not one accident at the track had been caused by a defective steering part since the testing method was made compulsory.

Figure 6 shows the first magnetic particle unit sent to the Speedway in 1936 to eliminate serious spindle failures, which had been occurring during the two previous years. By 1962, although not mandatory, owners were submitting many engine parts for testing prior to practice runs. Figure 7 shows a few of the many crankshafts rejected before failure in service and a few magnesium wheels found defective by the fluorescent penetrant method. These two methods continue to be widely used by the racing industry.

Improvements in Magnetizing Equipment

Until the mid 1930s, most magnetic particle inspectors made their own magnetizing equipment. About 1934, Doane introduced the low voltage, 60 hertz alternating current unit for steel mill bar stock testing. Up to this time, most magnetizing equipment used direct current from storage

FIGURE 8. Mobile magnetic particle unit in railroad shop (1937)

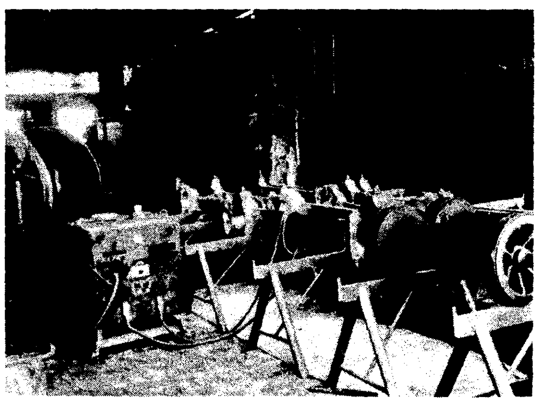
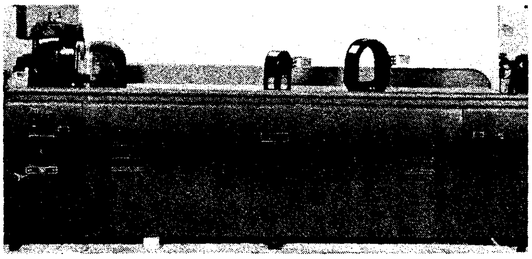


FIGURE 9. Standard design wet horizontal unit (1936) with motorized tailstock; used by the US Navy and US Army Air Corp



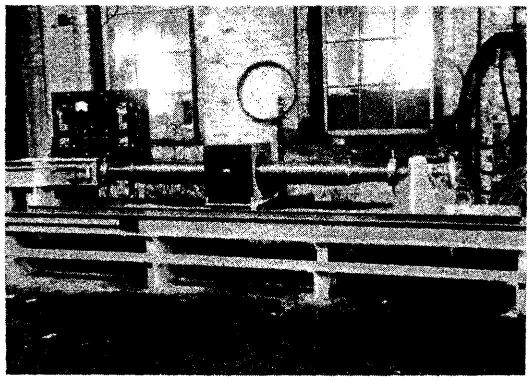
batteries. The unit had a transformer with two taps in the primary coil so that, by knife switches, the output from the secondary could be adjusted. Several machines of this type were designed to test heavy equipment in the railroads and other industries. One of these (shown in Fig. 8 in a railroad maintenance shop) is the prototype of today's mobile power packs. It operated from a 220/440 V, 60 Hz power supply and delivered up to 3,000 A of low voltage magnetizing current through 4/0 flexible cables. The unit was made mobile (wheeled) because most railroad parts were very heavy and it was easier to move the testing system.

Around 1938, the Navy and Army Air Corps agreed on a standard magnetic particle system design to be used in their overhaul shops (Fig. 9). It was a horizontal, wet method, direct current machine, with storage batteries and battery charger. The amperage was controlled by a carbon pile rheostat. The unit bore the designation *AN* for Army and Navy.

Another first came in 1938 — a series of systems designed to inspect only one type of object (Fig. 10). This special design was built for the Denver and Rio Grande Western Railroad for the testing of railroad car axles. Many severe road failures with costly traffic delays and loss of equipment had been occurring nationwide. During the first few months of extensive magnetic particle testing, 45 percent of all moving locomotive parts were found to be defective. After two years of planned overhaul programs, road failures due to fatigue cracking were virtually eliminated on the Denver and Rio Grande Western Railroad.

Before 1939, demagnetizers had been both crude and cumbersome. The use of alternating current for magnetization required special design efforts to attain closer current control. Research eventually produced a thirty-point motorized tapswitch that provided close control of the magnetizing current. This was a significant development that also provided the capability of rapid and automatic demagnetization of objects through a succession of short shots of

FIGURE 10. Magnetic particle test system for railroad axle units (1938); one of the first systems designed to inspect a single kind of test object



alternating current at diminishing amperages. Larger objects could be demagnetized while still in place on the magnetizing unit.

The 1930s also saw the introduction of the alternating current electromagnetic yoke. The yoke was limited then as it is today to the location of surface discontinuities and found its first uses as a preventive maintenance tool. The yoke was also reportedly used in the metallurgical laboratory of a steel mill as a means of locating discontinuities in sample disks 50 mm (2 in.) thick, cut from each end of forging quality billets.

Finally, this decade saw the first power plant applications of the magnetic particle method, including the testing of steam turbine blades during overhaul.

Education and the Magnetic Particle Method

During this era, growth in many industries was hindered by organizations that wanted to keep new developments proprietary. In industrial radiography for example, there was little published information available, even though H.H. Lester of Watertown Arsenal had demonstrated (as early as 1922) that penetration of thick sections of steel was practical. He showed that discontinuities such as cavities, cracks, porosity and nonmetallic inclusions could be revealed where the discontinuity thickness was as small as two percent of the metal thickness.

In 1938 in Germany, Rudolph Berthold published *The Atlas of Nondestructive Test Methods* which included the physical fundamentals and technical aids for magnetic particle testing. In 1939, Doane proposed a textbook on magnetic particle testing, to include all of the design, application and method information then available — much as this *Nondestructive Testing Handbook* does. Some individuals in his own firm disagreed with this proposal but Doane prevailed. The first edition of *Principles of Magnaflux Inspection* was published in February 1940 with Doane as the author. He coauthored a second textbook, the *Magnaflux Aircraft Inspection Manual*, with Willys E. Thomas in 1941.

PART 2

EXPANSION OF THE MAGNETIC PARTICLE INDUSTRY

The 1940s: Organization and Growth

Increased Wartime Production

The 1940s began with growing emphasis on military procurement. Purchasing groups came to the United States from Europe to buy military hardware. The major manufacturers expanded production of weapons, vehicles and aircraft. As a result, foundries, forging plants, machine tool and gear manufacturers, steel mills and landing gear producers were all affected.

As production increased, the need for magnetic particle testing increased. Makers of tractors and diesel engines also became users of the technique. Suppliers of castings and forgings showed genuine interest in the testing method. Many machine tool and turbine manufacturers purchased testing equipment for their metallurgical laboratories or testing departments. Purchase orders requiring US military specifications required the use of magnetic particle testing.

World War II not only created a need for more magnetic particle testing, it also created a need for testing equipment that could rapidly handle mass produced parts (see Figs. 11 and 12). Special purpose handling systems were designed for larger and heavier objects (steel propeller blades, propeller hubs, engine cylinders and engine mounts) and some of these systems were partially automated.

Up to this time, magnetic particle testing had been used on many types of welded structures, particularly welded aircraft assemblies. However, on heavier welds, radiography was the accepted nondestructive testing method and was called for in the American Society of Mechanical Engineer's *Boiler and Pressure Vessel Code.*

Because of the war, American shipbuilding soared and so did the future of magnetic particle testing methods, for the ships themselves and for their weaponry. The most common naval weapon was the 127 mm (5 in.) gun for destroyers and aircraft carriers. The gun's mounts were made of heavy steel plate welded together to form a fixed and a rotating platform; the welds were up to 150 mm (6 in.) thick. Magnetic particle testing found an immediate application for locating inclusions and laminations that interfered with

FIGURE 11. Automatic magnetic particle testing system for inspection of bolts and similarly shaped objects (early 1940s)

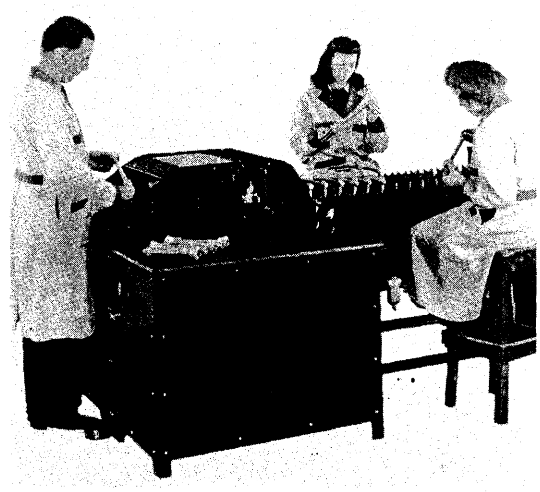
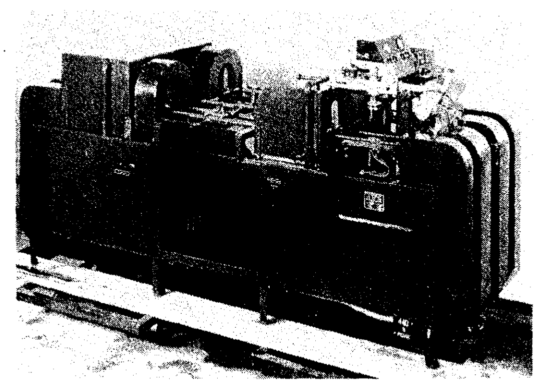


FIGURE 12. Conveyorized 20 mm (0.8 in.) magnetic particle testing unit (1942)



the making of crack-free root weld passes (early detection was critical before depositing more weld metal). Direct current testing with prods (Fig. 13) and the use of an automatic powder blower also originated at this time.

Effect of Military Specifications

The pace of production and the haste of all involved, including the military, caused a great deal of over inspection during the war. The first military specification on AN bolts required 100 percent testing in both directions, even though circumferential discontinuities were the only ones of importance. Many usable bolts were scrapped because of minor seams or inclusions.[5]

In the years after the war, proposed military specifications were usually reviewed by the potential users before being issued. This reduced but did not eliminate the problem of over inspection. There were still important differences between drawing specifications and floor inspection requirements.

Direct Current Testing and Quick Break Designs

The superiority of direct current magnetization for locating subsurface discontinuities had long been recognized. However, battery maintenance represented a growing problem because of the need for larger and heavier duty units. In 1941, the AN battery powered series of wet horizontal test machines was replaced on the assembly line by the ANQ (rectifier) series.

When a coil is used to impart a longitudinal field in a bar shaped object, special circuitry is required to ensure sufficient field near the ends of the test object for detection of circumferential discontinuities. The condition or effect required has been called *quick break* or *fast break*. Battery powered units had this feature built in.

Special quick break design considerations are required on rectifier powered machines. The lack of this special design can be catastrophic — one automobile producer dropped their sixty car per hour production rate to zero when steel conveyor pins began breaking in one of their main lines. The magnetic particle test of these pins had been performed with war surplus systems built before the quick break phenomenon was recognized.

This one occurrence was followed by others in the years following the war. Most of the trouble was caused by maintenance personnel who innocently removed what appeared to be an extra breaker in the circuit of their machines. Even with today's modern circuitry, it is important that all units using a coil for magnetizing be checked periodically to ensure that *quick break* is operating properly. In the 1960s, a device for quickly verifying the presence of this feature was introduced.

FIGURE 13. Mobile direct current (rectifier) power pack and powder blower (1942)

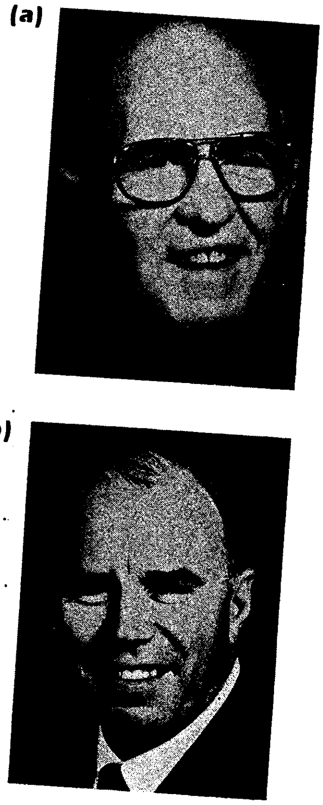
Fluorescent Magnetic Particle Testing

In 1941, the magnetic particle testing method took a significant step forward with the introduction of fluorescent magnetic particles. The first fluorescent powders consisted of loosely bound agglomerates of magnetic powders and separate fluorescent powders. The two tended to be trapped together to form fluorescent indications. The agglomerated mixture was an improvement over visible powder but was still not completely satisfactory.

Experimental work with the mixture of magnetic particles and fluorescent powders had been carried out by a number of individuals and groups. However, Robert and Joseph Switzer (Fig. 14a and 14b) are credited with first applying the idea of combining magnetic and fluorescent particles. The brothers developed a method of coating magnetic particles with fluorescent material and this greatly enhanced the particles' visibility. Pure black against pure white offers a 25:1 contrast ratio. Fluorescence in darkness offers contrast ratios as high as 1,000:1. Fluorescent particles can therefore be fewer in number while still offering a sizable increase in sensitivity for detection of fine discontinuities. The bonding process had another advantage: it allowed the use of water instead of oil or kerosene as a suspension vehicle.

Years later it was revealed that magnetic particle testing and fluorescent penetrant testing were very much a part of building the first atomic bomb under the Manhattan Project.[6] These testing methods were also vital factors in the building of the first atomic reactor, erected beneath the stands of Stagg Field at the University of Chicago. A.V. de Forest used both testing methods on various pieces of the reactor and the containers for the uranium fuel. Since that time, both methods have been intimately involved in all facets of the military and peaceful use of atomic energy.

FIGURE 14. Pioneers of the magnetic particle testing technique: (a) Robert Switzer and (b) Joseph Switzer, developers of the fluorescent particle test



Technical Societies and Education

The 1940s also witnessed the beginning of nondestructive testing symposiums and schools for industry. Every magnetic particle testing system put into operation required operators and inspectors, so people were hired by the thousands and assigned to inspection work. Many of them knew little about the equipment, the inspection method or what an operator was expected to do. Military documents required contractors to train inspection personnel in both theory and applications. Government inspectors then administered written and practical examinations before assigning government certification. Compounding the training problem was a shortage of supervisors and instructors.

Schools were soon established in important industrial centers. For the magnetic particle technique, Magnaflux Corporation offered lecture courses, generally three days long. During the war, more than fifty-five of their courses were presented to about five thousand people. After the war, permanent schools were established by many nondestructive testing firms, each specializing in the methods they knew best. Most nondestructive testing innovators, including pioneers like Phil Johnson, had a common philosophy: every defect has a cause — educated and constructive inspectors can suggest a cure.

Peacetime Production and Developments

Alfred de Forest said many times, "the closer the test can be brought to the hot steel, the more economical it is."[7] In other words, catch the discontinuity early and save money. During the war, nondestructive testing activities had been directed toward supplying the needs of war material contractors and military agencies.

After the war, most metalworking firms continued to emphasize production, not testing or intensive quality control and all the nondestructive testing techniques, including the magnetic particle method, had to be reintroduced. This was done by selling the realities and advantages of accurate testing. It was a slow educational process but by 1950 a consumer oriented economy had helped shift the emphasis toward quality.

Peacetime manufacturing for profit in the late 1940s saw an increasing acceptance of nondestructive testing. Many metalworking firms were specifying magnetic particle testing on purchased parts. Some firms (Cummins Engine Company and the Electro Motive Division of General Motors Corporation, for example) established detailed procedures for magnetic particle inspection of parts, including testing procedures and accept or reject criteria.

Developments in the hardware of magnetic particle testing also helped improve the accuracy of the technique and, in turn, the quality of products. In the 1930s, the first mobile power pack for weld testing had used direct current for magnetization. This provided a penetrating magnetic field (designed to supplement radiography for detecting subsurface discontinuities) but it restricted the mobility of the magnetic particles. A method of magnetizing called *surge magnetization* followed in the 1940s. It was possible, by suitable current control and switching devices, to provide a very high current for a short period (less than a second) and to then reduce the current without interrupting it to a much lower steady value.

This surge magnetizing technique was used for many years to allow deeper penetration, but still did nothing for powder mobility. Half-wave magnetizing current was introduced after the war and provided increased penetration and increased powder mobility. Despite the refinement of radiographic techniques and the introduction of ultrasound,

FIGURE 15. Special purpose magnetic particle testing unit for railroad car axles (late 1940s)

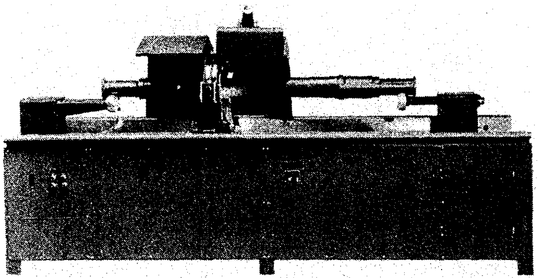


FIGURE 16. Magnetic particle testing of steam turbine rotor blades

half-wave magnetic particle testing is widely used today for the detection of both surface and near surface discontinuities in welds.

With the means available for magnetizing heavy cross sections in welds, castings and forgings, the rather simple technique of passing test objects through an alternating current coil for demagnetization was no longer always adequate. A demagnetizer that could penetrate deeply was necessary. One method utilized a direct current yoke and a resonant carrier-to-interference ratio (CIR) circuit. Properly designed for a specific job, this method provided the deepest penetration for demagnetizing. However, it was not practical in those applications where several kinds of test objects were involved.

The demagnetizer that did find wide acceptance during this period was one that could be built into any direct current power pack. A thirty-point switch and a set of breakers provided reversing and decreasing direct current at one reversal per second. This procedure was necessary for applications such as demagnetizing heavy crankshafts used in truck and off-road equipment.

The postwar years were most dramatic for the railroads. During this period, many inspectors learned what the term *copper penetration* meant: molten alloys from the bearings of railroad axle journals penetrated the grain boundaries of the heated journal. This provided the starting point for fatigue cracks and eventual axle failure. The condition could not be found visually nor with dry magnetic particles but was readily seen with fluorescent magnetic particle testing (Fig. 15). The first mandatory use of magnetic particle testing as a safety measure in railroads was introduced in 1949 when the American Association of Railroads (Wheel and Axle Committee) adopted the requirement for testing of journals.

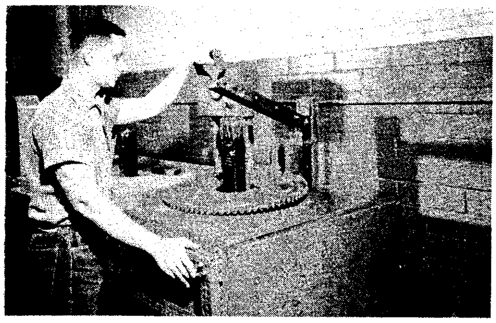
During the 1940s, developments also began in the utility industries (see Fig. 16) and the petrochemical industries. Firms laying pipelines, for example, began using magnetic particle testing on their field-made welds, particularly on the tie-in welds made after dropping the pipe sections into place below ground level.

The 1950s: Developing Markets

The early 1950s provided many new applications for magnetic particle testing. In aerospace, it was the jet age. Today, airline accidents are seldom traced to structural or engine component failure but this reputation had to be earned and magnetic particle testing played a major part in its achievement. Figure 17a shows the magnetizing of a jet engine compressor disk; Fig. 17b illustrates the examination of a compressor rotor assembly for transverse discontinuities in the blades. Figure 18 shows a mobile unit being used on a helicopter part in the field.

FIGURE 17. Special magnetizing units employing the induced current method for: (a) jet engine compressor disks; and (b) aircraft gas turbine compressor blading (assembled)

(a)



(b)

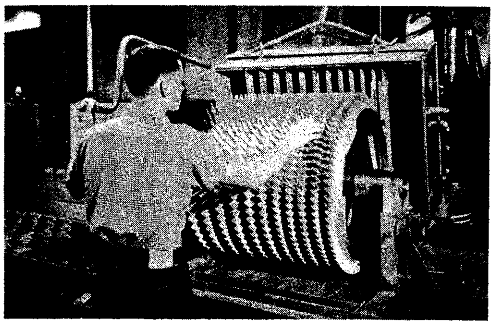
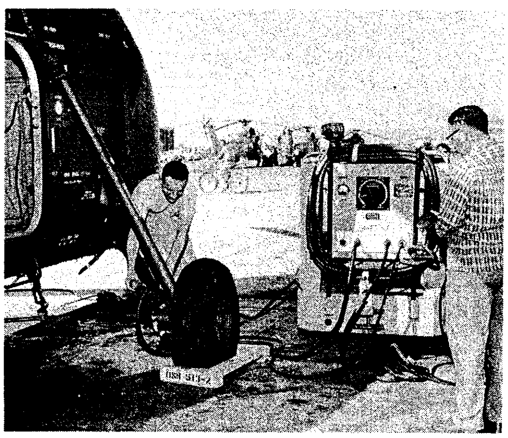


FIGURE 18. Inspection of landing gear components on a helicopter in the field using a portable magnetic particle testing system



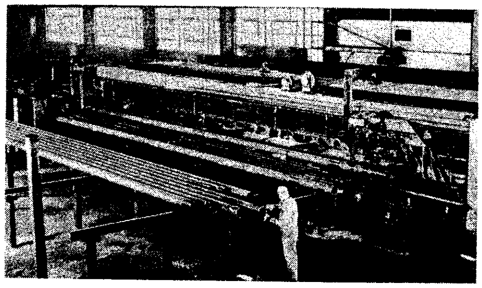
Magnetic Particle Testing in the Steel Industry

By the mid 1950s, many steel mills were considering magnetic particle testing as a means of increasing yield rather than just as a crack finding method. By 1957, the first fluorescent magnetic particle testing system was installed for the production testing of tube rounds (material that was subsequently pierced and rolled into oil well casing, pipe and tubing).

The installation of this system was significant because it demonstrated that high quality steel product could be obtained by spot conditioning of the semifinished product,

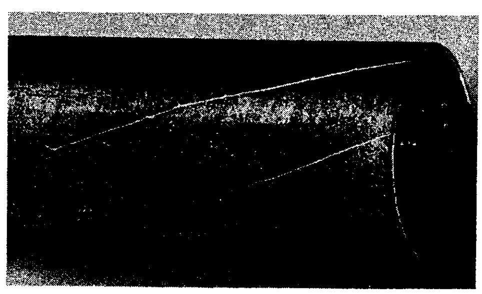
FIGURE 19. Automatic system for magnetic particle testing of seamless tubing: (a) loading side; (b) inspection station; and (c) example of fluorescent particle indication of spiral seams

(a)



(b)

(c)



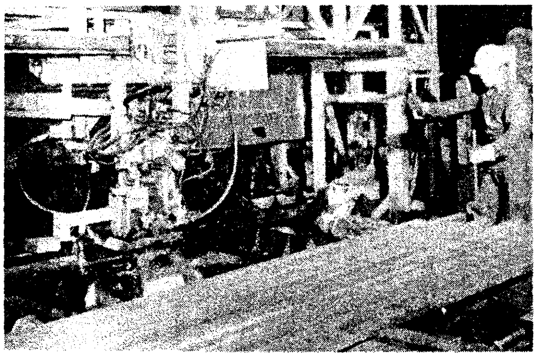
using magnetic particle testing to disclose detrimental seams. The method proved far superior to unaided visual testing, pickling and visual inspection, or skinning of the entire surface (in spite of its great waste, skinning was widely used at that time, especially for high quality steels). In 1958, another fluorescent magnetic particle system was installed for production testing of wire rod billets from 50 mm (2 in.) to 64 mm (2.5 in.) square and nominally 9 m (30 ft) long.

The success of these first two installations had a dramatic effect on the magnetic particle industry. Over the next decade, thirty more major systems were installed in the United States, Canada, Sweden, Great Britain, Italy and Australia. All of these systems incorporated design considerations not encountered before. The size and weight of the product, the effect of loose scale on the equipment, and the ambient temperature extremes in steel mills required the development of unique testing hardware.

Figure 19 shows the 100 percent production testing of seamless tubes ranging from 100 to 250 mm (4 to 10 in.) in diameter and up to 12 m (40 ft) in length. This automatic unit magnetized the tube by passing direct current through it while fluorescent magnetic particles in a water suspension were applied. Inspection under ultraviolet light revealed surface seams, tears and other damaging discontinuities. This was a finished test, coming at the end of the production process but before end trimming, threading or cutting into shorter lengths.

Figure 20 shows the ultrasound portion of a combination system for handling billets up to 100 mm (4 in.) square and 12 m (40 ft) long at rates of three per minute. Billets with discontinuities were segregated and diverted for proper conditioning. The system used ultrasound for detecting subsurface discontinuities and magnetic particle testing for surface discontinuities.

FIGURE 20. A combination ultrasonic and magnetic particle system for testing billets in the rolling mill



Magnetic Particle Testing in the Automotive Industry

During the 1950s, the automotive industry began to realize the potential of nondestructive testing. At that time, almost all steel foundries used prod testing on their castings

FIGURE 21. Mobile magnetic particle testing unit using prods; system employed half-wave current on a 3,400 kg (7,500 lb) steel casting (early 1950s)

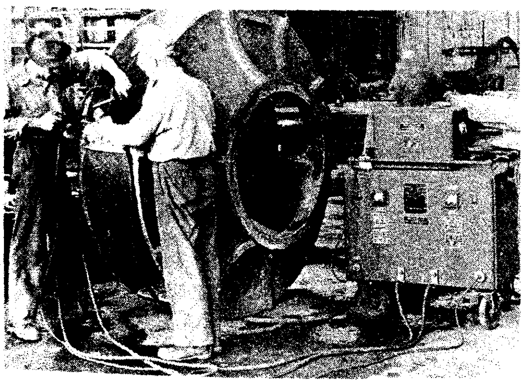


FIGURE 22. Production line yoke inspection of gray iron castings

(Fig. 21). Gray iron foundries discovered the handheld magnetic yoke for detection of handling cracks in materials. Such tests were often included on the production line (Fig. 22).

Automotive overhaul locations for trucks, buses and fleets made use of the wet horizontal system, often with a mobile unit as a power pack (Fig. 23). The grinding and heat treating departments of manufacturing plants followed suit, using small wet horizontal units for in-process testing (Fig. 24).

In automotive manufacture, parts considered critical and subject to high loading were referred to as *safety items* and

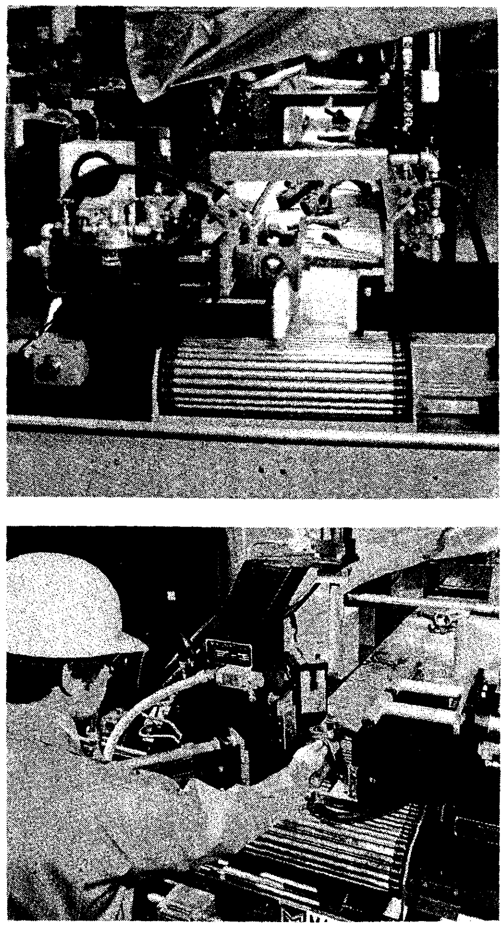
FIGURE 23. Wet horizontal and mobile magnetic particle unit in an automotive overhaul shop

FIGURE 24. Small wet magnetic particle unit for in-process testing after grinding or heat treating

FIGURE 25. Automated magnetic particle system for automotive safety parts

(a)

(b)



subjected to 100 percent magnetic particle testing. Ford Motor Company began 100 percent testing of steering knuckles and arms as early as 1948 and other auto producers were to follow suit in the coming decade (Fig. 25).

Magnetic Particle Testing for Forgings and Castings

During this period, malleable iron and steel foundries were dedicated to capturing business held exclusively by forge shops. Forgings were less prone to contain discontinuities and when they did they were less likely to fail. However, castings were much less costly and magnetic particle testing could be added to the production sequence with considerable savings still remaining. Foundries began offering guaranteed quality and were able to do so by checking the pilot runs 100 percent. They seldom had to buy back any castings.

Large castings and forgings, too large for processing on standard wet horizontal machines, were magnetized using prods and mobile power packs. Unfortunately, the procedure was tedious because large surface areas had to be painstakingly tested, a time consuming project when discontinuities in both directions were possible. Retesting after grinding sometimes revealed discontinuities missed during the initial test. In 1956, the first high amperage power pack was introduced, providing up to 8 kA of magnetizing current. This unit, installed at American Steel Foundry, was the first use of the overall magnetizing method, where the entire large casting was magnetized in one operation.

A short time later, Birdsboro Corporation began using an even larger power pack. It not only had a high output but was one of the first multidirectional magnetizing designs, one that could produce magnetic fields in a casting in more than one direction during the same operation. The system reduced testing time but still ensured that all critical surface areas were being checked. Figure 26 shows one of these units in operation.

For testing objects easily handled on a wet testing table, a fixtured machine was used in conjunction with the large power pack (Fig. 27). A special combination system was used when the test objects were very small and high production was required, as in jet engine compressor blades (Fig. 28). The type of magnetizing current provided on multidirectional units was direct current, alternating current, half-wave or a combination. The selection was made to suit the application.

FIGURE 26. High amperage direct current power pack for overall multidirectional magnetization of steel castings

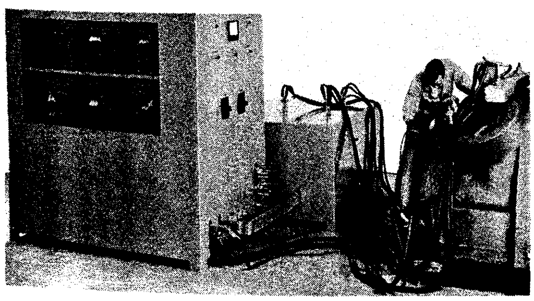


FIGURE 27. Multidirectional magnetizing of 540 kg (1,200 lb) steel missile forging

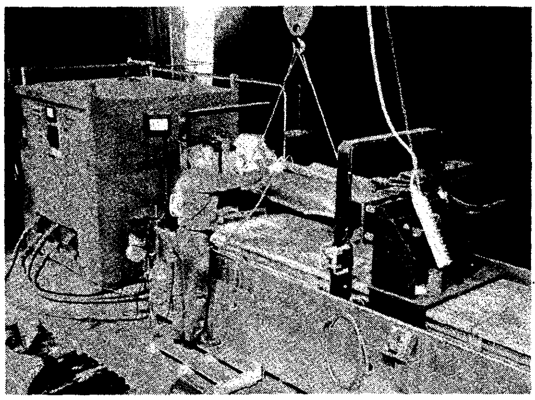
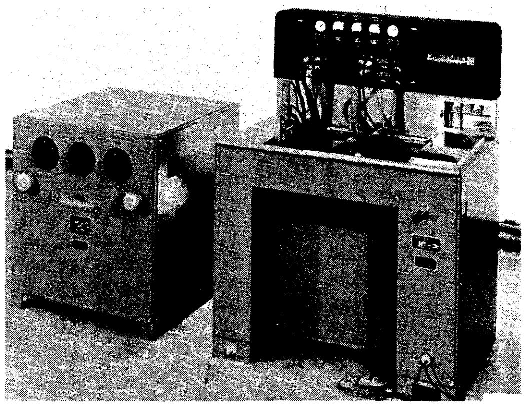


FIGURE 28. Multidirectional magnetizing system for jet engine blades



Preventive Maintenance Uses of Magnetic Particle Testing

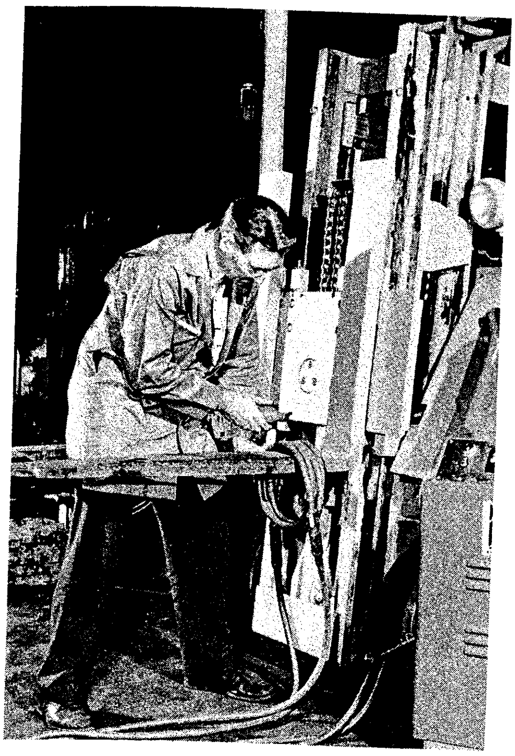
During the 1950s, magnetic particle testing equipment purchased for production was used more and more for preventive maintenance. Crane hooks, chain, forks on lift trucks, repair welds, flywheels, shafts, gears and hanger bolts gradually became part of planned preventive maintenance programs (Fig. 29). For explosion-proof locations, the permanent magnet yoke was used (Fig. 30) to prevent shutdowns.

In this period, shipyards began using the test on tailshafts, propellers, rudders and stern posts. In the oil fields, portable magnetic particle power packs were used on drill pipe, casing, tubing, drill collars, sucker rods and girth welds.

Structural weld testing with magnetic particle received its first impetus in California where the State Department of Education began to use welded, single story school buildings as a safeguard against earthquake damage (Fig. 31a). The practice of all welded fabrication spread slowly but has become a standard practice today. The year 1957 witnessed the first magnetic particle testing specification for welded bridges used by the California State Highway Department. This specification was subsequently adopted by many other technical societies and government agencies. Figure 31b shows the test of another critical weld: the base of a television mast on a building in downtown Chicago.

In 1952, Taber de Forest, the son of Alfred de Forest, developed a testing method using a rubber sheet or balloon inserted inside a pipe. When held in intimate contact with the test surface during magnetization, it retained the leakage field from the test piece. The sheet was filled with permanently magnetizable particles and the induced leakage field could be located on the sheet by means of magnetic particles. This was especially useful for inspecting the inside of pipe or other cavities where indications could not be directly observed.

FIGURE 29. Magnetic particle testing of a fork lift



Automated Visible Particle Scanning and Induced Current Magnetic Particle Tests

The first experimental scanner for detecting and recording magnetic particle indications was installed during the 1950s on a magnetic particle testing machine for handling large diameter resistance welded steel pipe (Fig. 32). The scanner saw black particles on a white background. It made use of a rotating mirror, a small elongated aperture and a

FIGURE 30. Permanent magnet yoke used in an explosion-proof room

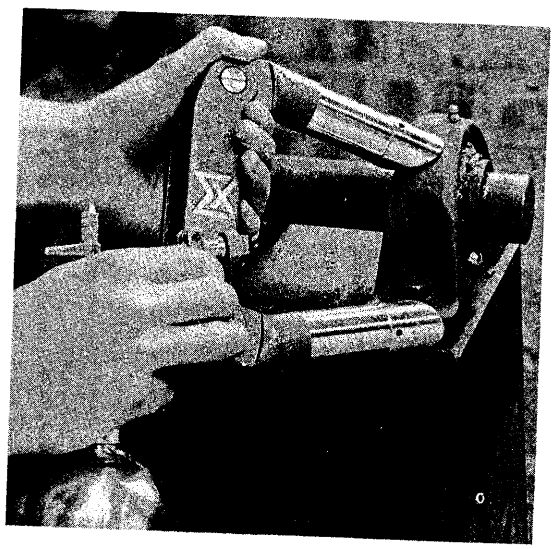


FIGURE 31. Examples of magnetic particle methods on steel structures: (a) testing welds of an I-beam in a single story welded structure; and (b) inspecting a weld at the base of a 85 m (285 ft) television tower

(a)

(b)

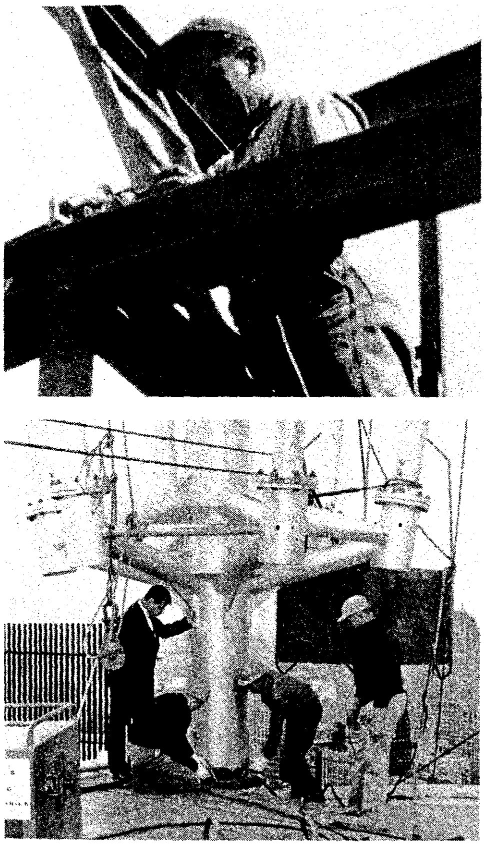


FIGURE 32. Dry powder magnetic particle testing of resistance welded pipe using a scanner for detecting and recording indications

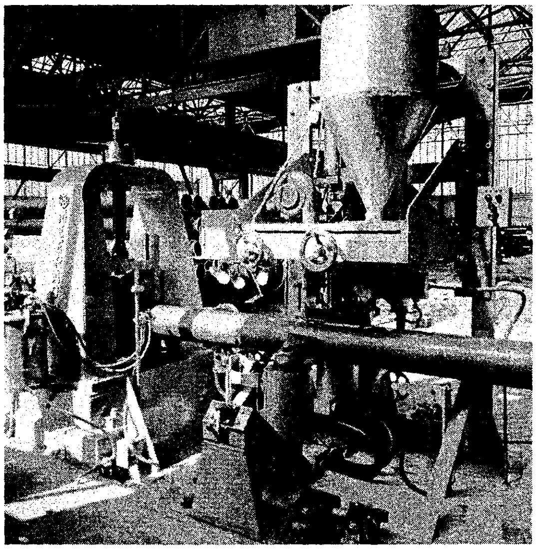
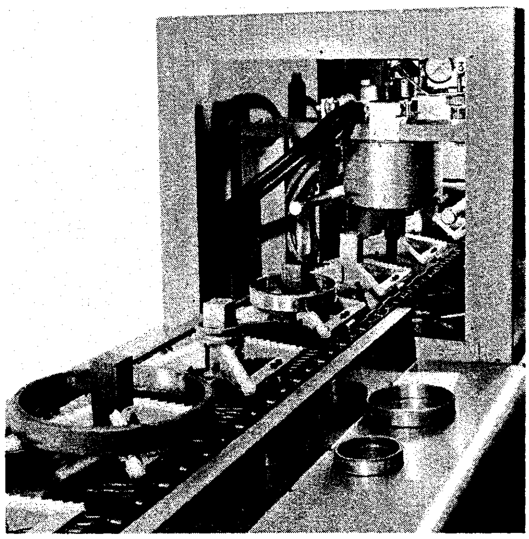


FIGURE 33. Noncontact magnetic particle system using the induced current method for testing of bearing races



photomultiplier tube. The refinement of fluorescent particles and a rotating prism with an ultraviolet light source considerably increased the system's sensitivity.

One of the first magnetic particle systems using induced current is shown in Fig. 33. The induced current method locates circumferential discontinuities without making contact to the bearing race. The unit provides magnetization by central conductor, inspection, magnetization by induced current, inspection and demagnetization. Another production unit using induced flux was later designed for the testing of hardened steel bearing balls, also eliminating the need for electrical contact with the test object.

The Nondestructive Testing Handbook

The Society for Nondestructive Testing (SNT) became very active during the 1950s. One of their important contributions at that time was the publication of the first edition *Nondestructive Testing Handbook*.

Volume 2 of that edition includes chapters on electrified particle and magnetic particle tests, test indications, principles and equipment. Work on the *Nondestructive Testing Handbook* began in 1950 and was continued by Robert McMaster until its publication in 1959. Carl Betz, Taber de Forest, Robert Eichen, Franklin Catlin, G.B. Baumeister and Kenneth Schroeder were among the magnetic particle authorities who contributed to the *Nondestructive Testing Handbook*'s first edition.

The 1960s: Industry Challenges

Advances in Test System Portability

Before developments in the 1960s, field testing was difficult with magnetic particle techniques. A typical testing unit measured 0.9 × 0.9 × 1 m (36 × 36 × 40 in.) and weighed 180 to 270 kg (400 to 600 lbs). Magnetizing current control was accomplished by adding long output cables. Often, two 27 m (90 ft) lengths of 4/0 cable and two 4.5 m (15 ft) lengths of 2/0 cable were needed to reduce the current to the level required for prod inspection at 150 mm (6 in.) spacing. A large crane was used to move the test system to the site and the inspector usually had to drag cables weighing 90 kg (200 lbs) through the structure.

In 1961, work was begun at the Mare Island Naval Shipyard to design and build a portable magnetic particle testing system with a full-time use duty cycle. In 1965, a unit weighing 19 kg (42 lbs) was approved for use by the US Navy. Over the following decade, improvements were made to the basic design, mostly in the area of current control. Such portable systems (see Fig. 34) helped lower the cost of testing and dramatically improved accessibility for magnetic particle testing in shipyards, high rise buildings, off-shore structures, bridges and pipelines.

Portability combined with the introduction of articulated legs for magnetizing yokes were the two developments that have had the greatest impact on contemporary magnetic particle system designs.

Advances in Fluorescent Indication Detection

Even though fluorescent magnetic particles were easy to see and provided for more rapid testing, the human eye was still necessary for most magnetic particle testing. Each test object had to be looked at and an evaluation had to be made. In the 1960s, work began in earnest to automate many forms of nondestructive testing. Laser beam technology soon became the focus of research for automating magnetic particle tests.

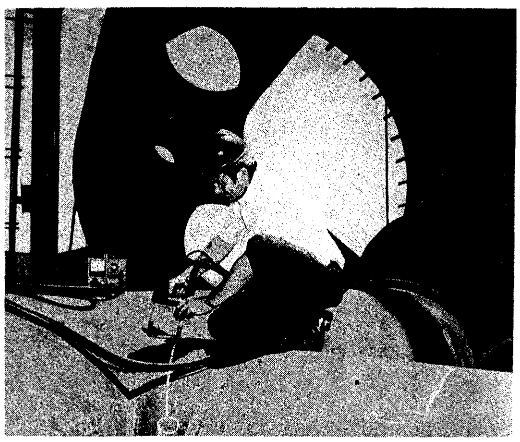
What was sought was a means of detecting and evaluating fluorescent magnetic particle indications more rapidly, more accurately and at lower cost. The first practical application came in the 1970s when a fully automatic magnetic particle scan unit was designed, built and successfully installed in a bearing plant (see Figs. 35 and 36). Bearings were magnetized and a bath applied. Bearings were then transferred to a turntable and rotated under a vibrating laser beam. Indications were seen by a phototube and an electric signal was produced to divert defective bearings into a reject bin. Automatic testing of torsion bars was another early application using a vibrating laser beam (Fig. 36c).

Advances in Measuring Magnetic Field Strength

Work on developing a reliable magnetic field gage began early in the history of magnetic particle tests. In 1938, a prototype of the Berthold magnetic field gage was developed at the Reichs Roentgenstelle in Germany. In the early 1940s, Lamellar test gages and wedge gages were used in Germany for checking test sensitivity and penetration depth.[8]

In the United States through the 1950s, there was no commonly used technique that permitted the exact measurement of field strength at a given point within a piece of magnetized iron or steel. Inspectors depended on rules of thumb and experience to determine what amount of magnetizing force should be used and in what direction it should be applied.

FIGURE 34. Portable magnetic particle testing system in use on an offshore oil drilling platform



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During the 1960s, devices were developed and manufactured with the intended purpose of ensuring that the field distribution was of the proper magnitude and direction. In effect, these were adhesive artificial discontinuities. They attempted to shunt some of the field out through the surface of the object into an external test piece and then back into the surface of the part again. One of these devices was the Berthhold field gage. Another was called a *magnetization indicator* or *quantitative shim*.

These indicators were made of low carbon rolled steel. Into each had been machined an artificial discontinuity in the form of a straight line. In use, the indicators were placed on the test object so that the artificial discontinuity lay in the direction of cracks that were expected to occur. The test object was then magnetized and magnetic particles applied in the usual manner. If the artificial discontinuity in the indicator was shown, then magnetization was considered acceptable.

The proper level of sensitivity for detecting various sizes of discontinuities was achieved by varying the artificial discontinuity's width and its depth below the surface. When used properly, these were a valuable testing component. They did, however, more truly indicate the magnetic field strength H through the indicator rather than the flux density B through the surface layers of the magnetized test object.

Other versions of the original flux shunting devices included a reusable model. It could be handheld by the operator while magnetizing. Another semireusable device was developed in Japan in 1962. It featured more precise artificial discontinuities and provided the discontinuities in a circular pattern that could be used to verify magnetizing force in more than one direction.

Development of Test System Components

In the early 1960s, some preventive maintenance and safety testing required more sensitivity than dry powder

FIGURE 35. Diagram of a laser scanning automatic discontinuity detection system based on the fluorescent magnetic particle technique

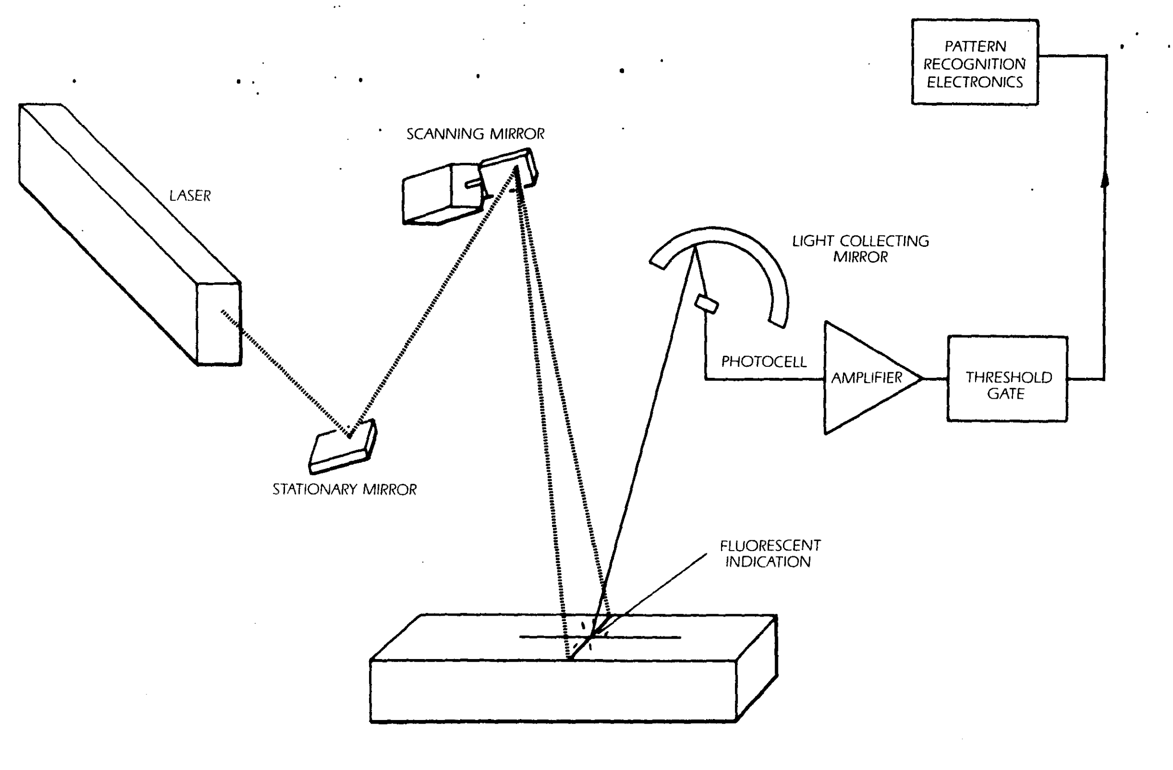
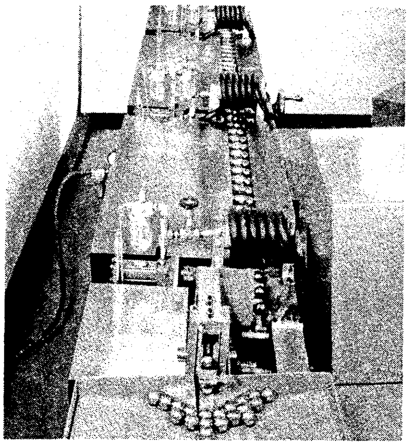
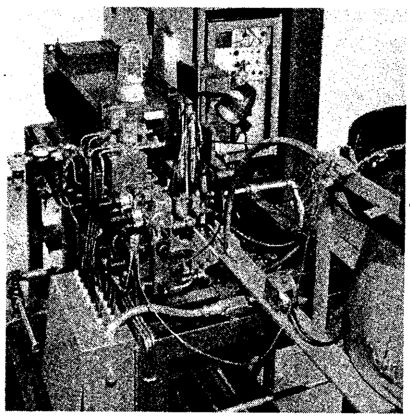


FIGURE 36. Magnetic particle systems employing laser technology: (a) system modified for use of lasers in tests of bearing rollers; (b) magnetic particle laser unit for rollers; and (c) laser scan testing of torsion bars

(a)



(b)



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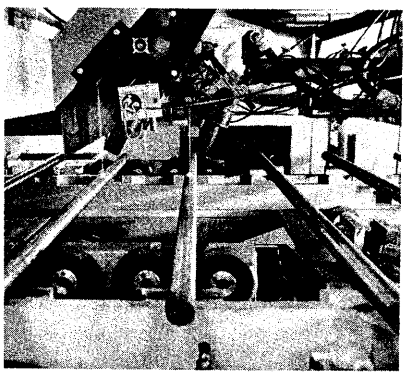


could provide. Pressurized cans of fluorescent magnetic particle suspension were introduced in a kit that also included an ultraviolet light source. The setup shown in Fig. 37 continued to be widely used into the 1980s by meeting the safety testing requirement of a six month check on all forks on lift trucks and crane hooks, a standard practice in many metalworking plants.

In 1962, copper oxide rectifiers, long the standard in direct current wet horizontal units, were replaced by rectifier stacks using more efficient silicon diodes.

The demands of the flourishing aerospace industry also encouraged advances in magnetic particle systems. Missile motor case components required special magnetizing techniques and fixturing in order to avoid arc burns from electrical contact and to provide sufficient magnetizing force in all directions. The Polaris, Titan III and Minute Man missiles typically used such motor cases. Some motor cases were as large as 3 m (10 ft) in diameter and 3.3 m (11 ft) or more in length, with metal thicknesses less than 6 mm (0.25 in.).

Figure 38 illustrates a yoke device that provided an induced longitudinal field used in conjunction with a special

FIGURE 37. Portable magnetic particle testing with aerosol and dry powder for preventive maintenance and safety inspection

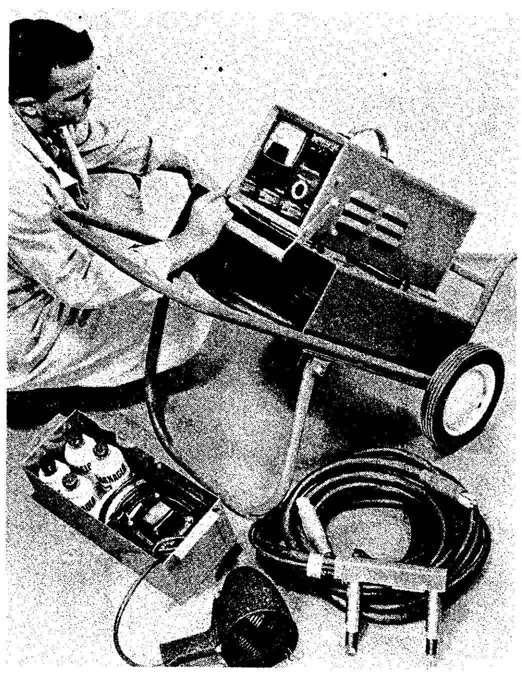
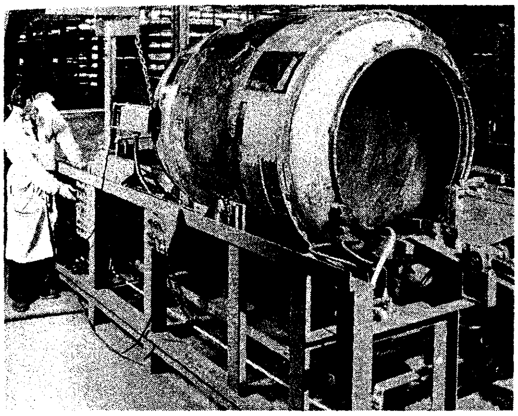


FIGURE 38. Induced magnetic field hardware: (a) special direct current induced field fixture using a yoke to ensure detection of all circumferential discontinuities; and (b) diagram of an induced field fixture

(a)



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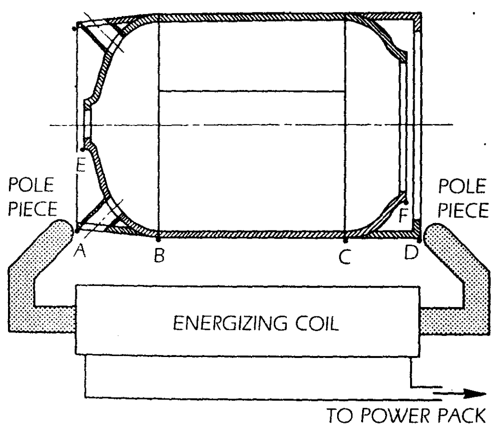
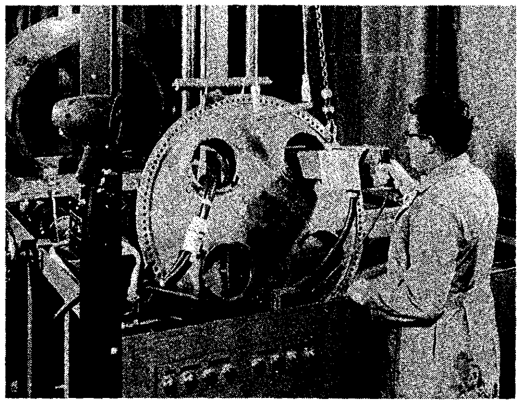


FIGURE 39. Special induced alternating current fixture for locating circumferential discontinuities around the nozzle area of a solid fuel motor case



central conductor arrangement (not shown) for testing thin walled motor cases with a circumferential field. Figure 39 shows a special fixture for inducing alternating current in the cases' nozzle area without making electrical contact with the test object. This technique was used for detecting critical circumferential discontinuities in the welded area.

In other industries, the method of magnetization called *short shot magnetizing* was being refined for the testing of small ball bearings and roller bearings. Introduced in 1966, the method's advantage was that it allowed through-current without over-heating or burning the finished surface.

Expanding Applications for Magnetic Particle Testing

In 1968, a lock was built in Sault Ste. Marie, Michigan. Its gates were 18 m (60 ft) high, 19 m (63 ft) wide and up to 140 mm (5.4 in.) thick. Both magnetic particle and ultrasonic testing were specified by the Corps of Engineers to detect cracks and lack of penetration. This is one of many applications now dependent on successful magnetic particle tests.

Many skyscrapers also specified magnetic particle and ultrasonic testing to verify weld integrity. The John Hancock Building and the Sears Tower in Chicago are typical. The Hancock Building's 100 stories total 332 m (1,107 ft) in height and the Sears Tower is 435 m (1,450 ft) tall. The Sears Tower required 775,000 magnetic particle tests, including recordkeeping and reporting. All was completed in compliance with the American Institute of Steel Construction, the American Welding Society and the American Society for Nondestructive Testing. Figure 40 represents a typical magnetic particle test of welds on a high rise tower.

Production applications in the 1960s included quality steel railroad wheels shown in Fig. 41a (the unit handled

FIGURE 40. Magnetic particle testing of welds on a thirty-two story building in Detroit, Michigan

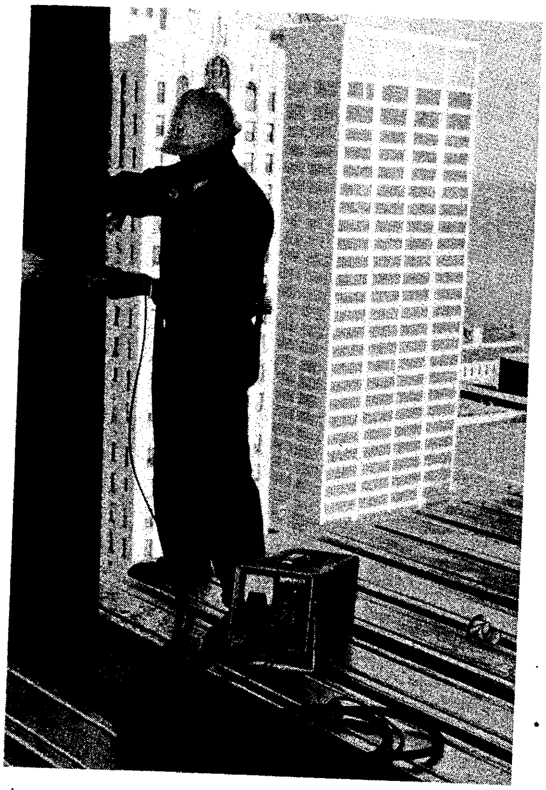
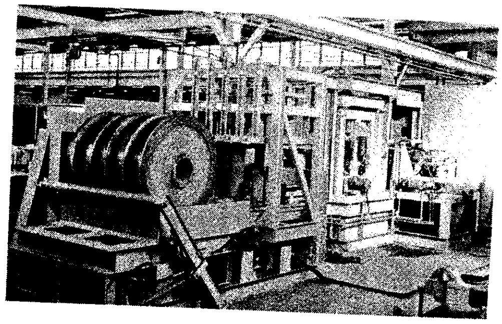


FIGURE 41. Production line applications of magnetic particle testing: (a) combination multidirectional magnetic particle and ultrasonic testing of railroad wheels; and (b) residual magnetic particle testing of nuts at 80 per minute

(a)



(b)

fifty-five to sixty-five wheels per hour). Inspection of nuts at 5,000 per hour was performed using the magnetic particle testing residual method (Fig. 41b). Many versions of semi-automatic magnetic particle systems were made for the testing of large crankshafts (Fig. 42). Multidirectional magnetizing of complex steel castings was introduced (Fig. 43). The conventional approach was used for very large gas turbine shafts and spindles used by utilities (Fig. 44).

During the 1960s, production billet testing systems were produced at the rate of two and sometimes three per year, handling larger and larger products at rates of two or more pieces per minute. Rotation of billets for the inspectors was provided by a Ferris wheel (Fig. 45) or by the chain sling turner (Fig. 46). Observed indications were marked by the inspector (Fig. 47) for conditioning. Before the end of the decade, the automatic indication detector was introduced (Fig. 48).

Advances in the Testing Profession

The first magnetic particle inspectors at nuclear and fossil fuel plants were a different breed of technician, working on an unprecedented scale. The individuals were expert in many nondestructive testing methods and they bore serious responsibilities. The 2.2 million kilowatt plant built for the Indiana and Michigan Electric Company near St. Joseph, Michigan can serve as an example of their efforts in the 1960s.

The plant's construction began in 1969 and the unit went on-line in 1976. Construction required on-site, around the clock magnetic particle testing with crews operating out of a

FIGURE 42. Semiautomatic magnetic particle testing of large crankshafts for transverse and longitudinal discontinuities

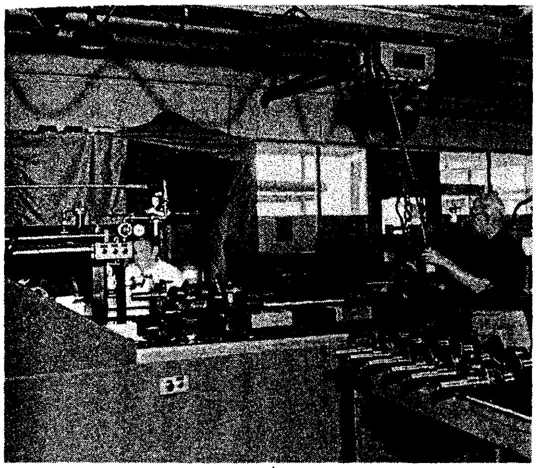
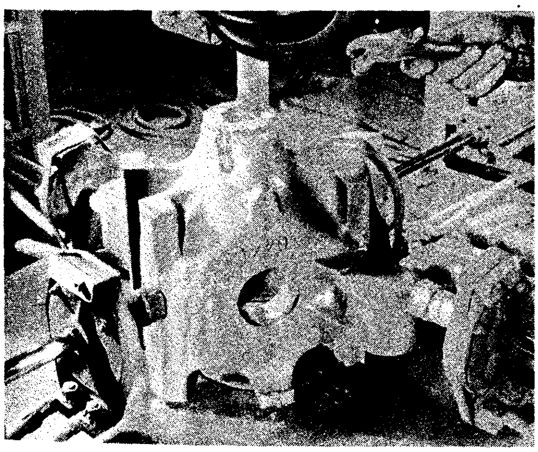


FIGURE 43. Three-way multidirectional magnetizing of complex steel castings in one operation



permanent testing laboratory. The twenty-four technicians on site were all qualified and certified in magnetic particle, penetrant, ultrasonic and radiographic testing.

Materials were monitored at manufacture and during incorporation into the system at the job site. Nondestructive

FIGURE 44. Magnetic particle testing system for very large gas turbine shafts and spindles

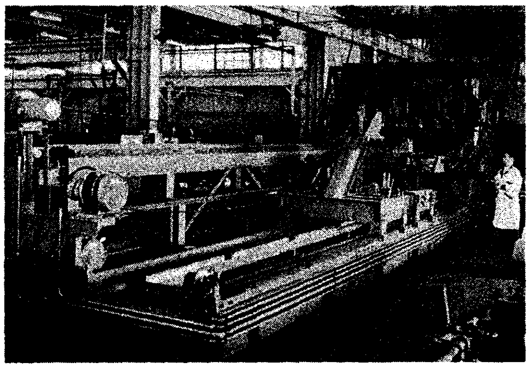


FIGURE 45. Magnetic particle billet testing using the Ferris wheel

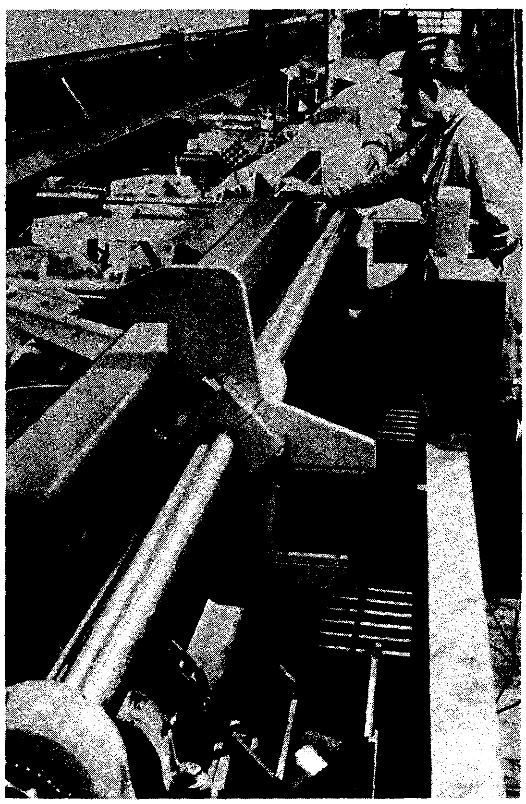


FIGURE 46. Magnetic particle billet testing using a chain sling turner

FIGURE 47. Fluorescent magnetic particle indications of seams at various depths in a billet

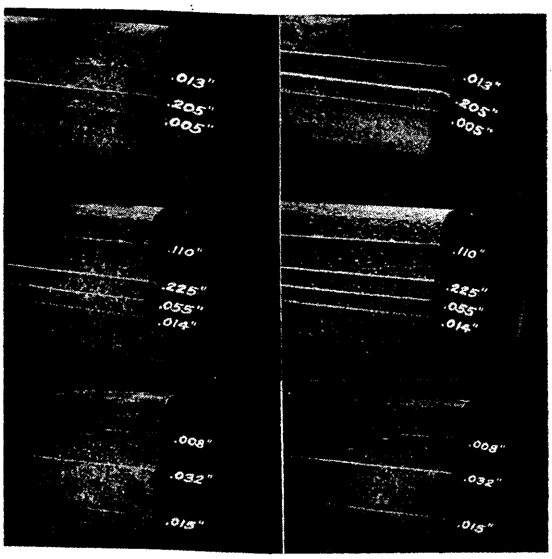
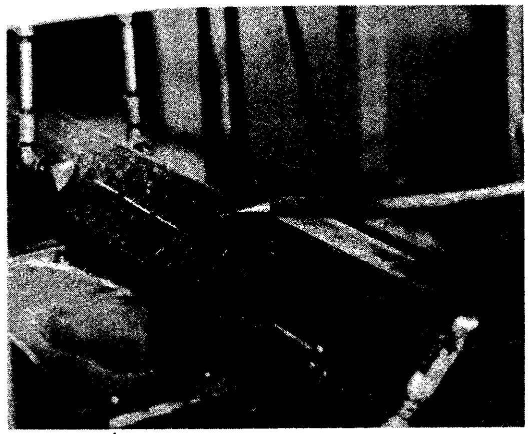


FIGURE 48. Automatic discontinuity indication detector for magnetic particle tests



testing was used to verify the integrity of valves, fittings, pipe joints, bolts, all types of welds and, most important, the final structure. The safety of people in and around the plant, and the economy of the unit's operation, were both directly linked to the performance of the nondestructive testing personnel on-site during construction.

The 1970s: Advanced Organization and Systems

During the 1970s, industries began recognizing the value of Recommended Practice SNT-TC-1A introduced by ASNT. The document began to be referenced in purchasing contracts and the military began including its main features in their own specifications. The era of Level I, II and III magnetic particle inspectors spread across the country; responsibility for certification of operators was in the hands of the firm making the product.

Advances in Systems and Components

In 1974, a magnetic particle slurry for discontinuity detection was introduced. Unlike dry powder or other magnetic particle suspensions, the slurry was most effective outside during rain and wind. It also allowed magnetic particle testing under water. The material was first used on pipeline welds in the field, on overhead structural welds and for underwater applications.

Later in the decade, special daylight fluorescent particles were introduced. They were designed to be dispensed under water from plastic containers and were used with special electromagnetic yokes for offshore testing.

In 1978, the first programmable component was introduced, replacing relay logic for controlling the sequencing of an automatic magnetic particle system. The unit was designed for testing of 155 mm (6 in.) artillery shells. In the same year, an in-line system was developed, using reversing direct current for the demagnetization of long tubular product traveling at speeds of 20 to 30 m (80 to 100 ft) per minute.

An electromagnetic portable magnetization indicator was introduced to verify reliable magnetization levels on test objects such as aircraft landing gears, complex castings and large welded fabrications. Unlike the earlier flux shunting devices that responded to a tangential magnetizing force through the indicator, this instrument responded to changes in permeability detected by a cross coil probe near the surface of the test object. Indicated magnetization levels correlated very well with results on parts containing natural discontinuities.

In 1979, a newly developed process allowed fluorescent magnetic particles to be manufactured directly to the desired narrow size range. Grinding of particles was no longer necessary. Inspection sensitivity could be controlled by both the type of particles and the type and strength of the applied magnetic field.

The 1980s: Industry Improvements

Early in 1980 came the introduction of fluorescent magnetic particles that were three to five times brighter than earlier products. The enhanced brightness made indications difficult to miss in dark testing booths. Out of the same research, daylight fluorescent particles were developed. They could be used wet or dry and were visible in daylight, under blue-white mercury arc illumination, under white fluorescent lights, and also under bright white incandescent light. They were not excited by yellow sodium vapor illumination.

As early as 1973, silicon thyristors were replacing silicon diode rectifier stacks in mobile magnetic particle testing units. By 1975, wet horizontal units were using silicon thyristors with solid state power packs. The use of solid state components allowed infinitely variable, fine current control between zero and maximum, replacing the tap switch's limited number of settings.

By 1981, silicon diode rectifier stacks in commercial direct current wet horizontal units were almost completely replaced by silicon thyristors. This change allowed controlling the magnitude of magnetizing current while at the same time converting alternating current to direct current. It also provided the additional advantage of eliminating the need to reverse the polarity of the direct current while demagnetizing.

In the mid 1980s, a wet horizontal magnetic particle system was developed with microprocessor control. The system produced detailed test data and supplied hardcopy for each test object, documenting such information as part number; type of magnetization used (head, coil or multidirectional); type and amount of current; duration of current; concentration of bath at the time of processing; inspector's name; date of testing; and disposition of the part.

Conclusion

Magnetic particle testing has been in use since the 1920s. The simplicity of its use is now understood to depend on electromagnetic phenomena that are defined by complex field theories. Yet the technique is still used as it was in the beginning — to locate discontinuities in ferromagnetic materials. Magnetic particle methods have been adapted to include computerized data collection systems and laser scanning modules — but magnetization, application of particles, interpretation and demagnetization are still the basic steps of the technique. Magnetic particle tests are specified as complementary to more recent techniques (ultrasonic testing, for example). Yet magnetic particle inspection is still the *only* required test for many structural and materials applications.

It is this combination of characteristics — a strong, original technique and an adaptability to contemporary testing requirements — that has given magnetic particle testing its many successful applications.

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SECTION 4

DISCONTINUITIES IN FERROMAGNETIC ALLOYS

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INTRODUCTION

Discontinuities can be defined as changes in the geometry or composition of an object. Such changes inherently affect the physical properties of the object and may in turn have an effect on the object's ability to fulfill its intended service life. Not all discontinuities are defects. The definition of *defect* changes with the type of component, its construction, its materials and the specifications or codes in force. It should be well understood that a harmless discontinuity in one object may be a critical flaw in another kind of object.

Detection of discontinuities is a process that is largely dependent on the discontinuity's physical characteristics — in the case of cracks, a critical parameter is the ratio of surface opening to crack depth. However, crack depth and width are not the only factors affecting detectability; length and orientation to the surface are also important.

In order to better detect and interpret magnetic particle discontinuity indications, it is necessary to know the basic material characteristics of the test object. Furthermore, it is also important to consider how the material is produced, what manufacturing processes are used to form the finished product and what discontinuities are typically initiated by the processing operations.

During the various stages of material processing, certain discontinuities can be expected. Typically, a discontinuity is categorized by the stage of manufacturing or use in which it initiates: inherent, primary processing, secondary processing and service related discontinuities. The text that follows is a description of discontinuities that may originate from the processing operations in each of the four categories. The listing is provided only for educational purposes and may not apply to all magnetic particle test objects.

PART 1
INHERENT DISCONTINUITIES

When ferromagnetic materials are produced, molten metal solidifies into ingot form, producing what is known as inherent discontinuities. Many of these are removed by cropping but a number of them can remain in the ingot. Such discontinuities then can be rolled, forged and sectioned along with the material in its subsequent processing operations.

The following text is a brief description of common inherent discontinuities that may occur in ferromagnetic materials (see Table 1).

Cold Shut

A cold shut is initiated during the metal casting process. It occurs because of imperfect fusion between two streams of metal that have converged. Cold shuts may also be attributed to surging, sluggish molten metal, an interruption in pouring or any factor that prevents fusion where two molten surfaces meet.

This discontinuity produces magnetic particle indications similar to those of cracks or seams with smooth or rounded edges similar to those of Fig. 1.

Pipe

During solidification of molten metal, a progressive reduction in volume occurs. In the case of a casting, there eventually can be insufficient molten metal for completely filling the top of the mold. As a result, a cavity forms, usually in the shape of an inverted cone or cylinder (see Fig. 2).

If this shrinkage cavity is not completely removed before rolling or forging into final shape, it becomes elongated and appears as voids called *pipe* in the finished product. Pipe can also result from extrusion, caused by the oxidized surface of a billet flowing inward toward the center of a bar at the back end. The presence of pipe is usually characterized as a small round cavity located in the center of an end surface.

Hot Tears

At the elevated temperatures associated with solidification, cast materials are susceptible to hot tears. Segregation of low melting point impurities results in localized loss of ductility and strength. Lacking these, the cooling metal can tear and crack in the mold because of restraint from the mold. In addition, uneven cooling in thin sections or corners that adjoin heavier masses of metal can result in higher metal surface stresses that in turn produce hot tears.

Hot tears appear on the surface as a ragged line of variable width and numerous branches. In some instances the cracks are not detectable until after machining because the tearing can be subsurface.

Blowholes and Porosity

Gas porosity or blowholes are rounded cavities (flattened, elongated or spherical) caused by the accumulation of gas bubbles in molten metal as it solidifies. A small percentage of these bubbles rise through the molten metal and escape. However, most are trapped at or near the surface of the ingot when solidification is complete (see Fig. 2). During rolling or forging of the ingot, some of these gas pockets are fused shut.

TABLE 1. Inherent discontinuities in ferromagnetic materials

Discontinuity	Location	Cause
Cold shut	surface or subsurface	the meeting of two streams of liquid metal that do not fuse together
Pipe	subsurface	an absence of molten metal during the final solidification process
Hot tears	surface	restraint from the core or mold during the cooling process
Porosity	surface or subsurface	entrapped gases during solidification of metal
Inclusions	surface or subsurface	contaminants introduced during the casting process
Segregation	surface or subsurface	localized differences in material composition

The remaining pockets may appear as seams in the rolled product. Deep blowholes that are not rolled shut may appear as laminations after becoming elongated in the rolling operation.

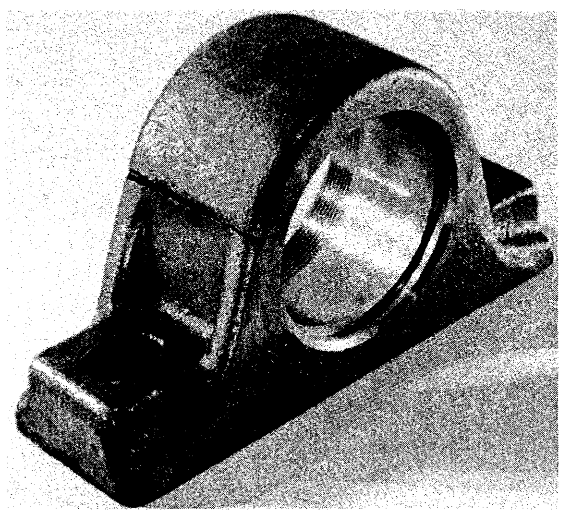
Nonmetallic Inclusions

Inclusions in ferrous alloys are usually oxides, sulfides or silicates introduced in the original ingot. During the melting operation, the use of dirty remelt, crucibles or rods, or poor linings may introduce nonmetallic inclusions into the molten metal. Other contributing factors are poor pouring practice and inadequate gating design that can produce turbulence within the mold.

Nonmetallic inclusions can become stress risers because of their shape, discontinuous nature and incompatibility with the surrounding material. In many applications, it is the presence of these inclusions that lowers the ability of a metal to withstand high impact, static or fatigue stresses. Moreover, the effect of inclusions depends on their size and shape, their resistance to deformation, their orientation relative to applied stress, and the tensile strength of the material. Many inclusions can be of a more complex intermediate composition than their host materials and each grade and type of metal has its own characteristic inclusions.

Typically, inclusions are mechanically worked (from rolling or forming), causing them to deform plastically into elongated shapes and to appear in longitudinal sections as stringers or streaks. In transverse cross sections, the inclusion's shape is more globular or flat (see Figs. 3 through 6).

FIGURE 1. Magnetic particle indication of a cold shut in a casting



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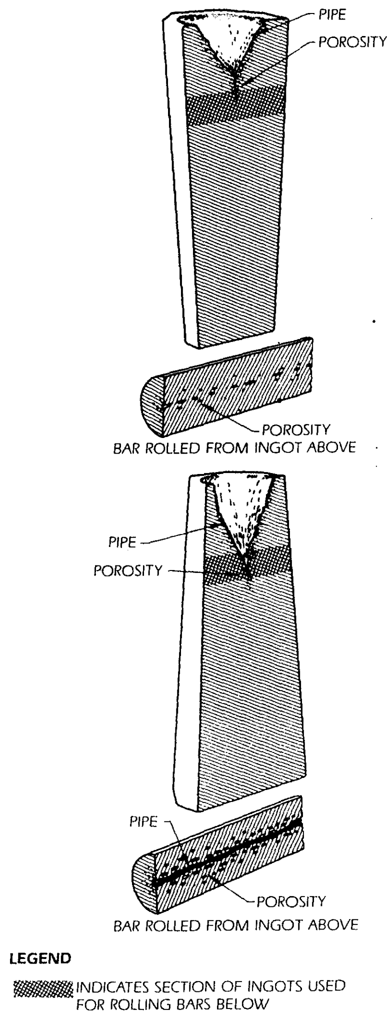
Segregation

Segregation is localized differences in a material's chemical composition. During solidification of molten metal,

FIGURE 2. Longitudinal section of two types of ingots showing typical pipe and porosity



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certain elements may concentrate in limited areas, resulting in an uneven distribution of some of the alloying elements of the steel. Equalization of the compositional differences can be achieved by hot working (forging or rolling). However, segregation is sometimes carried into the wrought product.

When not detected, segregation can affect corrosion resistance, forging and welding characteristics, mechanical properties, fracture toughness and fatigue resistance. Furthermore, quench cracks, hardness variations and other discontinuities are likely to result during heat treating of materials that exhibit segregation of alloying elements.

FIGURE 3. Inclusions present in wrought product were elongated through the rolling process and discovered at a weld upset that joined two rails together; magnetic particle indications shown in the web adjacent to the weld

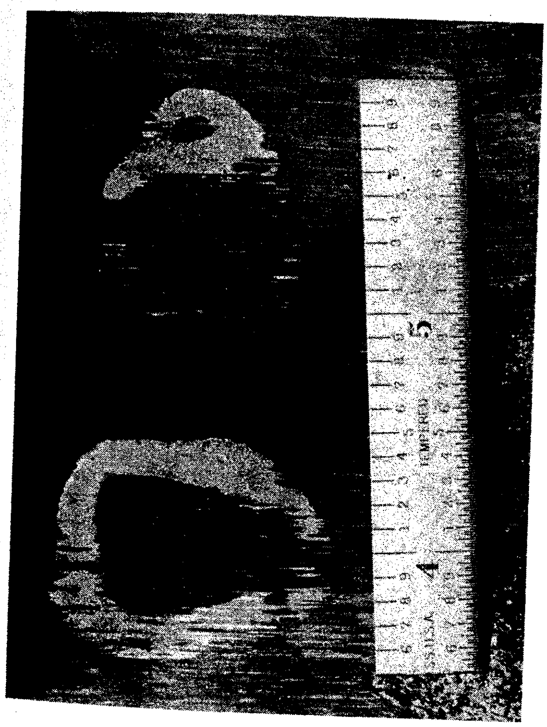


FIGURE 4. Cross section through rail sample, showing magnetic particle indications at center

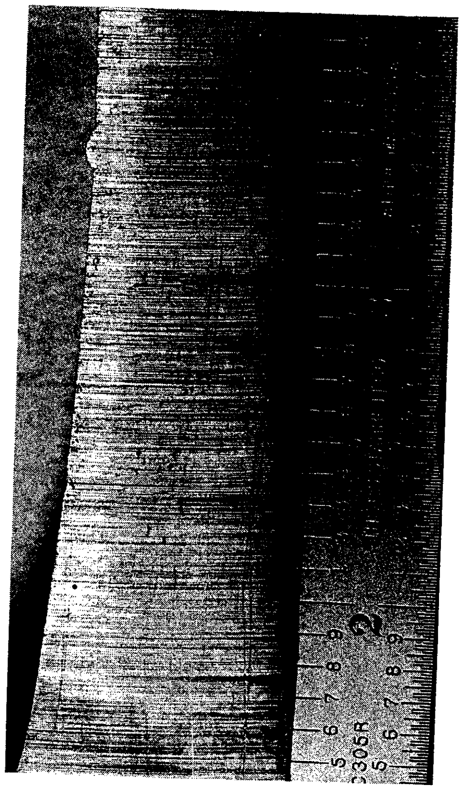


FIGURE 5. Microstructure of transverse (perpendicular to rolling direction) section through rail sample, away from weld

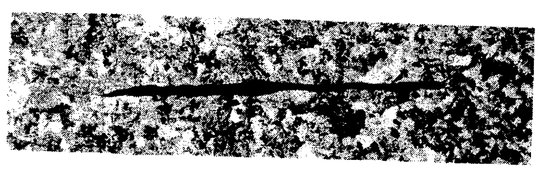
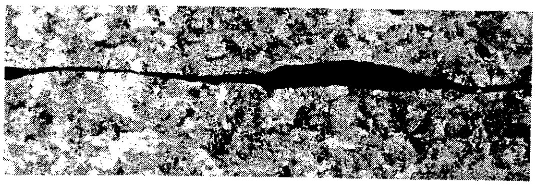


FIGURE 6. Microstructure of longitudinal section through rail sample; inclusion runs the length of the specimen



PART 2
PRIMARY PROCESSING DISCONTINUITIES

Discontinuities that originate during hot or cold forming are said to be primary processing discontinuities. The processing of a wrought product by rolling, forging, casting or drawing may introduce specific discontinuities into the product and inherent discontinuities that were at one time undetectable or insignificant may propagate and become detrimental.

The following is a brief description of common primary processing discontinuities that may occur in ferromagnetic materials (see Table 2).

Seams

As an ingot is processed, inherent surface discontinuities such as gas pockets, blowholes and cracks are rolled and drawn longitudinally. When these discontinuities exist, an underfill of material occurs during the rolling operation. Seams may also be initiated in the semifinishing and finishing mills because of faulty, poorly lubricated or oversized dies.

As a result of multiple passes during rolling operations, underfilled areas are rolled together to form a seam (see Fig. 7). The surfaces are typically oxidized and may be intermittently welded together to form very tight, usually straight cracks that vary in depth from the surface (see Figs. 8 and 9).

Laminations

Laminations are separations that are typically aligned parallel to the worked surface of a material. They may be the result of blowholes, internal fissures, pipe, inclusions, seams or segregations that are elongated and flattened during the rolling process. They can be surface or subsurface, are generally flat and extremely thin (see Fig. 10).

Laminations can be detected by magnetic particle testing at an end or at a transverse cross section taken through the rolled plate.

Stringers

Stringers are predominantly found in bar stock. They originate by the flattening and lengthening of nonmetallic inclusions during the rolling operation.

FIGURE 7. Formation of a seam: (a) underfill results when there is not enough metal to fill the rolls; and (b) a seam in the finished bar occurs when underfill is squeezed tight on a subsequent rolling pass

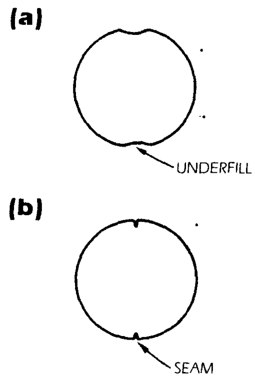


TABLE 2. Primary processing discontinuities in ferromagnetic materials

Discontinuity	Location	Cause
Seams	surface	elongation of unfused surface discontinuities in rolled products
Laminations	subsurface	elongation and compression of inherent discontinuities during the rolling process
Stringers	subsurface	elongation and compression of inherent discontinuities during the rolling process
Cupping	subsurface	internal stresses during cold drawing
Cooling cracks	surface	uneven cooling of cold drawn products
Laps	surface	material folded over and compressed
Bursts	surface or subsurface	forming processes at excessive temperatures
Hydrogen flakes	subsurface	an abundance of hydrogen during the forming process

FIGURE 8. Wet fluorescent magnetic particle indication of a seam in a steel billet

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FIGURE 9. Photograph showing seams in bars, from left: as-received condition, sand blasted surface, pickled surface and wet fluorescent magnetic particle indication

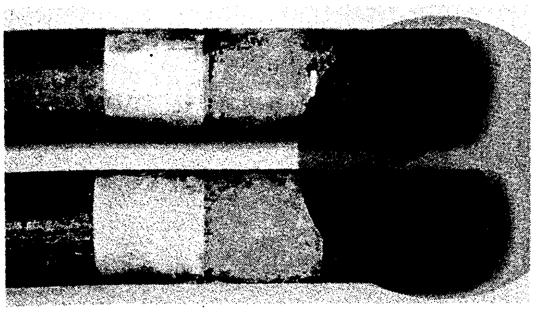

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FIGURE 10. Metallographic cross section showing laminations found in a resistance welded tube made from SA-178 material

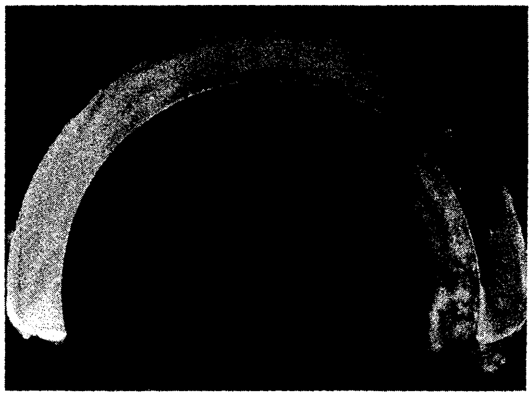
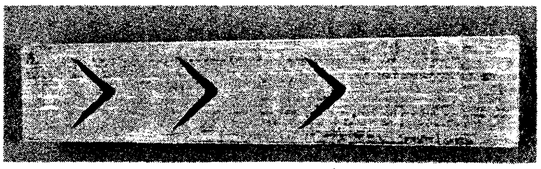


FIGURE 11. Cross section showing severe cupping in a 35 mm (1.4 in.) bar



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Stringers are typically subsurface, semicontinuous straight lines parallel to the length of the bar stock.

Cupping

Typically occurring during the extrusion operation or as a result of severe cold drawing, cupping is a series of internal ruptures (chevrons) in bar or wire as shown in Fig. 11. Because the interior of a metal cannot flow as rapidly as the surface, internal stresses build, causing transverse subsurface cupping cracks.

Cooling Cracks

After the rolling operation of cold drawn bars, cooling cracks may develop due to internal stresses caused by uneven cooling of the material. Such cracks are typically longitudinal and usually vary in depth and length. Although often confused with seams, cooling cracks do not exhibit surface oxidation.

Forged and Rolled Laps

Forging laps are the result of metal being folded over, forming an area that is squeezed tight but not welded together (see Figs. 12 and 13). They are caused by faulty dies, oversized blanks or improper handling of the metal in

FIGURE 12. Wet fluorescent magnetic particle indication of a forging lap in a connecting rod

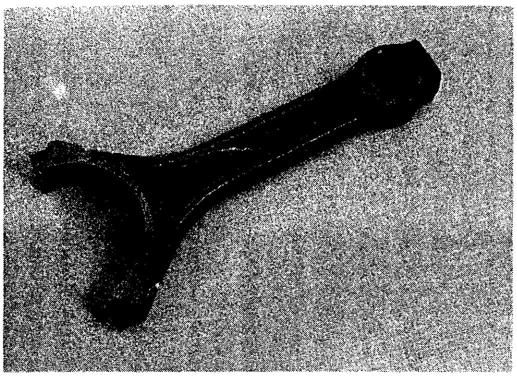

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FIGURE 13. Micrograph of a forging lap with included oxide in the lap

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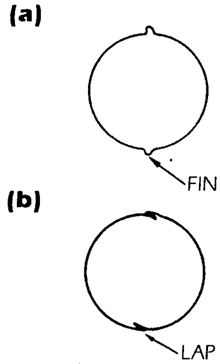
the die. Forging laps are usually open to the surface and are either parallel or at a small angle to the surface.

Rolled laps are a condition similar to a seam. Excessive material is squeezed out during a rolling pass, causing a sharp overfill or fin. When rotated for the following pass, the material is rolled back into the bar. Because of its heavily oxidized surface, the overfill cannot be welded together by the rolling operation. Rolling laps are usually straight or slightly curved from the longitudinal axis and are either parallel or at a small angle to the object surface (see Fig. 14).

FIGURE 14. Formation of a lap: (a) an overfill produces excess metal squeezed out of the rolls causing a fin; (b) a lap results when the projection is folded over and forced back into the bar's surface during a subsequent pass



Internal and External Bursts

Internal bursts are found in bars and forgings and result from excessive hot working temperatures. Discontinuities that exist prior to forming (porosity, pipe, inclusions or segregation) are pulled apart because of the high tensile stresses developed during the forming operation.

Rolled and forged metals may also develop internal bursts when there is insufficient equipment capacity for working the metal throughout its cross section (see Fig. 15).

External bursts typically occur when the forming section is too severe or where sections are thin. External bursts may also be formed when the capabilities of the equipment are not great enough: the outer layers of the metal are deformed more than the internal metal and the resulting stress causes an external burst. Forming during improper temperatures may also cause external bursts.

Hydrogen Flakes

Flakes are formed while cooling after the forging or rolling operations. They are internal fissures attributed to (1) stresses produced by localized metallurgical transformations and (2) decreased solubility of hydrogen (hydrogen embrittlement) resulting from excessively rapid cooling.

Hydrogen is available in abundance during all manufacturing operations. When permitted, hydrogen dissipates freely at temperatures above 200 °C (390 °F), so that the solubility of hydrogen in material proportionally increases with increasing time and temperature. Hydrogen flakes are usually found deep in heavy steel forgings, are extremely thin and are aligned parallel with the grain.

FIGURE 15. Cross section of a bar showing a forging burst near the centerline; arrow indicates the direction of working

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Welding Discontinuities

The following discontinuities are related primarily to the fusion welding process, although a few may also apply to resistance and solid state processes. This compilation covers only those discontinuities that typically lend themselves to detection by magnetic particle testing (see Table 3).

Acceptance or rejection of a weldment, based on the detection of a particular discontinuity, is determined by the requirements of the designer and the applicable code.

Cold Cracking

Cold cracking is also known as *underbead* or *delayed cracking*. It is a form of hydrogen induced cracking that appears in the heat affected zone or weld metal of low alloy and hardenable carbon steels. Cracking of this type may occur immediately on cooling or after a period of hours or even days. The principal factors contributing to cold cracking are (1) the presence of atomic hydrogen; (2) a hard martensitic microstructure in the heat affected zone; and (3) high residual tensile stresses resulting from restraint.

Sources of atomic hydrogen include moisture in the electrode covering, shielding gas or base metal surface (including hydrated rust), as well as contamination of the filler or base metal by a hydrocarbon (oil or grease). Dissociation of water vapor or a hydrocarbon in the welding arc results in the rapid diffusion of atomic hydrogen into the molten weld pool and subsequently into the base metal's heat affected zone. If the zone's cooling rate is high enough and the steel is hardenable enough (a function of carbon and alloy content), a martensitic microstructure may form and the hydrogen atoms may then collect at internal discontinuities. Residual stresses caused by weld shrinkage,

TABLE 3. Primary processing discontinuities in welds

Discontinuity	Location	Cause
Cold cracking	surface or subsurface	a combination of atomic hydrogen, hardenable material and high residual stresses
Hot cracking		
Solidification	surface or subsurface	dendritic segregation of low melting point constituents opening up during solidification
Liquation	surface or subsurface	HAZ segregation of material in the liquid state during solidification.
Lamellar tearing	surface	delamination of the base material during solidification and cooling of weld metal
Lack of fusion	subsurface	failure of the filler metal to coalesce with the base metal
Lack of penetration	surface or subsurface	inadequate penetration of the weld joint root by the weld metal
Porosity	surface or subsurface	vaporized constituents in the molten weld metal are entrapped during solidification
Inclusions		
Slag	subsurface	improper cleaning of a previous weld pass
Tungsten	subsurface	molten weld pool or filler metal comes in contact with the tip of a tungsten electrode
Oxide	subsurface	mixing oxides on the base metal surface into the weld pool
Undercut	surface	oversized weld pool (related to excessive amperage, travel speed and electrode size)
Overlap	surface	insufficient amperage or travel speed

or externally applied tensile stresses, result in hydrogen induced cracks initiating at the hydrogen rich discontinuities.

Cold cracks produce sharply defined, heavy magnetic particle indications if they are open to the test object surface, as in the case of underbead cracks that extend to the weld toe (Fig. 16). Weld metal cracks may be oriented in any direction and are often associated with nonmetallic inclusions (Fig. 17). Subsurface indications are less pronounced or may be undetectable, depending on depth.

Hot Cracking

Hot cracking is a term applied to several varieties of weld metal and heat affected zone cracking, all of which occur at elevated temperatures. The following types are two of the most common hot cracks.

Solidification cracking occurs near the solidification temperature of the weld metal and is caused by the presence of low melting point constituents, typically iron sulfides, that segregate to the weld metal dendrite surfaces during the liquid-to-solid transformation process. The shrinkage stresses induced by cooling cause cracks to open between the dendrite surfaces (Fig. 18).

One common form of solidification cracking is called *centerline hot cracking*, because it follows the longitudinal centerline of the deposited weld bead (see Fig. 19). During weld deposition, solidification of the progressing weld pool occurs from the outside in, beginning at both toes and meeting at the center. The low melting point impurities are pushed ahead of these two joining solidification fronts where they are concentrated at the centerline and open up as a longitudinal hot crack under transverse solidification shrinkage stresses. The likelihood of this occurrence is increased by high travel speed, high depth-to-width ratio of the weld bead and a small weld bead, particularly in the root pass.

Another frequently observed type of solidification cracking is called *crater cracking*, which occurs in the crater formed at the termination of a weld pass (Fig. 20). Crater cracks are typically star-shaped on the surface and are the result of three-dimensional shrinkage stresses brought about by crater solidification. Sudden termination of the welding arc, rather than pausing at the end of a weld pass to fill in the crater, is a common contributor to crater cracking.

Liquation cracking or hot tearing occurs in the heat affected zone of a weld when the temperature in that region results in the liquation of low melting point constituents (inclusions or segregated alloying elements). These form a liquid grain boundary film that is unable to support the

FIGURE 16. Cross section of a weld joint exhibiting hydrogen induced cold cracking in the heat affected zone (underbead): this crack is detectable by magnetic particle testing because it extends to the outside surface

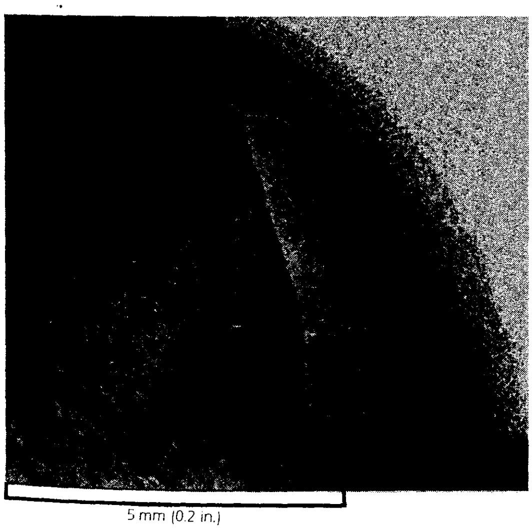

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FIGURE 17. Cross section of a weld joint exhibiting hydrogen induced weld metal cold cracking; this crack is oriented longitudinally but weld metal cracks may be oriented in other directions depending on joint restraint

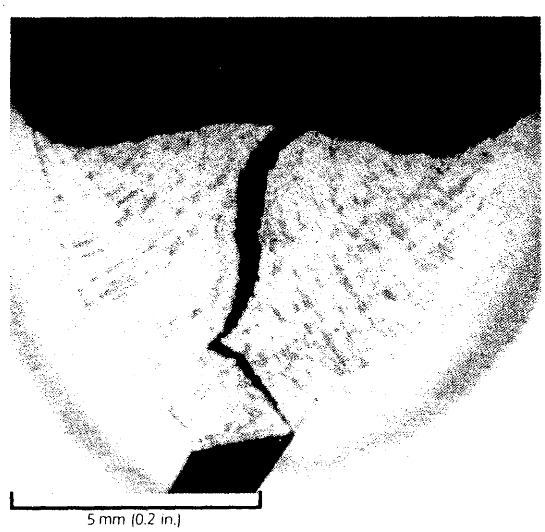

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FIGURE 18. Cross section of a weld joint exhibiting solidification cracking; the weld on the right side contains an interdendritic crack associated with a slag inclusion which acted as a nucleation site; note that the crack curves as it approaches the weld centerline, following the dendritic solidification pattern

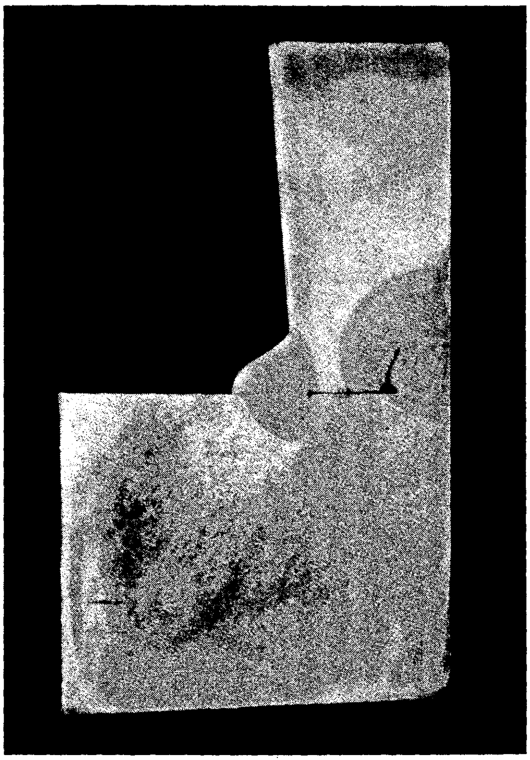

FIGURE 19. Section through a weld joint exhibiting centerline solidification cracking, a form of hot cracking

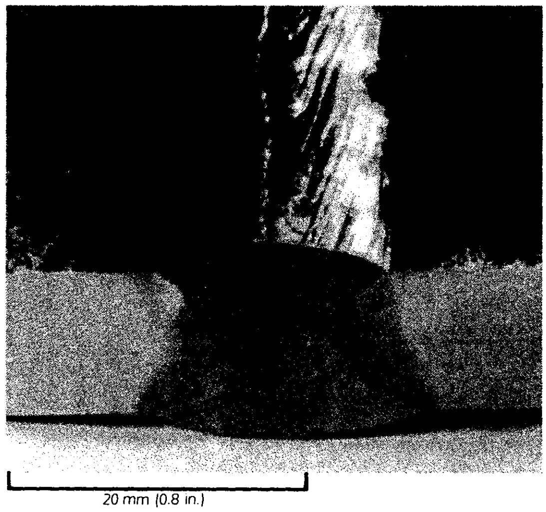

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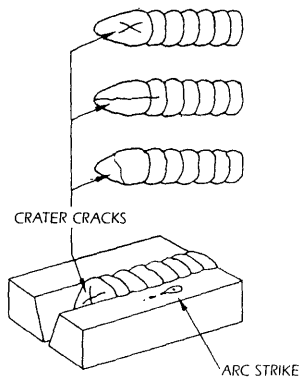
FIGURE 20. Location and typical appearance of crater cracks



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shrinkage stresses of the welding process. Such cracks are often microscopic in size but may link up under applied stresses to form a continuous surface or subsurface crack.

In general, hot cracking is associated with steels having high sulfur content and the effect is accentuated as carbon content increases. The detectability of hot cracks by magnetic particle methods is similar to that of cold cracks and depends on their proximity to the surface.

Lamellar Tearing

A lamellar tear is a base metal crack that occurs in plates and shapes of rolled steel exhibiting a high nonmetallic inclusion content. These inclusions are rolled flat in the steel plate manufacturing process, severely reducing strength and ductility in the through-thickness direction. When the shrinkage stresses induced by weld solidification are imposed in that direction on the base metal plate, separation of the base metal at the flattened inclusions might occur, as may shearing between those lamellar planes, resulting in a terraced fracture (Fig. 21).

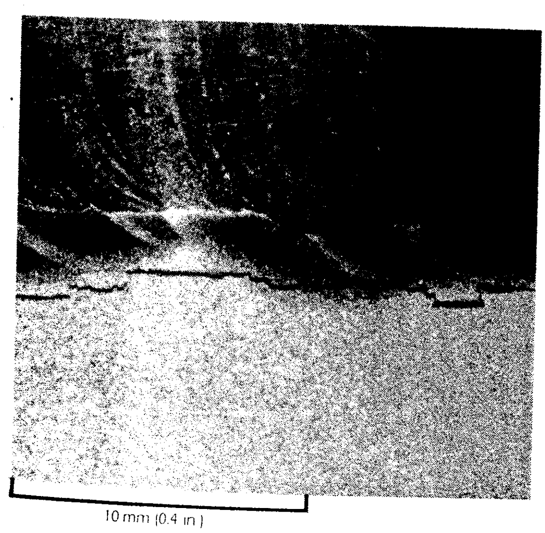
Lamellar tearing is readily detectable by magnetic particle techniques and is most often seen in base metal on the edge of a steel plate or structural shape, adjacent to a deposited weld bead (Fig. 22).

Lack of Fusion

Lack of fusion occurs when some portion of the weld filler metal fails to coalesce with the adjacent base metal or the weld metal from a previous pass. In welding processes that use no filler metal, lack of fusion refers to incomplete coalescence between the two base metal components being joined.

This condition is caused when the base metal surface fails to reach melting temperature after application of the weld metal. This typically occurs when welding a large component that can transfer heat rapidly because of its thermal mass, particularly when it is at a relatively low temperature prior to welding, thereby absorbing the heat applied to its surface by the welding process. Lack of fusion is often seen at the beginning of the first weld pass, where the base metal is at its lowest temperature during weld deposition; this is commonly called a *cold start* (see Fig. 23).

FIGURE 21. Typical location and appearance of lamellar tearing; this view is parallel to the rolling direction of the steel plate base metal



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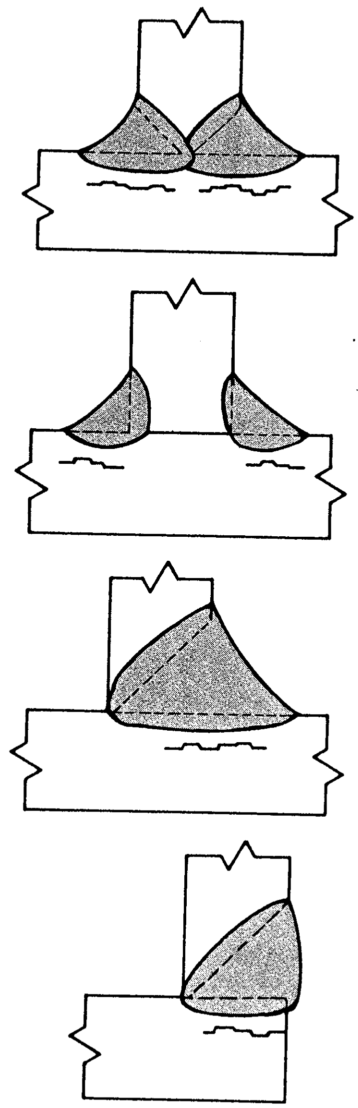
One welding process that is particularly susceptible to this discontinuity is gas metal arc welding (GMAW) in the short-circuiting arc mode, because of its inherently low heat input. Another frequent cause of lack of fusion is attempting to weld on top of a previously deposited weld pass that has been inadequately cleaned of slag or welding on a dirty base

FIGURE 22. Weld joint designs in steel plate that are prone to lamellar tearing; typical locations of tears are shown



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metal surface, so that the heat of the arc is unable to reach the underlying metal.

Lack of fusion may or may not occur near the outside surface of the weld joint. The closer it is to the surface, the sharper the magnetic particle indication. Lack of fusion is usually oriented parallel to the direction of welding and the test indication often appears at or near the toe of the weld.

Lack of fusion in autogenous welds (without filler metal) may be the result of large inclusions in the base metal or impurities that become trapped between the faying surfaces of the joint prior to welding. Susceptible processes are those that produce a relatively shallow melted zone at the faying surfaces and then expel most of that zone by a subsequent upsetting force (high frequency resistance welding, projection welding, flash welding, friction welding). Other causes of lack of fusion in autogenous welds include inadequate heating and insufficient upsetting force. Figures 24 and 25 show a typical discontinuity of this type.

FIGURE 23. Cross section of a weld joint exhibiting lack of fusion resulting from a cold start in a submerged arc weld

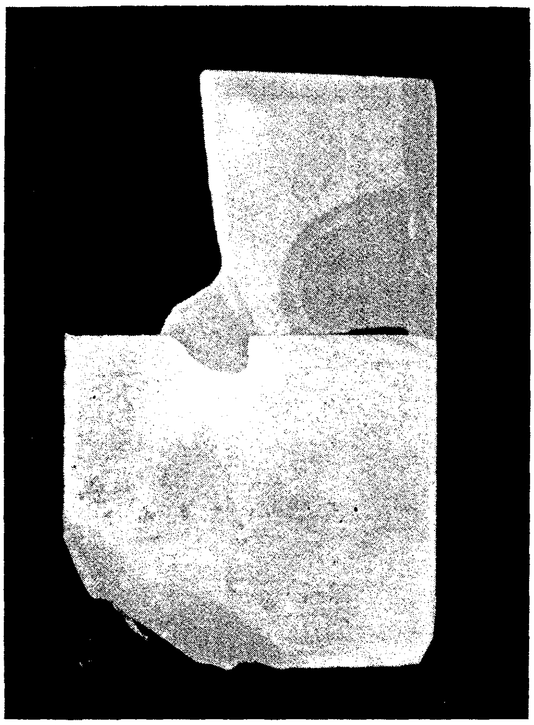
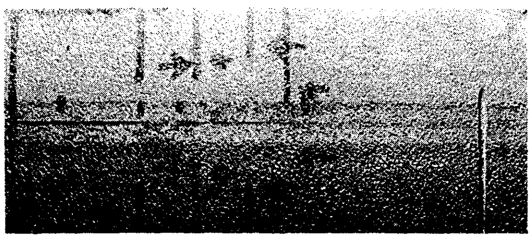


FIGURE 24. Magnetic particle indication of lack of fusion in a high frequency resistance welded tube



Lack of Penetration

Lack of penetration is sometimes confused with lack of fusion. Lack of penetration is inadequate (less than specified) penetration of the weld joint root by the weld metal (Fig. 26). The condition can result from a number of incorrect parameters, most of them related to welding technique. These include low amperage, use of an oversized electrode, excessive travel speed, improper electrode angle, improper arc manipulation and inadequate preweld cleaning.

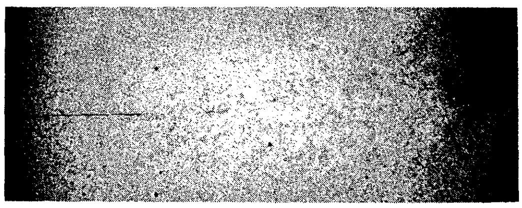
Often, the joint design does not facilitate good penetration because of too large a root land, too narrow a root gap or too small a bevel angle. Many procedures for double groove welds specify backgouging of the first pass on the first side prior to deposition of the first pass on the second side. If this is neglected or performed inadequately during the joining operation, lack of penetration will likely occur.

The magnetic particle indication produced by lack of penetration has an appearance similar to a subsurface longitudinal crack and usually follows the centerline of the weld.

Porosity

Porosity is composed of cavities or pores that form when some constituent within the molten weld metal vaporizes and forms a small pocket of gas that is entrapped when the weld metal solidifies. The pores can take a variety of shapes and sizes although they are usually spherical. One type of

FIGURE 25. Metallographic cross section of the tube shown in Figure 24, showing the depth of lack of fusion from the outside surface inward



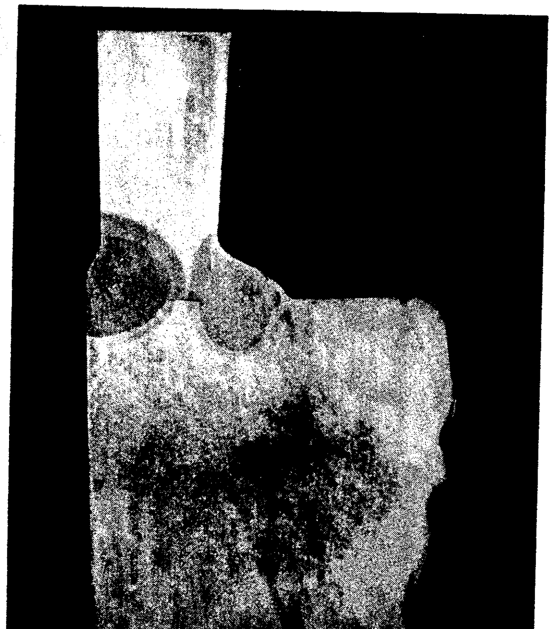
elongated pore is often called a *wormhole* (Fig. 27). The distribution of porosity within the weld metal may be clustered (usually results from improper initiation or termination of the welding arc) or linear (indicates gas evolution by welding over a contaminant confined to a linear junction such as a corner or crevice).

In general, porosity is often the result of dirt, rust or moisture on the base or filler metal surface before welding and can be prevented by maintaining cleanliness and dryness. Other contributing factors include base metal composition (such as high sulfur content), high solidification rate and improper welding technique (such as excessive arc length).

Often the surface discontinuities called *blowholes* are found where gas pockets have reached the surface of the weld pool but do not fully escape before solidification takes place. Blowholes should be removed before any subsequent weld passes are deposited because they are likely places for slag entrapment.

A magnetic particle indication of subsurface porosity is typically weak and not clearly defined. All but the smallest surface pores should be visible to the unaided eye.

FIGURE 26. Cross section of a weld joint exhibiting lack of penetration



Inclusions

Many weld processes use flux shielding, including shielded metal arc welding (SMAW), submerged arc welding (SAW) and flux cored arc welding (FCAW). Welds produced by these methods are particularly susceptible to discontinuities known as *slag inclusions*. Slag can be entrapped in the weld metal during solidification if it is unable to float out while the pool is still liquid. The factors that promote slag entrapment include high solidification rate, high weld pool viscosity, use of an oversized electrode and improper joint geometry.

Slag allowed to remain on the surface of a deposited weld bead is rarely completely dissolved by subsequent passes. Therefore, it is essential to remove all slag from each pass. Joint designs that exhibit a high depth-to-width ratio and weld beads with an excessively convex profile are promoters of slag entrapment (Fig. 28). A magnetic particle indication produced by a slag inclusion is weak and poorly defined and high magnetizing field strength is required for detection.

Tungsten inclusions are found in the weld metal deposited by the gas tungsten arc welding (GTAW) process and are usually the result of allowing the molten weld pool or the filler metal to come in contact with the tip of the tungsten electrode. This type of inclusion is virtually undetectable by magnetic particle methods.

FIGURE 27. Longitudinal section through weld metal containing wormhole porosity

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Oxide inclusions are particles of high melting point oxides present on the base metal surface. During welding, these oxides are then mixed into the weld pool. The magnetic particle indications produced by oxide inclusions of significant size and quantity are similar to those produced by subsurface porosity. Small and isolated oxides are extremely difficult to detect by magnetic particle methods.

Undercut

Undercut occurs at the toe of a weld when the base metal thickness is reduced. Essentially, a narrow crevice is formed in the base metal, paralleling the weld toe and immediately adjacent to it (Fig. 29a). Undercut lessens joint strength in the static sense by reducing the base metal section thickness. It also creates a stress concentration that reduces the impact, fatigue and low temperature properties of the joint. Undercut is caused by an oversized molten weld pool, which is in turn related to excessive amperage, travel speed and electrode diameter.

A magnetic particle indication produced by undercut appears less pronounced than that produced by lack of fusion. Undercut is easily detected by visual examination.

Overlap

Overlap is the protrusion of weld metal over the weld toe, producing a form of lack of fusion that creates a sharp mechanical notch or stress concentration (see Fig. 29b). The condition is caused by insufficient amperage or travel speed.

Overlap produces a magnetic particle indication at the weld toe similar to that produced by lack of fusion. It is often detectable by visual examination.

FIGURE 28. Cross section of a weld joint containing slag inclusions; note that the high depth-to-width ratio of the weld on the left side contributed to slag entrapment

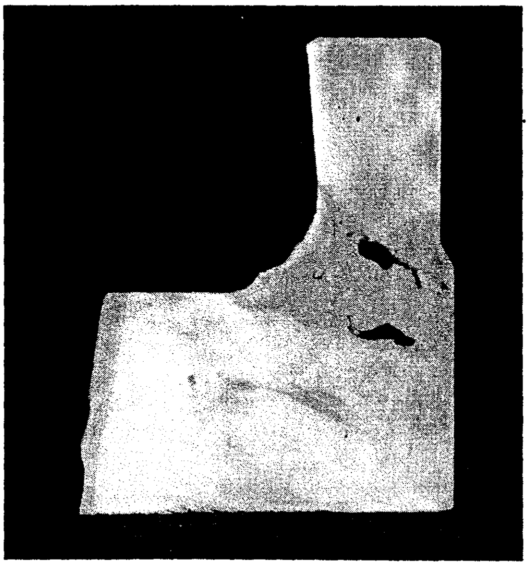
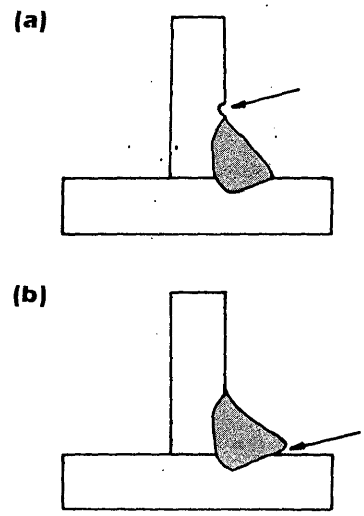


FIGURE 29. Diagram of weld discontinuities: (a) undercut (at arrow); and (b) overlap (at arrow)



PART 3
SECONDARY PROCESSING DISCONTINUITIES

Discontinuities that originate from grinding, heat treating, machining, plating and related finishing operations are categorized as secondary processing discontinuities. Such discontinuities may be the most costly because all previous processing costs are lost when the component is diverted from service.

The following text briefly describes the most common secondary processing discontinuities (see Table 4).

Grinding Cracks

Grinding cracks can be attributed to the use of glazed wheels, inadequate coolant, excessive feed rate or attempting to remove too much material in one pass. Grinding cracks develop where there is localized overheating of the base material. They are typically at right angles to the grinding direction and are very shallow. Often, grinding cracks are forked and sharp at the root (Fig. 30).

When located in high stress areas, such cracks may result in fatigue failures. Materials that have been hardened or heat treated can be more susceptible to grinding cracks because high residual stresses are retained during the quenching operation.

Heat Treating and Quench Cracks

To obtain a specific hardness and microstructure, materials are customarily heat treated. During this operation, the metal is heated and cooled under controlled conditions. However, in some cases, this process produces stresses that exceed the material's tensile strength and cause it to crack (Fig. 31). Similarly, when an object is heated to a very high temperature then rapidly cooled (in air, oil or water), quench cracks may develop.

During the transformation from austenite (a face centered cubic structure) to ferrite (body centered cubic) and martensite (body centered tetragonal) on cooling, a volumetric expansion occurs.

When an object is quenched following heat treating, the initial transformation occurs at the object's surface. Immediately after the quenching process begins, a layer of body centered tetragonal or body centered cubic material is formed at the surface. When the interior cools and transforms, volumetric expansion takes place but the interior expansion is restrained by the solidified layer. If the solid layer does not expand enough or if the internal expansion is great enough, cracking through the outer layer results.

A tempering process normally follows the quenching operation. Because of this exposure to a high temperature, the surface of quench cracks become oxidized. Identifying oxidation is one method of determining if a crack was caused by quenching.

Quench cracks serve as stress concentration sites for fatigue crack initiation and propagation. This may also serve as the initiation sites for overload failures. Some quenching operations are so severe that objects break up during the process.

The amount of volumetric expansion is governed primarily by the chemistry of the metal, particularly carbon. As the carbon content increases, so does the amount of expansion.

TABLE 4. Secondary processing discontinuities in ferromagnetic materials

Discontinuity	Location	Cause
Grinding cracks	surface	localized overheating of the material due to improper grinding procedures
Heat treating cracks	surface	uneven heating or cooling that produces stresses exceeding the tensile strength of the material
Quench cracks	surface	sudden cooling from elevated temperatures
Pickling cracks	surface	residual stresses being relieved
Machining tears	surface	improper machining practices
Plating cracks	surface	residual stresses being relieved

The severity of the quench can be lessened by using a lower carbon content material or by quenching in a less harsh media such as oil or an elevated temperature bath.

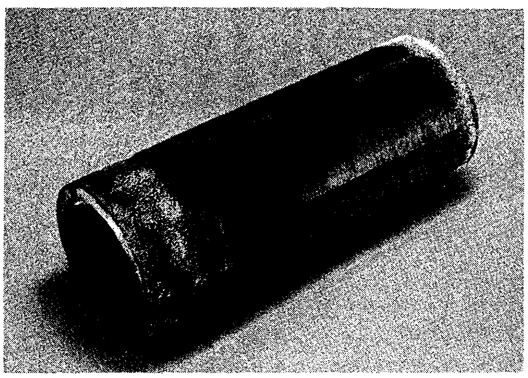
Heat treating and quench cracks usually emanate from locations of thin cross section, corners, fillets, notches or material thickness changes because these areas cool quicker and therefore transform first. Restricted movement of the material also influences the location of cracks during the heat treating or quenching operations. Heat treating or quench cracks are typically forked, surface indications that are randomly placed in any direction on the test object.

Pickling Cracks

A pickling operation is used to remove unwanted scale for the purpose of a more thorough test of the base material. It can also be used to prepare the surface for finishing operations such as plating. Pickling cracks are predominately found in materials that have high residual stresses (hardened or cold worked metals) and in materials with voids or similar discontinuities.

During pickling, hydrogen is generated at the surface of the material. The diffusion of hydrogen into the metal causes a breakdown of the molecular structure and a subsequent propagation of cracks. When high internal stresses are present with preexisting cracks or other discontinuities, hydrogen accelerates propagation of the crack to relieve the stresses in the material.

FIGURE 30. Wet fluorescent magnetic particle indication of grinding cracks in diesel engine connecting pin



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Machining Tears

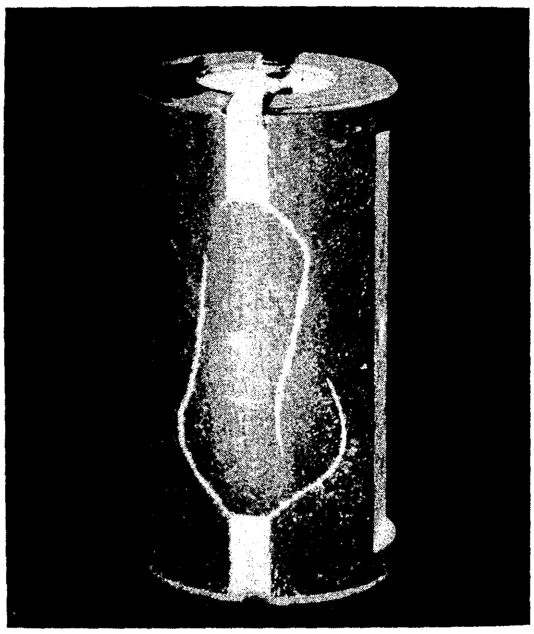
A dull machining tool shears metal off in a manner that produces rough, torn surfaces. As a result, the surface is work hardened to a degree that depends largely on the depth of cut, the type and shape of the tool and the material properties (Fig. 32).

Heavy cuts and residual tool marks from rough machining act as stress risers and can contribute to premature failure in a component. Stress risers may also occur at a change in section, such as in small fillet radii between two shaft sections of different diameters or the poor blending of fillets with shaft surfaces. Although difficult to detect, machining tears must be thoroughly and meticulously located.

Plating Cracks

Plating is used for decoration, corrosion protection, wear resistance and to correct undersized dimensions for a wide variety of steel components. However, specific plating

FIGURE 31. Magnetic particle indications of quench cracks



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materials produce residual stresses that can be either tensile or compressive. Plating materials that develop residual tensile stresses (chromium, copper and nickel) can reduce the fatigue strength of a component.

Plating cracks may develop when there is penetration of either hydrogen or hot plating material into the base metal (Fig. 33). This action produces crack propagation or initiation. Materials high in hardness or residual stresses are more susceptible to damage from hydrogen absorption during plating or pickling operations. Furthermore, cracks that initiate exclusively in the plating material may act as stress risers and cause cracking in the base material.

FIGURE 32. Magnetic particle indications of cracks resulting from cold working during machining

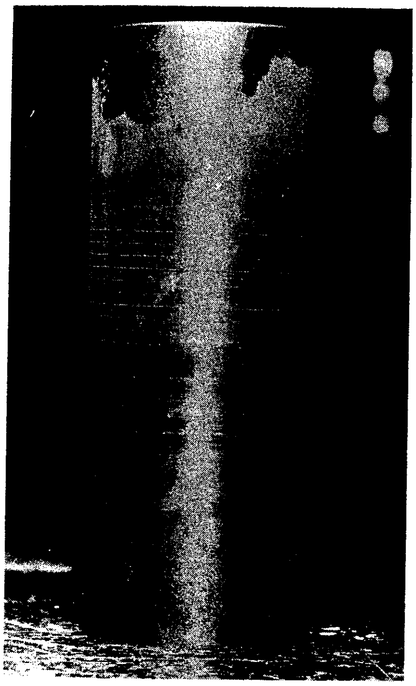

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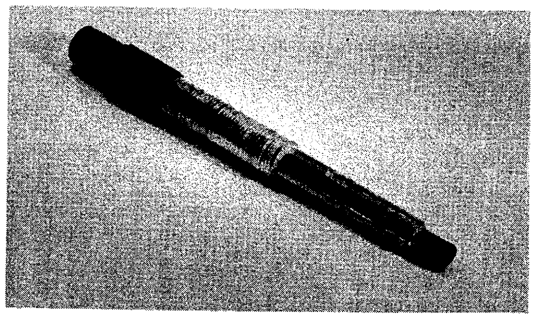
FIGURE 33. Wet fluorescent magnetic particle indications of plating cracks due to hydrogen embrittlement



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PART 4
SERVICE INDUCED DISCONTINUITIES

The life expectancy of a component is dependent on its service environment (both mechanical and chemical), the quality of its maintenance and the appropriateness of its design. It is essential for testing personnel to know the service conditions of a component in order to accurately perform a magnetic particle test. Although service induced discontinuities appear similar, the mechanisms that cause them are quite different in each case.

The following text briefly describes common service induced discontinuities (see Table 5) found in ferromagnetic materials.

Fatigue Cracking

Fatigue is a fracture mechanism induced by a cyclically applied stress that is lower in magnitude than the ultimate tensile strength of the material but high enough to initiate a crack or to propagate a preexisting crack.

Fatigue cracks can develop from stress risers such as machining or tooling marks, nonmetallic inclusions present at or near the material surface, pores, holes or notches, keyways and may even develop on a smooth surface (see Figs. 34 and 35).

As a fatigue crack begins to propagate, the stress intensity at the tip of the crack starts to increase. With every incremental growth period of the crack, there is a proportional, incremental increase in the stress intensity. This process continues until the stress intensity K reaches the critical value K_{IC} where failure occurs.

This K_{IC} factor, also known as the *fracture toughness*, is unique for each material. The variance in fracture toughness partially explains the behavior of fatigue cracks: why there is such a range of fatigue crack sizes; why some cracks may only propagate a small amount; and why others propagate through nearly all the material before final fracture.

Fatigue Crack Structure

From an external surface, a fatigue crack resembles any other crack, but internally a fatigue crack has certain unique characteristics. Macroscopically, features called *beach marks* or *clamshell marks* can be found. These distinct markings are the result of variations in cyclic loading, either in frequency, environment or stress. Such marks are actually small ridges that develop on the fracture surface and they indicate the position of the advancing crack at a given time. The geometry and orientation of beach marks can help establish the location of the crack origin and the direction of propagation (Fig. 36).

Microscopically, the fatigue fracture mechanism is characterized by features known as *striations*. Each striation represents one applied stress cycle. The distance between striations can be equated to the crack growth rate.

Striations and beach marks are not always observed on the fracture surface. Many times, loading is such that striations formed during the tensile or positive stress cycle are obliterated during compressive or negative stress. Striations appear more often in softer materials such as aluminum or low carbon steel.

Fatigue cracks normally originate on the surface but can begin below the surface at discontinuities if the applied and residual stresses exceed the subsurface fatigue strength of the material. When this occurs, a circular pattern of beach marks may form around the origin, producing a bull's-eye appearance.

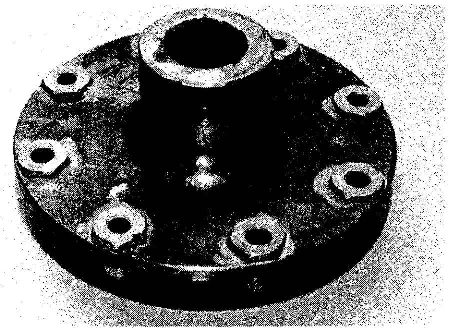
The probability of fatigue cracking can be dramatically reduced if the designer is aware of the material's fatigue properties and designs the component accordingly. Proper care in machining is necessary to ensure that no unanticipated stress risers are introduced. Additional fatigue resistance can be gained by stress-relieving a component or by shot peening to introduce a compressive stress on the object's surface.

TABLE 5. Service induced discontinuities in ferromagnetic materials

Discontinuity	Location	Cause
Fatigue	surface	cyclically applied stress below the ultimate tensile strength
Creep	surface or subsurface	material subjected to elevated temperatures and stress below the yield strength
Stress corrosion cracking	surface	combined effects of a static tensile load and a corrosive environment
Hydrogen cracking	surface or subsurface	combined effects of applied tensile or residual stress and hydrogen enriched environment

FIGURE 34. Helicopter rotor component: (a) no discontinuities revealed by visual examination; and (b) fatigue cracks revealed by wet fluorescent magnetic particle tests

(a)



(b)

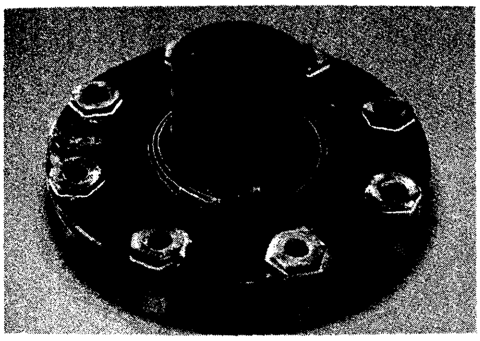


FIGURE 35. Magnetic particle indications of fatigue cracks in a gear

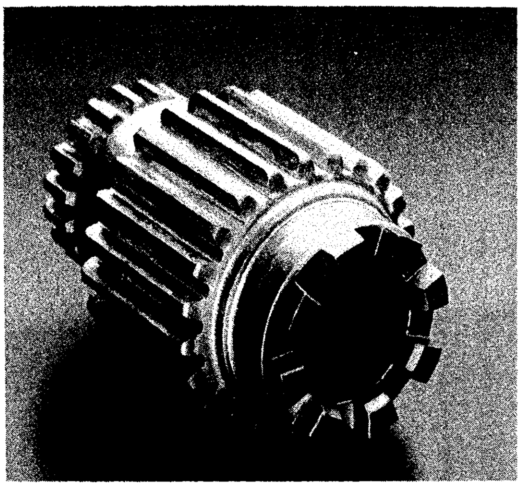
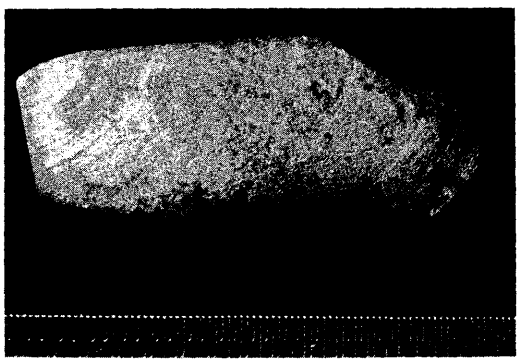


FIGURE 36. Photograph of a fracture surface typical of fatigue; note initiation area in the upper left corner



Creep Cracking

At temperatures greater than half the melting point and at stresses below the yield strength of the material, deformation can occur by the action of grains gradually separating over an extended period of time. This can eventually lead to cracking and finally to failure. This deformation or failure mechanism is called *creep*.

Figure 37 shows a schematic representation of creep or deformation with a constant load. The curve can be broken down into four regions. The first is the material's initial response to loading. This is usually elastic in nature and is applied very quickly, accounting for the vertical portion of the curve. The next portion of the curve is where the material's rate of straining or creep is decreasing with time. This is called *primary* or *transient creep*.

The third portion is called *secondary* or *steady state creep*. This period accounts for the majority of a component's life and the rate of creep is nearly constant. During this stage, small voids begin to form and grow at the triple points of the grain boundaries. Because the void formation is nearly constant, the creep rate can be predicted and the remaining service life of the component can be estimated, based on the steady state creep.

Once the material moves into the region of *tertiary creep*, the useful life of the material is over. In the tertiary stage, the creep voids have become so large that they begin to link, forming a crack network that quickly leads to failure.

Creep can be detected and controlled. Periodic tests, particularly those involving field metallography and circumferential measurement can be used to monitor the creep process (Figs. 38 and 39). By slightly decreasing operating temperature or stress, a substantial decrease in the creep rate yields greater service life. Figure 40 shows the effect that various temperatures have on creep.

It is generally recognized, that the most direct way to improve the creep properties of a metal is by adding alloying elements. Carbide forming elements, such as molybdenum, tungsten and to a lesser degree, chromium and vanadium, effectively enhance the creep resistance of steels.

FIGURE 37. Typical curve showing the three stages of creep: (a) constant load test; and (b) constant stress test

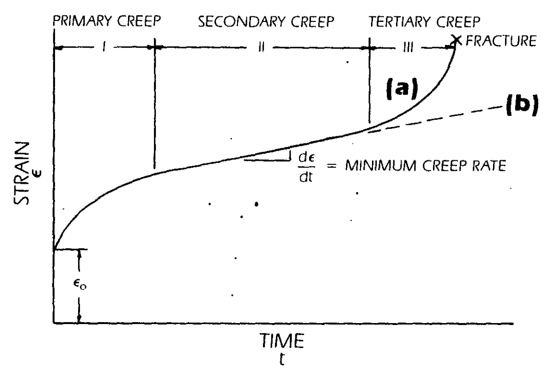
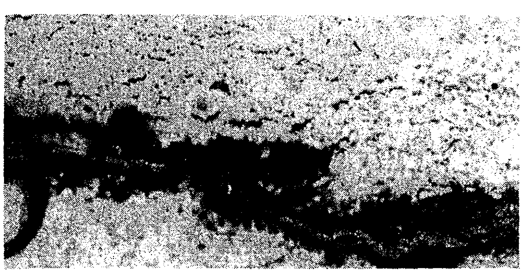


FIGURE 38. Photomicrograph of fracture and creep in various stages in heat affected zone near fusion zone interface



Nickel additions are beneficial if sufficient quantity is added to produce an austenitic structure that is more resistant to creep. Austenitic stainless steels (particularly 18Cr-8Ni types) have much better creep properties than carbon steels.

Aside from alloying additions, heat treatment has an effect on creep properties. Heat treatment generally controls grain size and it has been found that a coarser grain at elevated temperatures has higher creep strength than a finer grain.

Since materials can be subjected to such a variety of loads and temperatures for a particular application, the type of

FIGURE 39. Photomicrograph of linked creep voids in weld zone

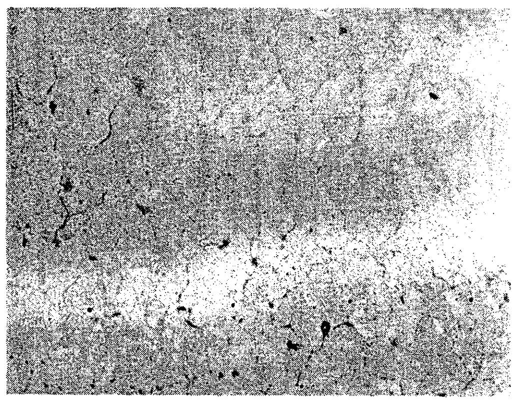
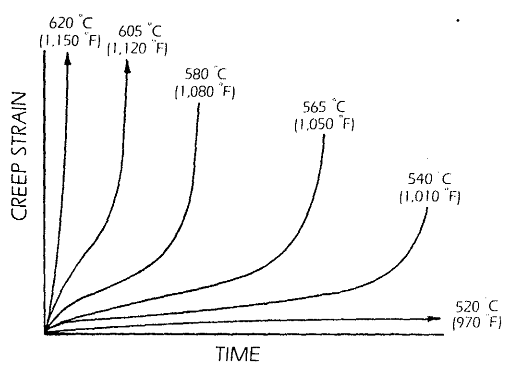


FIGURE 40. Curve showing the effect of temperature on creep over time



heat treatment should be based on the degree of stability that it imparts to the component initially and throughout its service life.

Stress Corrosion Cracking

Stress corrosion cracking is a fracture mechanism that results from the combined effects of a static tensile load and a corrosive environment. The stress involved can either be from actual applied loads or from residual stresses. One of the most common causes of this residual stress is the shrinkage that occurs during cooling of weld metal.

The corrosive environment varies from material to material. Some common examples of materials and their corrosive environments include: aluminum and austenitic stainless steels exposed to saltwater; copper and its alloys exposed to ammonia (NH_3); and mild steel exposed to sodium hydroxide (NaOH).

The stress intensity versus time dependence for a typical stress corrosion cracking situation is shown in Fig. 41. The basic stress-time curve can be expressed in terms of the initial level of K_I, which is based on the tensile load and a known crack length. The threshold value of stress intensity is designated K_{ISCC}. Crack growth does not occur if the stress intensity is below this value. If the initial stress intensity is above K_{ISCC}, a crack propagates. The higher the initial K_I or the closer the value gets to the critical stress intensity factor K_{IC}, the shorter the life of the component.

The initiation site of a stress corrosion crack may be a preexisting discontinuity or it may be a small pit acting as a stress riser and produced by corrosive attack on the surface (Fig. 42). Once a crack is formed, the corrosive environment penetrates the surface of the material. The tip of an advancing crack has a small radius and the attendant stress

FIGURE 41. Stress intensity versus time dependence for a typical stress corrosion cracking situation

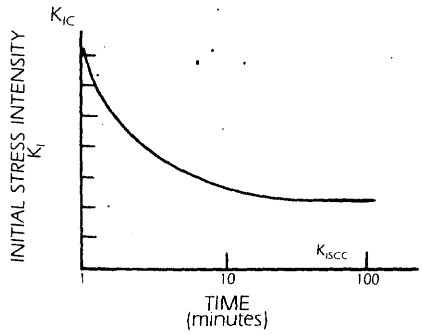


FIGURE 42. Stress corrosion cracking found in a stainless steel tube (dye penetrant was used to illustrate the random crack orientation and branching); note that similar cracking could exist in ferromagnetic alloys

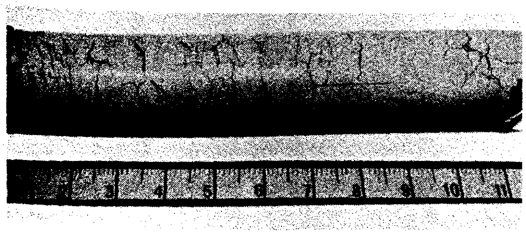


FIGURE 43. Photomicrograph showing a typical stress corrosion crack; note small pit produced by corrosive attack acting as a stress riser

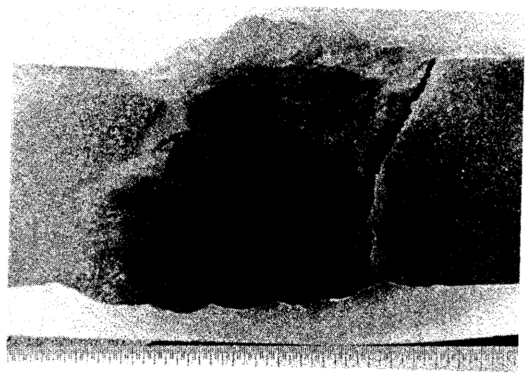
concentration is great. This stress at the crack tip ruptures the normally protective corrosion film and aids in the corrosion process (Fig. 43).

In addition to this, the formation of corrosion products by local attack in confined areas produces high stress levels in materials if the corrosion products occupy a larger volume than the metal from which they are formed. This wedging action of corrosion products in cracks has been measured to produce stresses over 34 MPa (5 ksi) which aid in the propagation of the crack.

Stress corrosion cracking produces brittle failure, either intergranular or transgranular, depending on the type of alloy or the corrosive environment. In most cases, while fine cracks penetrate into a the cross section of a component, the surface shows little evidence of corrosion.

In order to keep the stress intensity to a minimum, care must be taken to avoid stress concentrations, such as tooling marks, notches, arc strikes and large inclusions near the surface.

FIGURE 44. Photograph of hydrogen cracking found in the heat affected zone adjacent to a weld



Hydrogen Cracking

Hydrogen cracking or hydrogen embrittlement is a fracture mechanism that results from the corrosive environment produced by a hydrogen media and usually occurs in conjunction with an applied tensile stress or residual stress. Hydrogen is introduced into a material by processes such as electroplating, pickling, welding in a moist atmosphere or the melting process itself. Hydrogen may also come from corrosion or the presence of hydrogen sulfides, hydrogen gas, water, methane or ammonia.

If no crack or stress riser is present on a material surface, hydrogen can diffuse into the metal and often initiates cracks at subsurface sites, where triaxial stress conditions are at maximum levels. In low strength alloys, this condition can lead to what is known as *hydrogen blistering*.

If a crack is already present, it is quite common to see hydrogen induced cracking initiated at the tips of preexisting cracks.

In many instances, hydrogen is already present internally in a metal before it is placed into service. Hydrogen is readily absorbed into molten metal during the initial solidification of the material and during welding processes. The solubility of hydrogen is quite high at elevated temperatures and in some cases, metals can become supersaturated with hydrogen during cooling.

Hydrogen cracking follows grain boundaries and rarely shows any signs of branching (Fig. 44). When such cracking results from blistering or from a static load, it always originates below the component's surface. Hydrogen cracking from other causes can begin below the object's surface or at a stress riser.

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SECTION 5

BASIC ELECTROMAGNETISM

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INTRODUCTION

Table 1 lists the symbols used in this section and their corresponding units of measure from the International System of Units (SI). Table 2 lists important physical constants and their values in SI units. Table 3 provides factors for conversions to SI units.

Tesla, for example, is a unit that replaces *gauss* for the measurement of magnetic fields. In vacuum (or for practical purposes in air), a magnetic flux density (B) of 1 T corresponds to a magnetic field strength (H) of $10^7/4\pi$ A•m^{-1}.

TABLE 1. Symbols and units used in electromagnetics

Symbol	Quantity	SI Unit	Common Abbreviation
A	magnetic vector potential	weber per meter	Wb•m^{-1}
B	magnetic flux density	tesla	T
		weber per meter squared	Wb•m^{-2}
D	electric flux density	coulomb per meter squared	C•m^{-2}
E	electric field intensity	volt per meter	V•m^{-1}
F	force	newton	N
f	frequency	cycles per second	Hz
H	magnetic field strength	ampere per meter	A•m^{-1}
I	current	ampere	A
J	current density	ampere per meter squared	A•m^{-2}
L	inductance	henry	H
m, M	magnetic moment	ampere per meter	A•m^{-1}
V	voltage	volt	V
v	velocity	meter per second	m•s^{-1}
W	work	joule	J
w	energy density	joule per meter cubed	J•m^{-3}
q	electric charge	coulomb	C
S	area	meter squared	m^2
ℓ	length	meter	m
ds	differential area (vector)	meter squared	m^2
dl	differential length (vector)	meter	m
R	position vector	meter	m
$\hat{x}, \hat{y}, \hat{z}, \hat{r}, \hat{n}, \hat{\phi}, \hat{\Theta}, \hat{Q}, \hat{R}$	unit vectors	meter	m
V_m	electromotive force	ampere-turns	A•t
$\hat{n}$	normal (component of vector)		
J_s	surface current density	ampere per meter squared	A•m^{-2}
t	time	second	s
P	power	watt per second	W•s^{-1}
P_d	dissipated power	watt per second	W•s^{-1}
$\bar{P}$	Poynting vector	watt per meter cubed	W•m^{-3}
W_e	electric stored energy	joule	J
W_m	magnetic stored energy	joule	J
δ	skin depth	meter	m
$\epsilon, \epsilon_o, \epsilon_r$	permittivity	farad per meter	F•m^{-1}
μ, μ_o, μ_r	permeability	henry per meter	H•m^{-1}
σ	conductivity	siemens per meter	S•m^{-1}
ω	angular frequency	radian per second	rad•s^{-1}
ρ	charge density	coulomb per meter cubed	C•m^{-3}
$A_x, A_y, A_z, A_\theta, A_\phi, A_r, A_R$	components of a vector		
Λ	flux linkage		
χ	magnetic susceptibility		
τ	tangential component (vector)		
ρ_s	surface charge density	coulomb per meter squared	C•m^{-2}

Although they are dimensionless quantities, magnetic susceptibility and demagnetizing factors differ by a factor of 4π in the Gaussian and SI systems.

In the SI system, *relative permeability* μ_r ($\mu = \mu_r\mu_o$) and *relative permittivity* ϵ_r ($\epsilon = \epsilon_r\epsilon_o$) are used. Relative permeability and relative permittivity (dielectric constant) are dimensionless in the SI system.

The mathematics of electromagnetic field studies are briefly discussed in Part 8 of this section.

TABLE 2. Physical constants used in electromagnetism

Symbol	Quantity	Value (Units)
ϵ_o	permittivity of free space	8.8542×10^{-12} (F•m^{-1})
μ_o	permeability of free space	$4\pi \times 10^{-7}$ (H•m^{-1})
e	charge on an electron	-1.602×10^{-19} (C)
c	speed of light (vacuum)	2.9979×10^{8} (m•s^{-1})

TABLE 3. Conversion factors for SI units in study of electromagnetism

Multiply Non-SI Quantity	by	To Obtain SI Quantity
Flux density: gauss	10^{-4}	flux density: tesla
Field strength: oersted	$10^3/4$	field strength: ampere per meter
Susceptibility: emu/cc (dimensionless)	4	susceptibility (dimensionless)
Flux: lines	10^{-8}	flux: weber
Flux density: lines per square inch	0.155×10^{-5}	flux density: tesla
Demagnetizing factor (dimensionless)	1/4	demagnetizing factor (dimensionless)
Magnetic dipole moment: erg/G	10^{-3}	magnetic dipole moment: ampere per meter squared
Magnetization: emu/cc	10^3	magnetization: ampere per meter
Magnetization: gauss	$10^3/4$	magnetization: ampere per meter

PART 1

FUNDAMENTALS OF ELECTROMAGNETISM

Coulomb's Law

The nature of electromagnetism can be summarized by four vector quantities, their interaction, their relations with each other and with matter. These four time dependent vector quantities are referred to as *electromagnetic fields* and include: electric field intensity ($\overline{E}$), electric flux density ($\overline{D}$), magnetic field strength ($\overline{H}$) and magnetic flux density ($\overline{B}$).

The study of electromagnetic fields begins with the study of basic laws of electricity and magnetism and with the use of some basic postulates. In particular, it is customary to start with Coulomb's law. This law states that *the force between two stationary charges is directly proportional to the size of the charges and is inversely proportional to the square of the distance between them.*

Adding Gauss' and Ampere's laws provides a complete set of relations describing all electrostatic, magnetostatic and induction phenomena, but not the propagation of waves. To include wave propagation in electromagnetic field equations, the displacement current (continuity equation) is added to Ampere's law. By doing so, Maxwell's equations are obtained.

Alternatively, Maxwell's equations may serve as the basic postulates and, because they form a complete set describing all electromagnetic phenomena, the required relations may be deduced. By choosing Maxwell's equations as the starting point, an assumption of the equations' accuracy is implicitly made. This is not more troublesome than assuming that Coulomb's law applies or that displacement currents exist. In either case, the proof of correctness is experimental. This is an important consideration: it specifically states that Maxwell's equations and therefore the electromagnetic field relations cannot be proven mathematically.

Use of Maxwell's Equations

Maxwell's equations do not take motion into account and therefore do not include the induction of currents due to motion. To do so, it is necessary to add the Lorenz force equation and the so-called constitutive relations. It may also be useful to note that, by proper interpretation, relativistic effects can also be handled (this application is found in the literature).[1-5]

The approach in this section is to start with Maxwell's equations and derive from them all the necessary relations. In doing so, the equations are accepted as the basic postulates. In particular, at low frequencies, Maxwell's equations are identical to those of Coulomb, Faraday, Gauss and Ampere. The results derived here are general and, within the assumptions made in their derivation, apply to a wider range of applications. Only those electric and magnetic phenomena most directly related to nondestructive testing and, in particular, to magnetic particle testing are considered in detail here. Other electromagnetic phenomena are mentioned briefly for completeness of treatment.

Maxwell's equations are a set of nonlinear, coupled, second order, time dependent partial differential equations whose general solution is difficult to obtain. Some methods for the solution of the electromagnetic field equations are discussed below, including numerical methods that have become prominent in recent years.

Units of Measure and Terminology

One of the major sources for confusion when applying electromagnetic field theory is the system of units used for measurements. The *cgs* (*centimeter gram second* units, including the *electromagnetic system of units* or *emu*) and the *MKSA* (*meter kilogram second ampere* units) are among the most familiar, but other systems such as the *absolute magnetic*, the *absolute electric* and the so-called *normalized system* are also used. What is more disturbing is the fact that mixed units are often used. For example, it is common for practitioners to use SI (or MKSA) units such as the ampere for electrical quantities, and Gaussian emu units such as the gauss for magnetic quantities. Only SI units are used throughout this section. This may at times appear inconvenient (because of the very large or very small quantities involved) but the benefit gained in consistency far outweighs any inconvenience.

Another problem encountered in practice is the confusion between *magnetic field strength* (H), sometimes called *field intensity*, and *magnetic flux density* (B). The term *magnetic field* is often used for $\overline{H}$ or $\overline{B}$ or both, depending on the situation. To avoid such confusion, the quantity $\overline{B}$ is used consistently for the *magnetic flux density* while $\overline{H}$ is the *magnetic field strength*. Similarly, $\overline{E}$ is the *electric field intensity* and $\overline{D}$ is the *electric flux density*.

PART 2

FIELD RELATIONS AND MAXWELL'S EQUATIONS

Maxwell's equations are summarized in Eq. 1 through Eq. 4 in differential form and in Eq. 5 through Eq. 8 in integral form. Equation 9 is the Lorenz force equation which describes the interaction of electric and magnetic fields with electric charge.

$$\nabla \times \overline{E} = -\frac{\partial \overline{B}}{\partial t} \quad \text{(Eq. 1)}$$

$$\nabla \times \overline{H} = \overline{J} + \frac{\partial \overline{D}}{\partial t} \quad \text{(Eq. 2)}$$

$$\nabla \cdot \overline{D} = \rho \quad \text{(Eq. 3)}$$

$$\nabla \cdot \overline{B} = 0 \quad \text{(Eq. 4)}$$

$$\oint_c \overline{E} \cdot \overline{d\ell} = -\frac{d\Phi}{dt} \quad \text{(Eq. 5)}$$

$$\oint_c \overline{H} \cdot \overline{d\ell} = I + \int_s \frac{\partial \overline{D}}{\partial t} \cdot \overline{ds} \quad \text{(Eq. 6)}$$

$$\oint_s \overline{D} \cdot \overline{ds} = Q \quad \text{(Eq. 7)}$$

$$\oint_s \overline{B} \cdot \overline{ds} = 0 \quad \text{(Eq. 8)}$$

$$\overline{F} = q(\overline{E} + \overline{v} \times \overline{B}) \quad \text{(Eq. 9)}$$

Equations 1 and 5 are a statement of Faraday's law of induction. Equations 2 and 6 are a modified form of Ampere's law. The addition of the displacement current term ($\partial D/\partial t$) was Maxwell's contribution to the original laws of electricity. The displacement current, although often taken as an assumption, is nothing more than an expression that can be derived from the continuity equation. Equations 4 and 8 are Gauss' law for magnetic sources and they state the nonexistence of isolated magnetic charges or poles. Equations 3 and 7 are Gauss' law for electric charges.

At this point, the equations are neither linear nor nonlinear. This important behavior is determined through material properties and is not inherent in the equations. The material properties follow the constitutive relations:

$$\overline{B} = \mu\overline{H} \quad \text{(Eq. 10)}$$

$$\overline{D} = \epsilon\overline{E} \quad \text{(Eq. 11)}$$

$$\overline{J} = \sigma\overline{E} \quad \text{(Eq. 12)}$$

If any of these relations is nonlinear, the field relations are nonlinear. In particular, the permeability is known to be highly nonlinear for ferromagnetic materials. In some cases, the conductivity and permittivity may also be nonlinear.

The electric conductivity σ, magnetic permeability μ and the electric permittivity ϵ are generally tensor quantities. While for many practical purposes it can be assumed that they are scalar quantities, materials are encountered in practice that behave differently. These exceptions are defined through linearity, homogeneity and isotropy of the materials. Only for linear, isotropic, homogeneous materials are the material properties single-valued scalar quantities.

Linearity, Homogeneity and Isotropy

A medium is said to be *homogeneous* if its properties do not vary from point to point within the material. A medium is *linear* in a property when that property remains constant while other changes may occur. The permeability of most nonmagnetic materials is considered to be independent of the field. These materials are usually considered to be linear in permeability. A material is *isotropic* if its properties are independent of direction. This means that the permeability of an isotropic material must be the same in all three spatial directions.

A good example of an anisotropic material is a permanent magnet. Most materials, including iron, are anisotropic on the crystal level. Because these crystals are randomly oriented, it may often be assumed that a macroscopic material is isotropic. This is not necessarily the case for hard steels or for steels with large, preferred orientations.

Static Fields

By setting to zero all time derivatives in Maxwell's equations, the equations for the static electric and magnetic fields are obtained. The four equations become:

$$\nabla \times \overline{E} = 0 \qquad \text{(Eq. 13)}$$

$$\nabla \times \overline{H} = \overline{J} \qquad \text{(Eq. 14)}$$

$$\nabla \cdot \overline{D} = \rho \qquad \text{(Eq. 15)}$$

$$\nabla \cdot \overline{B} = 0 \qquad \text{(Eq. 16)}$$

$$\oint_c \overline{E} \cdot \overline{d\ell} = 0 \qquad \text{(Eq. 17)}$$

$$\oint_c \overline{H} \cdot \overline{d\ell} = I \qquad \text{(Eq. 18)}$$

$$\oint_s \overline{D} \cdot \overline{ds} = Q \qquad \text{(Eq. 19)}$$

$$\oint_s \overline{B} \cdot \overline{ds} = 0 \qquad \text{(Eq. 20)}$$

Equations 13 and 15 are the governing equations for electrostatic fields (Faraday's and Gauss' law). Equations 14 and 16 are Ampere's and Gauss' (magnetic) laws for magnetostatic applications. Note that Eqs. 13 and 15 do not contain the magnetic field while Eqs. 14 and 16 do not depend on the electric field. Thus, the equations for electrostatics and magnetostatics are completely decoupled and electrical quantities can be calculated without resorting to the magnetic field and vice versa.

As with the general system of equations, the Lorenz equation has to supplement these equations. Because of the decoupling of the two sets, Lorenz' force equation should be used in its electrostatic form for electrostatic fields:

$$\overline{F} = q\overline{E} \qquad \text{(Eq. 21)}$$

For magnetostatic fields, only the magnetic force exists.

$$\overline{F} = q\overline{v} \times \overline{B} \qquad \text{(Eq. 22)}$$

The electric current or, more conveniently, the electric current density $\overline{J}$ is the source of the magnetic field strength (see Eq. 14).

Equation 18 is particularly useful because it allows the calculation of the magnetic field strength and the determination of its direction. If the integration is taken such that the normal to the surface enclosed by the contour C is in the direction of the current, then the field is described by the right hand rule: if the current is in the direction of the thumb, the field is in the direction of the fingers (see Fig. 1). The total current I in Eq. 18 is the current enclosed within the contour.

The Magnetic Vector Potential

Equation 14 is a cross product and results in a vector quantity $\overline{J}$. Because the cross product of a vector is also a vector, the magnetic flux density $\overline{B}$ may be written as the curl (cross product) of another vector $\overline{A}$.

$$\overline{B} = \nabla \times \overline{A} \qquad \text{(Eq. 23)}$$

Thus, Ampere's law (Eq. 14) can be written as:

$$\nabla \times \frac{1}{\mu}(\nabla \times \overline{A}) = \overline{J} \qquad \text{(Eq. 24)}$$

The vector A is called a *magnetic vector potential*. For an isotropic linear medium, the following vector identity can be used to simplify this expression:

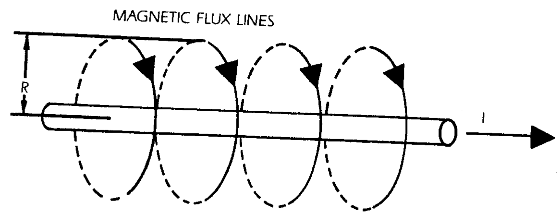
$$\nabla \times \nabla \times \overline{A} = \nabla(\nabla \cdot \overline{A}) - \nabla^2\overline{A} \qquad \text{(Eq. 25)}$$

A vector is only defined when both its divergence and curl are specified. The divergence may be specified in different ways. The simplest is to set it equal to zero in Eq. 25. Ampere's law then becomes:

$$\nabla^2\overline{A} = -\mu\overline{J} \qquad \text{(Eq. 26)}$$

which is the vector Poisson equation.

FIGURE 1. The right hand rule: if the thumb of the right hand is in the direction of the current, the fingers show the direction of the field



Equation 23 defines the magnetic vector potential. This definition of the magnetic vector potential $\overline{A}$ allows the use of a simpler Poisson equation instead of the original field equations.

Biot-Savart Law

The purpose of field relations is to solve field problems. Any of the relations obtained previously may be used for this purpose. In particular, Eq. 14 can be used for general field problems while Eq. 18 is useful for solution of highly symmetric problems. In problems where no such symmetry can be found but which are simple enough not to require the solution of the general Eq. 26, another method can be used. For these types of problems, the magnetic vector potential is used in still another form. Considering the current in a straight wire in Fig. 2, the following can be written at point *P*:

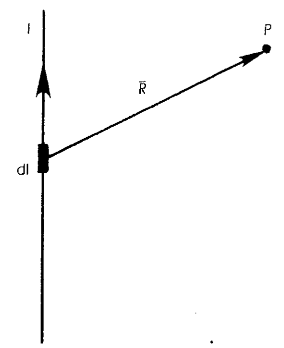
$$d\overline{A} = \frac{\mu I}{4\pi} \frac{\overline{d\ell}}{R} \qquad \text{(Eq. 27)}$$

In Eq. 27, the definition of the magnetic vector potential in Eq. 23 has been used. In order to find the total magnetic vector potential, this differential is integrated over a closed contour to obtain:

$$\overline{A} = \frac{\mu I}{4\pi} \oint_c \frac{\overline{d\ell}}{R} \qquad \text{(Eq. 28)}$$

In order to find the field strength or the flux density, it is necessary to find the curl of this expression by performing the operations in Eq. 23.

FIGURE 2. A straight current carrying wire and the relation of the current and the field at point P



If the magnetic vector potential in Eq. 28 is substituted back into its definition, the following expression is obtained for the flux density:

$$\overline{B} = \frac{\mu I}{4\pi} \oint_c \frac{\overline{d\ell} \times \hat{r}}{R^2} \qquad \text{(Eq. 29)}$$

where $\hat{r}$ denotes a unit vector in the direction of $\overline{R}$ in Fig. 2.

This expression, known as the *Biot-Savart law*, allows the calculation of the flux density directly. It is particularly useful for situations where the current paths are clear and the required contour integration is in the direction of the currents.

PART 3
ELECTROMAGNETIC FIELD TYPES AND BOUNDARY CONDITIONS

Steady State Alternating Current Fields

Low frequency alternating current fields are unique in that a simpler form of Maxwell's equation can be used. The displacement current term $(\partial D/\partial t)$ in Eq. 2 or Eq. 6 depends on frequency and is very small for low frequencies. In fact, this term may be neglected within conducting materials and for all frequencies below about $10E + 13$ Hz. If this assumption is introduced and the term neglected, the *pre-Maxwellian set of equations* is obtained.

By introducing a phasor notation for all vectors, the time dependency is not explicitly used and the transformed system is both simpler in presentation and in solution. A general vector can be expressed as a phasor by the following definition:

$$A(x,y,z,t) = \text{real}\,[\tilde{A}(x,y,z)e^{j\omega t}] \quad \text{(Eq. 30)}$$

Maxwell's equations (in differential form) can now be written as:

$$\nabla \times \tilde{E} = -j\omega\tilde{B} \quad \text{(Eq. 31)}$$

$$\nabla \times \tilde{H} = \tilde{J} + j\omega\tilde{D} \quad \text{(Eq. 32)}$$

$$\nabla \cdot \tilde{D} = \rho \quad \text{(Eq. 33)}$$

$$\nabla \cdot \tilde{B} = 0 \quad \text{(Eq. 34)}$$

In this form, all time derivatives were written as:

$$\frac{\partial \tilde{A}}{\partial t} = j\omega\tilde{A} \quad \text{(Eq. 35)}$$

This version of Maxwell's equations is often called the *quasistatic form* and is very convenient for many alternating current calculations at low frequencies, including alternating current leakage fields. The following equation is obtained by a method similar to that used to obtain Eq. 26.

$$\nabla \times \frac{1}{\mu}(\nabla \times \tilde{A}) = \tilde{J} + j\sigma\omega\tilde{A} \quad \text{(Eq. 36)}$$

This equation, often called *the curl-curl equation* is a diffusion equation and is the basis of many analytical and numerical methods. By using the vector relation in Eq. 25, Eq. 36 can be written as:

$$\nabla^2\tilde{A} - \nabla(\nabla \cdot \tilde{A}) = -\mu\tilde{J} + j\omega\mu\sigma\tilde{A} \quad \text{(Eq. 37)}$$

Here, the divergence of the magnetic vector potential may be chosen in any convenient, physically sound method. By choosing a zero divergence and rewriting the Laplacian $\nabla^2\tilde{A}$ in its differential form, a partial differential equation can be written for two dimensional (Eq. 38), axisymmetric (Eq. 39) and three-dimensional geometries (Eq. 40). Equations 37 through 40 assume linear permeability.

$$\frac{1}{\mu}\left(\frac{\partial^2 A_z}{\partial x^2} + \frac{\partial^2 A_z}{\partial y^2}\right) = -J_s + j\omega\sigma A_z \quad \text{(Eq. 38)}$$

$$\frac{1}{\mu}\left(\frac{\partial^2 A_\phi}{\partial r^2} + \frac{1}{r}\frac{\partial A_\phi}{\partial r} + \frac{\partial^2 A_\phi}{\partial z^2} - \frac{A_\phi}{r^2}\right) = -J_s + j\omega\sigma A_\phi \quad \text{(Eq. 39)}$$

$$\frac{1}{\mu}\left(\frac{\partial^2 \tilde{A}}{\partial x^2} + \frac{\partial^2 \tilde{A}}{\partial y^2} + \frac{\partial^2 \tilde{A}}{\partial z^2}\right) = -J_s + j\omega\sigma\tilde{A} \quad \text{(Eq. 40)}$$

These equations were obtained by substituting the magnetic vector potential in Maxwell's equations. Because other potentials (vectors or scalars) can be defined, the field equations may be obtained in terms of these functions or in terms of the original field quantities $\tilde{B}$ and $\tilde{H}$. A Poissonian (or Laplacian) form as in Eq. 40 are particularly useful because of the standard methods available for their solution.

Time Dependent Fields

Instead of neglecting terms in Maxwell's equations, if the complete sets in Eqs. 1 through 4 or Eqs. 5 through 8 are used, then the general time dependent form of Maxwell's equations is obtained. As was mentioned above, this form is completely general and, when combined with the appropriate boundary conditions, can be solved to obtain all electromagnetic phenomena, including those related to static fields. In practice, exact solutions are rarely obtained because of the complexity involved. Approximations or numerical methods are often required for the solutions of this type of problem.

Wave Propagation

When describing wave propagation, the time dependent form must be used. A wave equation may be obtained by using the definition of the magnetic vector potential in Eq. 23. By substituting this into Eqs. 1 and 2 and using the constitutive relations in Eqs. 10 and 11, the following equation is obtained.

$$\nabla \times \nabla \times \overline{A} = \mu \overline{J} + \mu\epsilon \frac{\partial}{\partial t}\left(-\nabla V - \frac{\partial \overline{A}}{\partial t}\right) \quad \text{(Eq. 41)}$$

Using the vector identity in Eq. 25, Eq. 41 can be written as:

$$\nabla^2\overline{A} - \mu\epsilon \frac{\partial^2 \overline{A}}{\partial t^2} = -\mu\overline{J} + \nabla\left(\nabla \cdot \overline{A} + \mu\epsilon \frac{\partial V}{\partial t}\right) \quad \text{(Eq. 42)}$$

Because the magnetic vector potential requires the definition of the curl and the divergence, it is possible to define its divergence in whatever way the situation requires. The following form may be chosen:

$$\nabla \cdot \overline{A} + \mu\epsilon \frac{\partial V}{\partial t} = 0 \quad \text{(Eq. 43)}$$

Equation 42 then becomes:

$$\nabla^2\overline{A} - \mu\epsilon \frac{\partial^2 \overline{A}}{\partial t^2} = -\mu\overline{J} \quad \text{(Eq. 44)}$$

This is a nonhomogeneous wave equation for the magnetic vector potential. It is considered a wave equation because its solution represents waves traveling at a velocity $(\mu\epsilon)^{-1/2}$.

This particular form was found by choosing to use the magnetic vector potential. Similar wave equations may be found in terms of the electric scalar potential (Eq. 45), the magnetic field strength (Eq. 46) or the electric field intensity (Eq. 47).

$$\nabla^2 V - \mu\epsilon \frac{\partial^2 V}{\partial t^2} = -\frac{\rho}{\epsilon} \quad \text{(Eq. 45)}$$

$$\nabla^2\overline{H} - \mu\epsilon \frac{\partial^2 \overline{H}}{\partial t^2} = 0 \quad \text{(Eq. 46)}$$

$$\nabla^2\overline{E} - \mu\epsilon \frac{\partial^2 \overline{E}}{\partial t^2} = 0 \quad \text{(Eq. 47)}$$

The last two equations were obtained under source-free conditions and are therefore homogeneous wave equations for the magnetic field strength and electric field intensities respectively.

If phasors are used in Eqs. 46 and 47, instead of time dependent vectors, similar forms are obtained for wave equations where the time derivative is replaced by $j\omega$. Thus, the wave equations in Eq. 46 and 47 can be written as:

$$\nabla^2\overline{H} - k^2\overline{H} = 0 \quad \text{(Eq. 48)}$$

and

$$\nabla^2\overline{E} - k^2\overline{E} = 0 \quad \text{(Eq. 49)}$$

The constant k is defined as:

$$k = \omega\sqrt{\mu\epsilon} \quad \text{(Eq. 50)}$$

These equations are known as the *homogeneous Helmholz equations* and describe the harmonic form of the electromagnetic waves.

Skin Depth

In a linear isotropic material, after substitution of the constitutive relations in Eqs. 10 through 12 and using the vector identity in Eq. 25, Eqs. 1 and 2 become:

$$\nabla^2\overline{E} - \sigma\mu \frac{\partial \overline{E}}{\partial t} - \epsilon\mu \frac{\partial^2 \overline{E}}{\partial t^2} = 0 \quad \text{(Eq. 51)}$$

$$\nabla^2\overline{H} - \sigma\mu \frac{\partial \overline{H}}{\partial t} - \epsilon\mu \frac{\partial^2 \overline{H}}{\partial t^2} = 0 \quad \text{(Eq. 52)}$$

Thus, $\overline{E}$ and $\overline{B}$ satisfy identical wave equations with a damping (dissipative) term proportional to the conductivity and magnetic permeability of the material. In a good conductor such as most metals, the second order derivative may be neglected for low frequencies since it is due to the displacement current in Maxwell's second equation. For example, Eq. 52 becomes:

$$\nabla^2 \overline{H} - \sigma\mu \frac{\partial H}{\partial t} = 0 \qquad \text{(Eq. 53)}$$

These are simple diffusion equations. If an alternating magnetic field strength $H_0 \exp(j\omega t)$ or $E_0(j\omega t)$ is applied parallel to the surface of the conductor, the electric field intensity $\overline{E}$ or the magnetic field strength $\overline{H}$ is attenuated exponentially with distance below the surface. The attenuation is $\exp(-x/\delta)$ where x is the distance below the surface and δ is the *skin depth* given by:

$$\delta = \sqrt{\frac{2}{\sigma\mu\omega}} \qquad \text{(Eq. 54)}$$

This is an important factor to consider for alternating current magnetic particle testing because, even at 60 Hz, the skin depth can be quite small. For example, for a typical ferromagnetic material with a conductivity of $\sigma = 0.5 \times 10^7$, a relative permeability $\mu_r = 100$ and a frequency of 60 Hz, the skin depth δ is 3 mm. This is probably an overestimate because a linear material was assumed in the derivation.

For this reason, alternating current magnetic particle methods, such as the so-called *swinging field* methods, generally detect only discontinuities which are open to the surface. These methods are more sensitive to surface breaking discontinuities because the applied field is concentrated at the surface.

Electromagnetic Boundary Conditions

Electromagnetic fields behave differently in different materials. The constitutive relations in Eqs. 10 through 12 are a statement of this behavior. When different materials are present, the fields across the boundaries between these materials must undergo some changes to conform to both materials. In such cases, the field may experience a discontinuity at the boundary. In order to find the necessary conditions that apply at material boundaries, assume two different materials as in Fig. 3 and apply Maxwell's equations at the boundary. For convenience, the integral form is used. By doing so, the following four conditions are obtained:

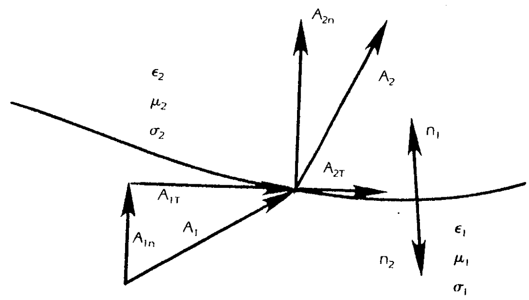
$$E_{1T} = E_{2T} \qquad \text{(Eq. 55)}$$

$$\hat{n} \times (H_{1T} - H_{2T}) = \bar{J}_s \qquad \text{(Eq. 56)}$$

$$\hat{n} \cdot (D_{1n} - D_{2n}) = \rho_s \qquad \text{(Eq. 57)}$$

$$B_{1n} = B_{2n} \qquad \text{(Eq. 58)}$$

FIGURE 3. Boundary conditions between two materials



The boundary conditions are the same for the magnetostatic and time varying fields. These conditions are summarized as follows:

1. The tangential component of the electric field intensity E and the normal component of the magnetic flux density B are continuous across the boundary.
2. The normal component of the electric flux density D and the tangential component of the magnetic field strength H are discontinuous across the boundary. The discontinuity depends on the existence of surface charges and currents. For situations where no such charges or currents exist, either component may be continuous, depending on the materials and the fields involved.

The four conditions presented in Eqs. 55 through 58 can be used in order to describe the fields in different materials and across their boundaries.

The four conditions are not entirely independent and should be specified with care. For example, in time varying fields, specification of the tangential component of $\overline{E}$ (Eq. 55) is equivalent to the specification of the normal component of B (Eq. 58). Similarly, specification of the tangential component of H is equivalent to that of the normal component of D. Only two of the four may be specified independently (the tangential component of $\overline{E}$ and the tangential component of $\overline{H}$ or any other acceptable combination). Over-specification of boundary conditions may result in contradiction of conditions and may therefore be in error.

The boundary conditions in Eqs. 55 through 58 were obtained by using Maxwell's equations directly. In order to render these relations more useful, it is convenient to introduce the constitutive relations in these conditions and find the interface conditions for some special classes of common materials. Two such groups of materials often found in practice are:

1. boundary conditions between two lossless media (a lossless medium is one that has zero conductivity with arbitrary permittivity and permeability; two perfectly insulating materials are considered here); and
2. boundary conditions between a lossless material and a good conductor.

At the boundary between two good insulators, no current densities and free charges are normally present. Thus, all four components in Eqs. 55 through 58 are continuous. These then can be rewritten using the constitutive relations in Eqs. 10 and 12 as:

$$\frac{D_{1\tau}}{D_{2\tau}} = \frac{\epsilon_1}{\epsilon_2} \quad \text{(Eq. 59)}$$

$$\frac{B_{1\tau}}{B_{2\tau}} = \frac{\mu_1}{\mu_2} \quad \text{(Eq. 60)}$$

$$\epsilon_1 E_{1n} = \epsilon_2 E_{2n} \quad \text{(Eq. 61)}$$

$$\mu_1 H_{1n} = \mu_2 H_{2n} \quad \text{(Eq. 62)}$$

At the interface between a good conductor and an insulator, both surface current densities and free charges may exist. The electric field is zero inside a perfect conductor and both the tangential component of the electric field and the normal component of the electric flux density must be zero inside the conductor. The boundary conditions then become:

$$E_{1\tau} = 0 \quad \text{(Eq. 63)}$$

$$\hat{n} \times (H_{1\tau} - H_{2\tau}) = \bar{J}_s \quad \text{(Eq. 64)}$$

$$\hat{n} \cdot D_{1n} = \rho_s \quad \text{(Eq. 65)}$$

$$B_{1n} = B_{2n} \quad \text{(Eq. 66)}$$

Note that while Eqs. 63 through 66 are correct for the static field, for the time varying field, both $\bar{B}$ and $\bar{H}$ must also be zero inside a perfect conductor. Thus, Eqs. 63 through 66 must be modified for the time varying case to:

$$E_{1\tau} = E_{2\tau} = 0 \quad \text{(Eq. 67)}$$

When $H_{2\tau} = 0$, then:

$$\hat{n} \times H_{1\tau} = \bar{J}_s \quad \text{(Eq. 68)}$$

When $D_{2n} = 0$, then:

$$\hat{n} \cdot D_{1n} = \rho_s \quad \text{(Eq. 69)}$$

$$B_{1n} = B_{2n} = 0 \quad \text{(Eq. 70)}$$

Note that the boundary conditions in Eqs. 67 through 70 only apply for perfect conductors. This rarely arises except for simplified problems and for superconductors. In the case of a superconductor, these boundary conditions are also correct for the static field.

Proper application of the field equations and imposition of the correct boundary conditions result in a correct solution to the field equations.

The Continuity Equation

Since charge cannot be destroyed or created, the only possible way to charge a body is through flow of charge from one point to another. This is stated mathematically by the continuity equation:

$$\nabla \cdot \bar{J} = -\frac{\partial \rho}{\partial t} \quad \text{(Eq. 71)}$$

This often neglected relation is fundamental to understanding field behavior and is responsible for two important aspects of electromagnetic fields: Kirchoff's current law and the linking of electric and magnetic quantities. Observing that the continuity equation is in fact a statement of the divergence of the current density, the displacement current term in Maxwell's equations is shown to be a statement of the continuity equation or preservation of charge. Ampere's law, before Maxwell's modification is:

$$\nabla \times \bar{H} = \bar{J} \quad \text{(Eq. 72)}$$

The divergence of the curl of a vector is zero (identically).

$$\nabla \cdot (\nabla \times \bar{H}) = 0 \quad \text{(Eq. 73)}$$

Thus, this equation can be written as:

$$\nabla \cdot (\nabla \times H) = \nabla \cdot \bar{J} + \frac{\partial \rho}{\partial t} = 0 \quad \text{(Eq. 74)}$$

From Gauss' law (Maxwell's third equation), this can be written as:

$$\nabla \cdot (\nabla \times \bar{H}) = \nabla \cdot \left(\bar{J} + \frac{\partial \bar{D}}{\partial t}\right) \quad \text{(Eq. 75)}$$

And the following is the correct form of Ampere's law:

$$\nabla \times \overline{H} = \overline{J} + \frac{\partial \overline{D}}{\partial t} \qquad \text{(Eq. 76)}$$

Note that this form is only necessary when both electric and magnetic quantities are present. The continuity equation need not be taken into account explicitly for purely electrostatic solutions because this implies static charges and therefore Eq. 71 is always satisfied implicitly. For direct current magnetic applications, Eq. 71 is again satisfied because any flow of charges is constant. The only time the equation needs to be introduced directly is when the displacement currents are large compared to conduction currents (at very high frequencies).

PART 4

EFFECT OF MATERIALS ON ELECTROMAGNETIC FIELDS

Material Properties and Constitutive Relations

Magnetic properties are important because of their effect on the behavior of materials under an external field (under active excitation) or when the external field is removed (residual magnetism). The magnetic properties are often discussed using the magnetic permeability of materials. This important quantity is defined through the constitutive relation in Eq. 10.

Permeability governs two important features of the magnetic field and therefore affects any application that uses the magnetic field. Flux density B is often the quantity of interest and has higher values for high values of the permeability for a given source field strength H. Secondly, the permeability also defines whether the field equation is linear or nonlinear.

The permeability of free space is $\mu_0 = 4\pi \cdot \times 10^{-7}$ H•m^{-1}. Other materials may have larger or smaller permeabilities. Table 4 lists the relative permeabilities of some important materials.

The magnetic properties of materials are defined through the interaction of external magnetic fields and moving charges in the atoms of the material (static charges are not influenced by the magnetic field since no magnetic forces are produced in Lorenz' law). Atomic scale magnetic fields are produced inside the material through orbiting electrons. These orbiting electrons produce an equivalent current loop that has a magnetic moment.

$$\overline{m} = \hat{z} I \pi a^2 \qquad \text{(Eq. 77)}$$

Where:

πa^2 = the area of the loop;
I = the equivalent current (see Fig. 4a); and
$\hat{z}$ = a unit vector normal to the plane of current flow.

Many such atomic scale loops or magnetic moments exist and the material volume contains a certain magnetic moment density. If N magnetic moments per unit volume are present, and if these moments are aligned in the same direction, a total magnetization is generated. The magnetization $\overline{M}$ is then given by:

$$\overline{H}_{in} = \overline{M} = N\overline{m} \qquad \text{(Eq. 78)}$$

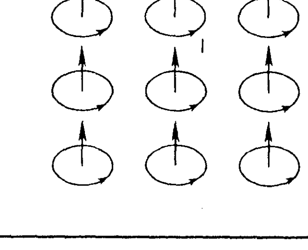
The magnetic flux density of the material is then given by:

$$\overline{B}_{in} = \mu \overline{M} \qquad \text{(Eq. 79)}$$

The terms $\overline{H}$, $\overline{m}$ and $\overline{M}$ are vectors. This implies that a net magnetic field or flux density can only exist if these vectors are aligned in such a way that a total net vector $\overline{M}$ exists. If the independent vectors $\overline{m}$ are randomly oriented, as is often the case, the net magnetization is zero.

For the purposes of this chapter, three types of magnetic materials are important: *diamagnetic*, *paramagnetic* and *ferromagnetic*.

FIGURE 4. Representation of material properties: (a) the field due to a current loop; and (b) current loops created by spinning electrons



Diamagnetic Materials

In these materials, the internal magnetic field due to electrons is zero under normal conditions. In an external magnetic field, an imbalance occurs and a net internal field opposing the external field is produced. Thus, $\overline{M}$ in Eq. 78 is negative with respect to the applied field. The magnetization is proportional to the external field through a quantity called the *magnetic susceptibility* of the material x_m.

$$\overline{M} = x_m \overline{H}_{ex} \qquad \text{(Eq. 80)}$$

In terms of the applied flux density, this becomes:

$$\overline{B} = \mu_o(1 + x_m)\overline{H}_{ex} \qquad \text{(Eq. 81)}$$

The magnetic permeability of any material can be written as:

$$\mu = \mu_o(1 + x_m) \qquad \text{(Eq. 82)}$$

In diamagnetic materials, the magnetic susceptibility is very small and negative. Its magnitude is usually on the order of 10^{-5}. The net effect is that the relative permeabilities exhibited by diamagnetic materials are slightly smaller than 1.0. This group of materials includes many familiar metals including pure copper and lead.

Under special conditions such as temperatures less than -150 °C, some materials may become superconducting. An ideal superconductor has a magnetic susceptibility of -1 and a permeability of 0. A superconductor expels magnetic flux (the Meissner effect) from its interior.

Paramagnetic Materials

This group of materials exhibits properties similar to diamagnetics except that the magnetic susceptibility is positive. In the presence of an applied magnetic field strength, the atomic magnetic dipole moments can align to form a net magnetic dipole density. The effect is still relatively small, producing observed relative permeabilities slightly larger than 1.0.

The permeability of paramagnetic materials remains constant over a large range of applied magnetic field strengths. Examples of materials in this group are air, aluminum and some stainless steels.

Ferromagnetic Materials

Ferromagnetic materials vary from diamagnetic and paramagnetic materials in two critical ways: (1) their susceptibility is very large; and (2) there is a pronounced variation in the internal structure of their magnetic moments. In these materials, many atomic moments are aligned in a certain direction within a very small region called a *magnetic domain*. Neighboring domains have a similar structure, with the net magnetic domain in one direction. In the demagnetized state, the magnetic domains tend to be aligned randomly, exhibiting a net internal field that is either very small or zero.

This domain model is depicted in Fig. 5. When an external magnetic field is applied, those domains that have

FIGURE 5. Domains in a ferromagnetic material: domain-8 is aligned with the field and will grow as $\overline{H}$ is increased; domain-3 is aligned against the field and will shrink as $\overline{H}$ is increased

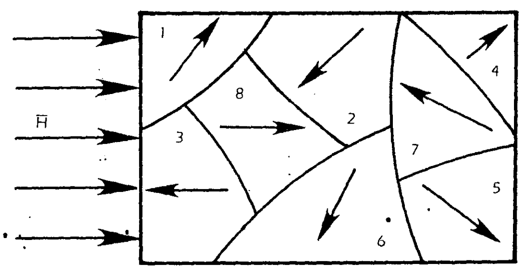


TABLE 4. Relative permeabilities for some materials; values given for ferromagnetic materials represent approximate maximum relative permeabilities

Type of Magnetic Material	Relative Permeability
Diamagnetic materials	
Gold	0.999964
Silver	0.99998
Copper	0.999991
Lead	0.999983
Water	0.999991
Mercury	0.999968
Bismuth	0.99983
Paramagnetic materials	
Vacuum	1.0
Air	1.00000036
Aluminum	1.000021
Ferromagnetic materials	
Cobalt (99 percent annealed)	250
Nickel (99 percent annealed)	600
Iron (99.8 percent annealed)	6,000
Iron (99.95 percent annealed in hydrogen)	2.0×10^5
Supermalloy™ (annealed, controlled cooling)	1.0×10^6
Steel (0.9 percent carbon)	100
Iron (98.5 percent, cold rolled)	2,000

a net field aligned in the direction of the applied field grow in size while the other domains shrink. The internal field and the external field H are aligned in the same direction producing a larger total flux density B. The above argument is related to the hysteresis curve of a ferromagnetic material and explains why any such curve has a saturation region: beyond a certain field, all the magnetic domains are aligned with the field and an increase in the magnetic field strength cannot increase the net magnetization. Materials typical of this group are iron, steels, nickel and some stainless steels. Table 4 summarizes some of the more important ferromagnetic materials and their permeabilities. Table 5 lists conductivities of various materials and Table 6 is a listing of dielectric constants.

As is evident from any hysteresis curve, the permeability of ferromagnetic materials is not constant but varies with the field. This is exhibited through the slope of the initial magnetization curve to which the permeability is tangent. Thus, most ferromagnetic materials are highly nonlinear materials.

TABLE 5. Conductivities of some materials

Material	Conductivity (siemens per meter)
Silver	6.1×10^7
Copper (100 percent IACS)	5.8×10^7
Gold	4.1×10^7
Aluminum	3.5×10^7
Tungsten	1.8×10^7
Brass	1.1×10^7
Iron (pure)	1.0×10^7
Soft steel	0.8×10^7
Carbon steel (1 percent carbon)	0.5×10^7
18-8 stainless steel	1.4×10^6
Nichrome	0.9×10^6
Mercury	1.0×10^6
Graphite	1.0×10^5
Carbon	3.0×10^4
Germanium	2.3
Sea water	4.0
Silicon	3.9×10^{-4}
Bakelite™	1.0×10^{-9}
Glass	1.0×10^{-12}
Rubber	1.0×10^{-13}
Mica	1.0×10^{-15}
Quartz	1.0×10^{-17}

TABLE 6. Dielectric constants (relative permittivities) for some materials

Material	Relative Permittivity
Vacuum	1
Air	1.0006
Rubber	3
Paper	3
Bakelite™	5
Quartz	5
Glass	6
Mica	6
Water	81
Barium titanate	1,200
Barium strontium titanate	10,000

PART 5
MAGNETIC CIRCUITS AND HYSTERESIS

Magnetic Circuits

The two equations that define the static magnetic field are Eq. 14 and Eq. 16. These are written below both in differential and integral form in terms of $\overline{B}$:

$$\nabla \times \overline{B} = \mu \overline{J} \qquad \text{(Eq. 83)}$$

$$\nabla \cdot \overline{B} = 0 \qquad \text{(Eq. 84)}$$

$$\oint_c \overline{B} \cdot \overline{d\ell} = \mu I \qquad \text{(Eq. 85)}$$

$$\oint_s \overline{B} \cdot \overline{ds} = 0 \qquad \text{(Eq. 86)}$$

These are Ampere's and Gauss' laws for the static field. They can also be viewed as defining a vector quantity $\overline{B}$ through its curl and divergence.

The line integral of the magnetic field strength around a closed path is defined as a *magnetomotive force* (or magnetomotance):

$$V_m = \oint_c \overline{H} \cdot \overline{d\ell} = NI \qquad \text{(Eq. 87)}$$

The units of the magnetomotive force are customarily expressed as *ampere-turns* although the correct unit is the *ampere*. The modification from I to NI simply states that, if the total current inside the closed contour is divided into N wires, then the number of turns may be used for convenience.

The Use of Circuit Theory

A magnetomotive force $V_m = NI$ causes a magnetic flux Φ to exist within the closed contour mentioned in Eq. 87. If for any reason this flux is contained within a material, it may be assumed that a flux flows within the material. This concept allows flux to be treated much the same way as current and therefore circuit theory concepts may be used for the solution of some specific field problems.

To develop this concept, it is convenient to use a toroid (Fig. 6). The gap is assumed to be small and the flux densities inside the toroid and the gap are assumed to be the same. This in effect neglects any fringing effects in the gap. If the field strength is denoted in the gap as H_g and in the toroid as H_ℓ, then the fields can be calculated in terms of the flux density B_ℓ in the toroid and the permeabilities of the gap and the toroid (μ_0 and μ) as:

$$H_\ell = \frac{B_\ell}{\mu} \qquad \text{(Eq. 88)}$$

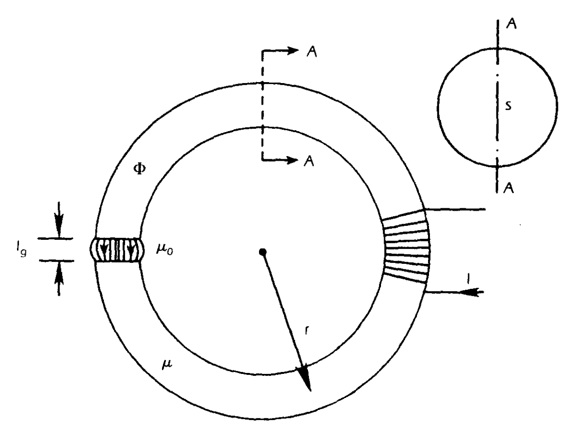
and

$$H_g = \frac{B_\ell}{\mu_o} \qquad \text{(Eq. 89)}$$

By substituting these in Eq. 87, the magnetic flux density is found to be related to the lengths of the gap (ℓ_g) and the length of the material in the toroid ($2\pi r - \ell_g$) where r is the mean radius of the toroid:

$$B_\ell = \frac{\mu_o \mu NI}{\mu_o(2\pi r - \ell g) + \mu \ell g} \qquad \text{(Eq. 90)}$$

FIGURE 6. A toroid with an air gap used to define the magnetic circuit concept



If it is assumed that the magnetic flux density is uniform within a material (it is uniform inside a toroid but rarely in other shapes), the flux can be calculated as:

$$\Phi = Bs \qquad \text{(Eq. 91)}$$

The total flux through the toroid or the gap is therefore:

$$\Phi = \frac{NI}{\dfrac{2\pi r - \ell g}{\mu s} + \dfrac{\ell g}{\mu_o s}} \qquad \text{(Eq. 92)}$$

Written in terms of the magnetomotive force V_m, the equation for the flux can be written as:

$$\Phi = \frac{V_m}{R_\ell + R_g} \qquad \text{(Eq. 93)}$$

where

$$R_\ell = \frac{\ell_\ell}{\mu s} \qquad \text{(Eq. 94)}$$

and

$$R_g = \frac{\ell g}{\mu_o s} \qquad \text{(Eq. 95)}$$

The forms of Eq. 94 and 95 are analogous to that of the direct current resistance ($R = \rho\ell/a$) and are therefore called *magnetic resistances* or *reluctances*. The reluctance of the gap is R_g and R_ℓ is the reluctance of the material in the toroid. The units for reluctance are 1 per henry ($1 \cdot H^{-1}$). Similarly, if magnetomotive force is considered analogous to voltage and flux analogous to current, Eq. 93 is analogous to Ohm's law.

For any closed magnetic path, the equation can be written as:

$$\sum_i N_i I_i = \sum_j R_j \Phi_j \qquad \text{(Eq. 96)}$$

Similarly, by using the divergence of the magnetic flux density $\nabla \cdot B = 0$, the law for a junction is:

$$\sum_i \Phi_i = 0 \qquad \text{(Eq. 97)}$$

For simplicity, an analogous magnetic circuit can be defined as in Fig. 7. Because of its simplicity, this approach has found considerable use in many areas, especially in devices with closed paths (transformers and machines). The approach is quite limited in scope because of the approximations used to derive the concept. First, the fringing effects cannot be neglected for large air gaps. Second, there are always some leakage fields that cannot be taken into account. Finally, the permeability has been assumed to be constant. In most cases of practical importance, the permeability of a material is field dependent (Eq. 98).

Hysteresis

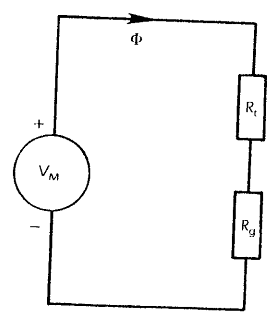
The constitutive relation between the magnetic field strength and the magnetic flux density is shown in Eq. 10. The behavior of the field within different materials has been described above. However, these do not describe all phenomena that exist within materials.

Inspecting Eq. 10 shows that by increasing the magnetic field strength H, the flux density B increases by a factor of μ. However, for ferromagnetic materials, Eq. 10 must be written as a nonlinear equation:

$$\overline{B} = \mu(H)\overline{H} \qquad \text{(Eq. 98)}$$

An alternative way to look at this phenomenon is to inspect the domain behavior of a ferromagnetic material. Initially, the domains are randomly oriented. As the applied

FIGURE 7. Equivalent magnetic circuit representation



field increases, domains begin to grow by displacing other domains and eventually occupying most of the material volume. Any further increase of the field has little effect on the domains and therefore has little effect on the flux density in the material; thus the permeability depends strongly on the applied field.

Magnetization Curves

A plot of the relation in Eq. 98 describing the flux density as a function of the field strength is a useful way to look at magnetic materials. For linear materials (materials for which the permeability is constant at any field value), this curve is a straight line whose slope is equal to the permeability. Ferromagnetic materials behave differently. The curves in Fig. 8 describe the behavior of iron. Initially, the applied field strength is zero and so is the flux density.

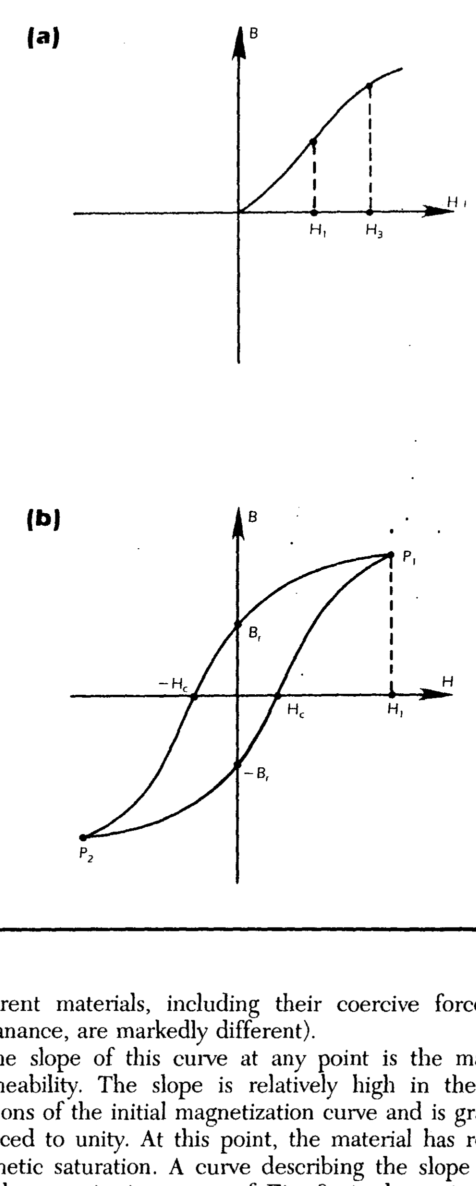
As the field is increased, the flux density also increases but, unlike linear materials, the curve is not linear. At some field value H_1, the curve starts bending and the slope of the curve is reduced significantly. Any increase beyond the field H_3 increases the flux density but not at the same rate as at lower points on the curve. In fact, the slope in this section of the curve approaches unity, meaning that the relative permeability approaches 1. This region is called *saturation* and is dependent on the material tested. The whole curve described in Fig. 8a is called a *magnetization curve*. Since it starts with zero applied field it may also be called an *initial magnetization curve*.

Hysteresis Curves

Reducing the applied field moves the curve to the left, rather than retracing the initial magnetization curve (Fig. 8b). The flux density is reduced up to the point B_r where the applied field is zero. This residual flux is called *remanance* or *retentivity* and is typical of all ferromagnetic materials. Applying a reverse magnetic field further reduces the flux density up to the point H_c where an applied field strength exists without an associated flux density. The field strength at this point is called the *coercivity* or the *coercive force* of the material. Further increase in the negative field strength traces the magnetization curve through point P_2 where a saturation point has again been reached, except that in this case the field strength and the flux density are negative.

If the applied field is decreased to zero, a point symmetric to B_r is reached. Similarly, by increasing the applied field strength to a value equal (but positive) to H_c, the flux density is again zero. Further increase in the field strength brings it back to the point P_1. Repeating the process described above results in a retracing of the outer curve but not that of the initial magnetization curve. This unique magnetization curve is called the *hysteresis curve* and is typical of all ferromagnetic materials (hysteresis curves of different materials, including their coercive forces and remanance, are markedly different).

FIGURE 8. Hysteresis curve: (a) the initial magnetization curve and (b) the hysteresis curve



The slope of this curve at any point is the magnetic permeability. The slope is relatively high in the lower portions of the initial magnetization curve and is gradually reduced to unity. At this point, the material has reached magnetic saturation. A curve describing the slope of the initial magnetization curve of Fig. 8a is shown in Fig. 9. Figure 9 shows that for this material (iron), the initial relative permeability is low, increases gradually and then, as the field approaches saturation, decreases and approaches 1.

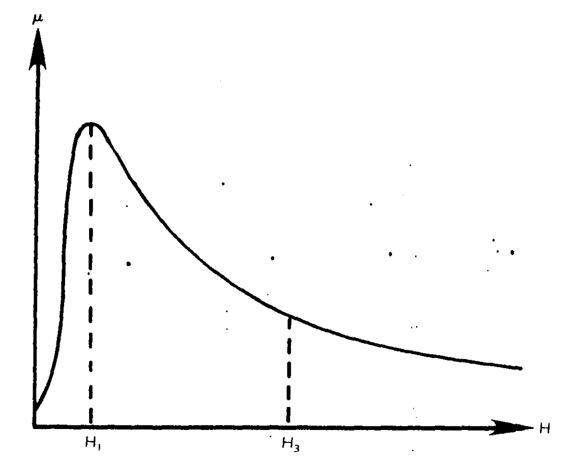
The hysteresis curve in Fig. 8b has four distinct sections described by the four quadrants of the coordinate system.

Particularly important are the first and second. The curve in the first quadrant is created by an applied field or source and is therefore called a *magnetization curve*. In particular, the initial magnetization curve can only be described by starting with an unmagnetized sample of the material and then increasing the field within the material. This section of the curve is referred to as the active part of the curve. All direct current applications of magnetic particle testing that depend on active magnetization are governed by this section of the curve.

The second quadrant (with the limits at B_r and H_c) is called the *demagnetization curve*. It is important for two reasons. First, any magnetic material, after being magnetized, relaxes to the point B_r or more commonly to a point in the second quadrant. Secondly, this is the quadrant in which permanent magnets operate. The coercivity and remanance of ferromagnetic materials are very different from each other and define to a large extent the classification of magnetic materials. The coercivity and remanance of some important materials are shown in Table 7.

The area under the hysteresis curve represents energy. This is understood by referring to the Poynting theorem. In devices such as transformers, this is a detrimental property because the energy is dissipated, primarily in the magnetic core of the device. In other cases, including permanent magnets or switching magnetic devices, this property is useful.

FIGURE 9. Initial permeability curve for iron



Magnetization

In order to magnetize a sample, it is necessary to apply a magnetic field to the sample. The form in which this field is applied may vary depending on practical considerations but the same basic effect must be obtained: the field in the sample must be increased to a required value.

In general, if a sample is initially demagnetized, the field is gradually increased through the initial magnetization curve to a required point. If a residual method is being used, the field is reduced to zero and the material relaxes to a point in the second quadrant of the hysteresis loop. For previously magnetized samples, it is usually better to demagnetize the sample first and then to magnetize it to the required point.

Demagnetization

The hysteresis curve indicates that when the source of a field is reduced to zero, there is a remanant flux density in the material. This remanant or residual field is sometimes used for testing purposes but in many cases it is desirable to

TABLE 7. Coercivity and remanence of some important materials; figures for H_c and B_r are approximate and are strongly dependent on thermoelectrical history

	Coercive Force H_c (amperes per meter)	Remnant Flux Density B_r (weber per square meter)	Saturation Flux Density B_s (weber per square meter)
Soft magnetic materials			
Iron (pure annealed)	100	1.2	2.16
Supermalloy™	0.2	10^{-4}	0.8
Steel (0.9 percent carbon, hot rolled)	4,000	1.0	2.0
Silicon iron (4 percent silicon)	20	0.5	1.95
Ni-Zn ferrite	16	0	0.34
Hard magnetic materials			
Carbon steel (0.9 percent carbon)	4,000	1	
Alnico V	44,000	1.2	
Alnico VIII	126,000	1.04	
Samarium cobalt	560,000	0.84	

demagnetize a test object before a controlled field is applied or to demagnetize it after a test.

Demagnetization cannot be achieved simply by creating a field opposing the original source field. The demagnetization process is complicated by shape effects that usually cause different operating points to exist in different sections of the material (see the curve in Fig. 8).

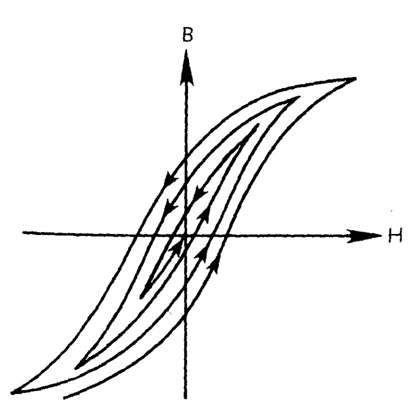
Effective demagnetization of materials can be achieved by heating the material beyond the Curie temperature and then cooling it in a zero field environment. Under most circumstances, this method is impractical because of the metallurgical effects associated with it.

A practical demagnetization approach is to cycle the material through the hysteresis curve while gradually reducing the magnetic field strength to zero. The effect is shown in Fig. 10. If started with a high enough field strength and reduced slowly, this procedure results in a properly demagnetized sample. In practice, demagnetization is performed by applying an alternating current field and gradually reducing its amplitude to zero. Complete demagnetization is usually a very time consuming process. In practical situations, it is usually limited to reducing the flux density to some acceptable level.

Minor Hysteresis Loops

It often happens while a sample is at some operating point on the hysteresis curve (either on the initial magnetization curve or on the outer loop) that a relatively small change in magnetization occurs. An example of this is a large direct current corresponding to a point on the hysteresis curve and a small alternating current superimposed on it.

FIGURE 10. Demagnetization of ferromagnetic materials



Alternatively, if the magnetizing current is suddenly decreased and then increased again, the same effect is created. This situation results in a change in the hysteresis curve as shown in Fig. 11. Thus, a small oval curve similar to the hysteresis curve is described at the initial point. These loops are called *minor hysteresis loops* to distinguish them from the normal (or major) hysteresis loop. Since permeability is defined as the ratio of $\overline{B}$ and $\overline{H}$, the permeability of a minor loop may be defined as $\Delta B/\Delta H$:

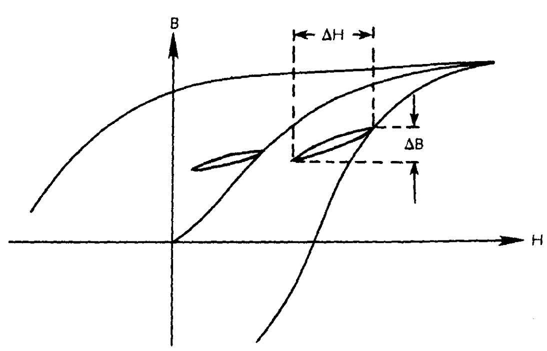
$$\mu_{inc} = \frac{\Delta B}{\Delta H} \qquad \text{(Eq. 99)}$$

Also called an *incremental permeability*, this quantity depends on the location of the minor curve on the hysteresis and decreases as the normal magnetization increases. The slope of minor loops is always smaller than that of the major loop at a given point. Thus, the incremental permeability is lower than the normal permeability at any point on the hysteresis curve. As the material approaches saturation, the relative incremental permeability approaches unity.

Hysteresis Curve as a Classifier

When applying electromagnetic fields, it is necessary to distinguish between applications, specialties and frequency ranges. For example, electromagnetic nondestructive testing is classified as a discipline separate from palaeomagnetism (terrestrial magnetism), even though exactly the same principles are involved and, often, the same methods are used. Moreover, within each discipline different applications are distinguished.

FIGURE 11. Major and minor hysteresis loops



In nondestructive testing, *active leakage field*, *residual leakage field*, *eddy current* and other electromagnetic phenomena are used. This distinction helps focus the treatment of different problems. Often, the distinction parallels that of the various areas of electromagnetic fields: active leakage fields are associated with magnetostatics; residual leakage fields with source-free magnetostatics; and eddy currents with steady state alternating current fields.

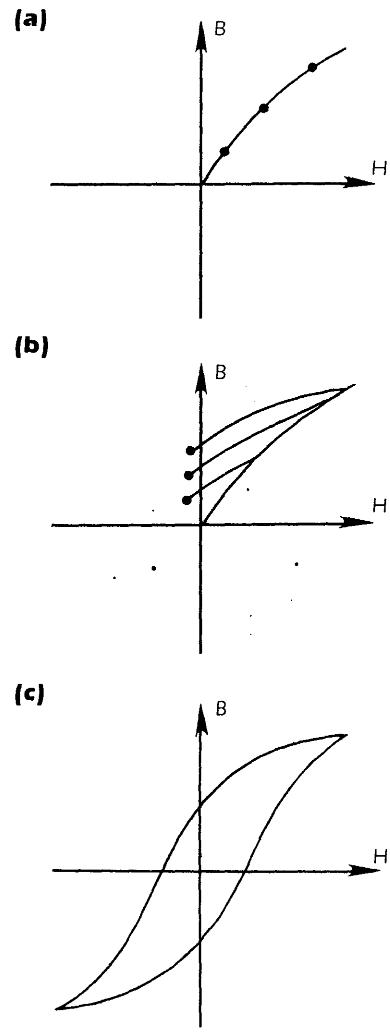
It is far more practical to distinguish between the various applications based on the point of operation on the hysteresis curve. This offers a visual description as well as some physical insight into the application.

Active leakage field methods are those that employ the initial magnetization curve (Fig. 12a). The point on the initial magnetization curve is obtained by increasing the current from zero to some predetermined value. It is possible to apply a field to an initially magnetized sample but this is usually not done because of the difficulty in determining the exact operating point.

Residual leakage fields are obtained when an active excitation is removed and the operating points of the material are allowed to relax into the second quadrant (Fig. 12b). Similarly, alternating current leakage methods may be defined as those that employ a normal hysteresis curve. The operating point is on the major loop (Fig. 12c).

Eddy current methods require alternating current excitation but this is usually very low. In terms of the hysteresis curve, it may be said that the operating point is at the origin although small hysteresis loops are described around the origin as in Fig. 12c.

FIGURE 12. Classification of testing methods: (a) active leakage fields (direct current); (b) residual leakage fields; and (c) alternating current operation



Energy Lost in a Hysteresis Cycle

The energy stored in the magnetic field is given as a volume integral of an energy density w:

$$W = \int_v w dv \qquad \text{(Eq. 100)}$$

After integrating over the hysteresis curve or over any part of it, the area under the curve may be written as:

$$w = \int_0^B H dB \qquad \text{(Eq. 101)}$$

The units of this integral are those of a volume energy density and, under linearity assumptions ($dB = dH$), the energy density becomes $w = \mu H^2/2$. If this is then integrated over the volume of material in which the magnetic field exists, the total work done by external sources can be written as:

$$W = \int_v \left(\int_0^B H dB \right) dv \qquad \text{(Eq. 102)}$$

The fact that energy is transformed in the process becomes apparent by considering that work needs to be performed in order to change the magnetic field in the volume of a material. The expression in Eq. 102 is the work done for a complete cycle over the hysteresis loop. If the field changes at a certain frequency, the energy per cycle in Eq. 102 must be multiplied by the frequency to obtain:

$$P_d = Wf \qquad \text{(Eq. 103)}$$

This equation is exact but of limited use because it requires integration over the hysteresis loop. Being a complex function and in many cases only known experimentally, the hysteresis loop is difficult to integrate. For practical purposes, an approximate expression in terms of the maximum induced flux density B_{max} is often used. The dissipated power is:

$$P_d = \eta f B_{max}^{1.6} \qquad \text{(Eq. 104)}$$

This expression is credited to Charles Steinmetz and assumes that the constant η is known. It ranges from 0.001 for silicon steels to about 0.03 for hard steels. It is an experimental value and the equation is only correct for relatively large saturation fields (above 0.1 T). For low saturation flux densities, the equation cannot be used.

Eddy Current Losses

In addition to hysteresis losses, the change in flux density inside conducting materials generates induced electromagnetic forces in those materials. The existence of this electromagnetic force, and the relatively large conductivity of most metals, results in a relatively large current flowing inside the material in a path that is a mirror image of the source generating the field. It is difficult to calculate the eddy current generated for any particular situation but the relative quantity involved is easy to obtain.

For any conductor, the electric field due to the induced electromagnetic force is directly proportional to the magnetic field as:

$$\overline{E} \propto \frac{d\overline{B}}{dt} \propto f\overline{B} \qquad \text{(Eq. 105)}$$

The dissipated energy due to heating losses (I^2R) is related to the square of the electric field. In terms of Eq. 105 and the magnetic field, this becomes:

$$\sigma E^2 \propto \sigma f^2 B^2 \qquad \text{(Eq. 106)}$$

This relation clearly indicates that the losses due to eddy currents can be very large, especially for large flux densities and higher frequencies. Eddy current losses may be reduced by: (1) reducing the conductivity of the materials involved (ferrites); (2) by special alloying to produce very narrow hysteresis curves (silicon steels); and (3) by breaking the eddy current paths (laminated cores).

The total losses in magnetic materials due to hysteresis and eddy current losses can be summarized in terms of the actual field as:

$$P_d = Nf + k\frac{B^2 f^2}{\rho} \qquad \text{(Eq. 107)}$$

In terms of the saturation flux density B_{max}, total losses may be written as:

$$P_d = k_1 f B_{max}^{1.6} + k_2 f^2 \frac{B_{max}^2}{\rho} \qquad \text{(Eq. 108)}$$

The constants k, k_1 and k_2 depend on geometry as well as on material properties.

PART 6

CHARACTERISTICS OF ELECTROMAGNETIC FIELDS

Energy in the Electromagnetic Field

In order to examine the energy in a magnetic field it is convenient to look first at the general time dependent expression for energy. This expression includes stored magnetic energy, stored electric energy and dissipated energy. The following vector identity is used:

$$\nabla \cdot (\overline{E} \times \overline{H}) = \overline{H} \cdot \nabla \times \overline{E} - \overline{E} \cdot \nabla \times \overline{H} \quad \text{(Eq. 109)}$$

Into this expression, a substitution is made: the expression for the curl of $\overline{E}$ and $\overline{H}$ from Maxwell's first and second equations.

$$\nabla \cdot (\overline{E} \times \overline{H}) = -\overline{H}\frac{\partial \overline{B}}{\partial t} - \overline{E} \cdot \frac{\partial D}{\partial t} - \overline{E} \cdot \overline{J} \quad \text{(Eq. 110)}$$

Assuming the energy flow in a volume v bounded by an area s, it is then possible to integrate this expression over the volume v. Before this, transform the left side from a volume integral to an area integral using the divergence theorem (Eq. 168).

$$\oint_s (\overline{E} \times \overline{H}) \cdot \overline{ds} = -\frac{\partial}{\partial t}\int_v \left(\frac{\overline{H} \cdot \overline{B}}{2} + \frac{\overline{E} \cdot \overline{D}}{2}\right) dv - \int_v \overline{E} \cdot \overline{J} dv \quad \text{(Eq. 111)}$$

The left side of the expression represents the total flow of energy through the area bounding the volume. The expression $\overline{E} \times \overline{H}$ is a power density with units of W•m^{-2}. The power density is called a *Poynting vector*.

$$P = \overline{E} \times \overline{H} \quad \text{(Eq. 112)}$$

The advantage of such an expression is that it also indicates the direction of the energy flow, information that is important for wave propagation calculations.

The first term on the right side of Eq. 111 represents the time rate of increase in the potential or stored energy in the system. It has two components: the stored electric energy and the stored magnetic energy. These energy densities reduce to simpler expressions for the static electric and magnetic fields.

$$w_e = \frac{\epsilon E^2}{2} \quad \text{(Eq. 113)}$$

$$w_m = \frac{\mu H^2}{2} \quad \text{(Eq. 114)}$$

The second term at the right side of Eq. 111 is the power dissipated and the power due to sources that may exist in the volume v. If no such sources exist, this term represents ohmic losses.

The Poynting theorem describes all of a system's energy relations: electrostatic, magnetostatic or time dependent. Because the cross product between the electric field and the magnetic field is taken, these two quantities must be related, otherwise the results have no meaning.

The expression in Eq. 111 is an instantaneous quantity. For practical purposes, a time averaged quantity is more useful. This can be done by averaging over a time T (usually a cycle of the alternating current field).

$$P_{av} = \frac{1}{T}\int_0^T P(t)dt \quad \text{(Eq. 115)}$$

Force in the Magnetic Field

The force in the magnetic field is governed by Lorenz' force equation given in Eq. 9. For the purposes here, the electric force (Coulomb's law) $\overline{F}_e = q\overline{E}$ is not important and was removed from Lorenz' equation. This in effect assumes that the charge q only experiences a magnetic force:

$$\overline{F} = q(\overline{v} \times \overline{B}) \qquad \text{(Eq. 116)}$$

Here, $\overline{v}$ is the velocity of the charge.

While forces on charges are important in themselves, the force on current carrying conductors is more important in conjunction with magnetic fields. If it is assumed that an element of conductor $d\ell$, with a cross sectional area s carries N charge particles per unit volume moving with an average velocity v, then the magnetic force that this conductor experiences is:

$$d\overline{F} = Nqs|v|\overline{d\ell} \times B \qquad \text{(Eq. 117)}$$

Since $Nqs\overline{u}$ is the total current in the conductor, the magnetic force becomes:

$$d\overline{F} = I\overline{d\ell} \times \overline{B} \qquad \text{(Eq. 118)}$$

In order to obtain the force due the complete conductor, integration is taken over the length of the conductor.

$$\overline{F} = I \oint_c \overline{d\ell} \times \overline{B} \qquad \text{(Eq. 119)}$$

Another important consideration is that of the force exerted on a current carrying conductor due to the field of a second conductor. This is treated by assuming that the field B is due to one conductor. If there are two conductors, the force on conductor-1 due to the field of conductor-2 is:

$$F_{21} = \frac{\mu}{4\pi} I_1 I_2 \oint_{c1}\oint_{c2} \frac{\overline{d\ell}_1 \times (\overline{d\ell}_2 \times \hat{R}_{21})}{R_{21}^2} \qquad \text{(Eq. 120)}$$

Similarly, the force on conductor-2 due to conductor-1 is:

$$F_{12} = \frac{\mu}{4\pi} I_2 I_1 \oint_{c2}\oint_{c1} \frac{\overline{d\ell}_2 \times (\overline{d\ell}_1 \times \hat{R}_{12})}{R_{12}^2} \qquad \text{(Eq. 121)}$$

In these equations, the integration is assumed to be over the entire (closed) path of the currents. This is not merely a convenience but is required to ensure that the forces $\overline{F}_{12}$ and $\overline{F}_{21}$ are equal and opposite in direction. In other words, integration over part of the contours will violate Newton's third law (action and reaction forces).

Forces in the magnetic field may also be expressed in terms of the energy stored in the magnetic field. A system's mechanical work is done at the expense of its potential energy, so that:

$$\overline{F} \cdot \overline{d\ell} = -(\nabla\omega) \cdot \overline{d\ell} \qquad \text{(Eq. 122)}$$

The force due to this reduction in the stored energy is therefore:

$$\overline{F} = -\nabla\omega \qquad \text{(Eq. 123)}$$

This expression for the force is particularly convenient when the actual current distributions are not known or are too complicated to permit calculation of the flux densities of each current separately.

Because the magnetic field energy may be expressed in terms of inductances (see Eq. 131), the force in the magnetic field may also be expressed in terms of inductances. Thus, for example, the force between two conductors carrying currents I_1 and I_2, having inductances L_1, L_2 and mutual inductance L_{12} can be written as:

$$\overline{F} = I_1 I_2(\nabla L_{12}) \qquad \text{(Eq. 124)}$$

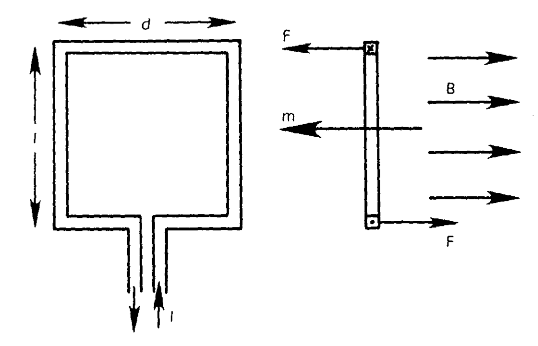
The stored energy is calculated as:

$$W = \frac{1}{2}L_1 I_1^2 + L_{12}I_1 I_2 + \frac{1}{2}L_2 I_2^2. \qquad \text{(Eq. 125)}$$

Torque in the Magnetic Field

The torque on a current carrying system may be calculated by using the definition of torque: the product of force and the moment arm length. For simplicity, consider the

FIGURE 13. A rectangular loop and the direction of the forces and torque on the rotating loop



square loop in Fig. 13. If this definition is used, the torque is equal to:

$$\overline{T} = \hat{s}IsB \sin\theta \qquad \text{(Eq. 126)}$$

where s is the area of the loop. The product of current and area is defined as a magnetic moment m.

$$\overline{m} = I\overline{s} \qquad \text{(Eq. 127)}$$

The magnetic moment has a direction normal to the area s and in the direction described by the right hand rule. Thus, torque is a vector quantity and can be written as:

$$\overline{T} = \overline{m} \times \overline{B} \qquad \text{(Eq. 128)}$$

Inductance

Inductance is a property of the arrangement of conductors in a system. It is a measure of the flux linked within the a measure of the magnetic energy stored in the system of conductors. Flux linkage is defined as the flux that links the whole system of conductors, multiplied by the number of conductors or turns in the system. For a simple solenoid, this is defined as:

$$\Lambda = N\Phi = N\int_s \overline{B} \cdot \overline{ds} \qquad \text{(Eq. 129)}$$

In effect, this includes only the flux that passes through the center of the solenoid. The integration is over the cross sectional area of the solenoid. A more complicated definition can be used, one that includes flux linkages that do not link all the conductors, but this has little practical use because of the difficulties in calculation.

If the system under consideration is linear, the field is directly proportional to the current and the inductance of a system (coil) may be defined as the ratio of the flux linkage and the current. The unit of measure for inductance is the henry (H).

$$L = \frac{N\int_s \overline{B} \cdot \overline{ds}}{I} \qquad \text{(Eq. 130)}$$

The inductance in Eq. 130 can be calculated, provided that the flux linkages can be obtained. In many practical situations, it is more convenient to use an energy relation.

$$W = L\frac{I^2}{2} \qquad \text{(Eq. 131)}$$

PART 7
MODELING ELECTROMAGNETIC FIELDS

Modeling of Leakage Fields

Modeling of leakage fields can take many forms. Indeed, any attempt to explain a phenomenon may constitute a model. It is customary to refer to a model as a process by which a particular problem or set of problems may be solved and, with the solution, gain some insight into the processes and interactions involved. The more general the model, the more useful it becomes and the wider its application is likely to be.

Because of the importance of leakage fields in a variety of applications, including magnetic particle testing, their modeling has received considerable attention. It is important to remember that an air gap, regardless of application, gives rise to leakage fields. Modeling of leakage fields comprises three categories: (1) experimental or empirical modeling; (2) analytical modeling; and (3) numerical modeling.

When a process is classified, there is a temptation to assign values to different methods. No such claims are made here. The various methods of modeling are presented and only their usefulness is stressed.

Nature of the Leakage Field

As a first approximation, leakage fields around discontinuities may be considered to be superpositions of dipolar fields. It is therefore of interest to present a simple model that illustrates the nature of such a field. Consider a discontinuity in the shape of a long cylinder with its axis parallel to the surface, its center a distance h below the surface and with the applied magnetic field strength H_0 parallel to the surface and perpendicular to the cylinder axis. This situation is illustrated in Fig. 14.

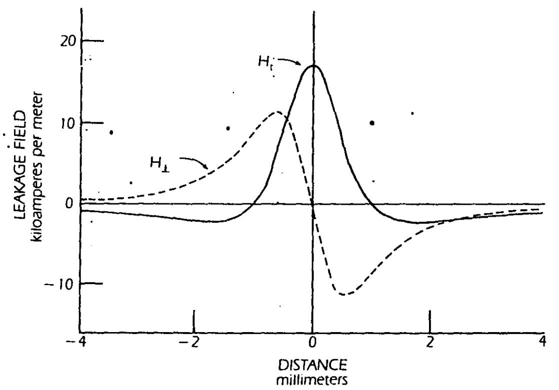
The discontinuity is assumed to be in a material with a permeability of μ_1. The leakage field at the surface above the discontinuity is the point of interest. It has been shown[6] that the leakage field is closely approximated by a dipole field. The tangential and normal (perpendicular) components of the field at the surface can be written as:

$$H_t = m \frac{h^2 - x^2}{(h^2 + x^2)^2} \qquad \text{(Eq. 132)}$$

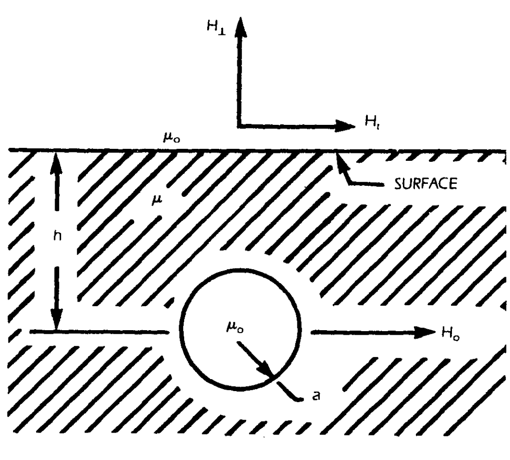
$$H_\perp = -2m \frac{hx}{(h^2 + x^2)^2} \qquad \text{(Eq. 133)}$$

FIGURE 14. Magnetic leakage field over distance for (a) the tangential and normal (perpendicular) components of the leakage field from a cylindrically shaped discontinuity (the numerical quantities shown are for $\mu \gg \mu_0$, a = 1 mm, h = 1 mm and H_0 = 6.4 kA•m^{-1}); and (b) the geometry of the test arrangement

(a)



(b)



Where:

x = the distance along the surface in the direction of the applied field; and
m = is a magnetic dipole moment (per unit length).

Assuming that $\mu \ll \mu_0$, then m is given by:

$$m = 2H_0 a^2 \quad \text{(Eq. 134)}$$

The shape and magnitude of these field components are illustrated in Fig. 14. Note that the tangential component of the field is a maximum just above the discontinuity, whereas the perpendicular component is zero at the same location. Although the leakage field illustrated in Fig. 14 is for an idealized case, a linear magnetic material and a simple geometrical shape for the discontinuity, real leakage fields have shapes that look like a distortion of the leakage field shown in Fig. 14.

The magnitude of the leakage field is nearly independent of permeability, provided that this is much greater than μ_0. While this is the case for nearly all ferromagnetic materials, such materials are not linear. The effect of a nonlinear magnetic material on the leakage field can be explored through experimentation or through numerical modeling.

Large but slowly varying *bias fields* may be added to the leakage fields. For example, the tangential field has the added value H_0 because of the boundary conditions on the tangential field component. For a nonparallel (to the surface) field strength, the magnetizing field strength may also have a normal component resulting in a bias field in that direction.

The Leakage Field's Role in Formation of Magnetic Particle Testing Indications

In magnetic particle testing, discontinuities are detected by the indications formed when magnetic particles are attracted to leakage fields caused by discontinuities. The formation of such an indication is a complex process and has thus far been difficult to model realistically.

Particles of the size used in magnetic particle testing are affected in their motion by the following: (1) gravitational forces; (2) viscous forces; (3) leakage field forces; (4) exciting field forces; (5) image forces; and (6) interactions between particles.

Viscous forces include those due to the motion of the medium in which the particle is suspended. Image forces are the attraction of the magnetized particle to its electrical image in the material being tested. Particle interactions are very important and depend on (1) particle shape; (2) magnetization; (3) surface tension; and (4) the number of particles per unit volume.

A small magnetic particle of approximately spherical shape can be characterized by diameter d, density ρ and a dipole moment $\overline{m}$. The energy W of this dipole in a magnetic field strength $\overline{H}$ is given by:

$$W = -\mu_0 \overline{m} \cdot \overline{H} \quad \text{(Eq. 135)}$$

The magnetic force on this dipole is the negative gradient of the energy. Consider two cases: (1) a permanently magnetized particle with a moment that does not vary with position; and (2) a permanently magnetized particle with a moment proportional to the field strength $\overline{H}$. The latter case is more characteristic of magnetic particles and the force can be written as:

$$\overline{F} = \propto \mu_0 V(\overline{H} \cdot \nabla)\overline{H} \quad \text{(Eq. 136)}$$

Here, V is the volume of the particle and $\propto$ is a proportionality constant relating the particle magnetization and the field strength $\overline{m} = \overline{M}v = \propto\overline{H}v$.

If the particle has a low remanance and a nearly spherical shape, then the field magnitudes of interest (its magnetization) depend mainly on the demagnetizing factor N associated with its shape and are given by:

$$\overline{M} \sim \frac{1}{N}\overline{H} \quad \text{(Eq. 137)}$$

For a sphere, N = 1/3 and hence $M = 3H$. Using Eqs. 135 and 137, the force on such a spherical particle directly above the cylindrical discontinuity shown in Fig. 14 has the magnitude:

$$\overline{F} \sim \frac{2\overline{H}\mu_0 v H^2 a^4}{h^5} \quad \text{(Eq. 138)}$$

The force calculated for a spherical particle is only a small fraction of the gravitational force (for particles with densities similar to iron) and isolated particles are not captured by the leakage field. A cooperative effect is required, in which the particles chain together to reduce the demagnetization factor. If the particles chain together before they are in the vicinity of the leakage field, they may be too large to be affected by the leakage field, or they may be too strongly attracted to their own image and may stick to the surface, forming a confusing background.

Because of these complexities, magnetic measurements on bulk powders by themselves give very little information regarding their suitability for magnetic particle testing. Many other factors must be considered and currently the best test of such powders is to compare their ability to form indications under actual test conditions.

Experimental or Empirical Modeling

Experimental modeling methods are those derived from measurements in tests — either actual or simulated. In its pure form, this method of modeling constitutes a series of experiments designed to prove a point or to produce a product. In practice, the technique is nearly always part of a larger process and is used in conjunction with other methods, particularly analytical modeling.

Considering the difficulty of solving Maxwell's equations for a nonlinear material, it is not surprising that experimental modeling is featured so prominently in analysis of leakage fields and magnetic particle testing. Yet from a practical point of view, empirical methods have limitations. As their name implies, the methods' results are empirical and therefore applicable to the problem tested and perhaps to a limited number of similar problems. Their extension to other applications is not always possible or advisable. While a series of tests can be devised to model surface breaking cracks, the same model cannot be used for subsurface discontinuities or inclusions.

The value of such models is limited because of its empirical nature and the extension of such models to other geometries is more or less speculative. This does not mean that accurate, controlled experimental data are not valuable in modeling. Both analytical and especially numerical modeling rely on such data for confirmation.

The limitation of experimental methods are many and, although very useful at times, it is not possible to rely solely on experimental methods for modeling.

Analytical Modeling

Analytical models are those derived from elementary field and circuit theory relations. At the very base of this approach is the fact that some simplifying assumptions can be made about the testing environment. These assumptions may include those that are satisfied with few or no errors like linearity in calculations. There are also assumptions that imply large errors or even a modification of the test geometry, including symmetry considerations, boundary conditions and discontinuity shape approximations.

In spite of extensive simplification, analytical models are extremely complicated and their results tend to be limited to a single geometry or class of problems.

Analytical models are attempts to solve the governing equations directly. Solution of Maxwell's equations can provide all the data and understanding necessary for meaningful application of electromagnetic methods and for design of instrumentation and tests. This ideal situation is badly hindered by the fact that Maxwell's equations cannot be solved analytically except for the most trivial situations. For this reason, simplified models have been sought which, while simplifying the problem, still provide a reasonable description of the actual behavior.

Perhaps the most successful methods for representing leakage fields are those that employ analogy: one situation has a simple solution and another situation is analogous to that solution. The basis for this approach is in the analogy between the electrostatic field in Eq. 17 and Eq. 19 and the magnetostatic field in Eqs. 18 and 20. If a solution to an electrostatic problem is found, the solution to an analogous agnetostatic problem can also be found. For the solution of leakage field problems (direct or alternating current), variations on the analogy between the electrostatic dipole distribution and the actual magnetostatic field were sought in the early period of field modeling.

Perhaps the earliest efforts at using this equivalent solution was an attempt to solve the field distribution of recording heads.[7] Because the geometry included an air gap over which a leakage field is generated, the same solution applies to leakage fields from discontinuities in either active or residual excitation. The gap of the recording head (Fig. 15) is modeled by assuming a constant magnetic potential difference across the gap. Assuming that this potential produces a constant flux density B_0 in the gap, the magnitude of B_0 is given by $\mu V/b$ where $2b$ is the gap width and μ is the permeability in the gap. The flux density above the gap can also be calculated as:

$$B_x = -\frac{1}{\pi} B_0 \left[\tan^{-1}\frac{b+x}{y} + \tan^{-1}\frac{b-x}{y} \right] \quad \text{(Eq. 139)}$$

and

$$B_y = \frac{1}{2\pi} B_0 \ln \left[\frac{y^2 + (b+x)^2}{y^2 + (b-x)^2} \right] \quad \text{(Eq. 140)}$$

Similarly, the field in a magnetic layer above the gap can be calculated based on the assumptions outlined above.

A similar approach was introduced in an attempt to find a direct equivalent magnetic dipole to an electrostatic dipole.[8,9] This was done by assuming that opposite magnetic charges are uniformly distributed on the opposing walls of a rectangular slot. Assuming a charge density s, the field at a point p (Fig. 15) is:

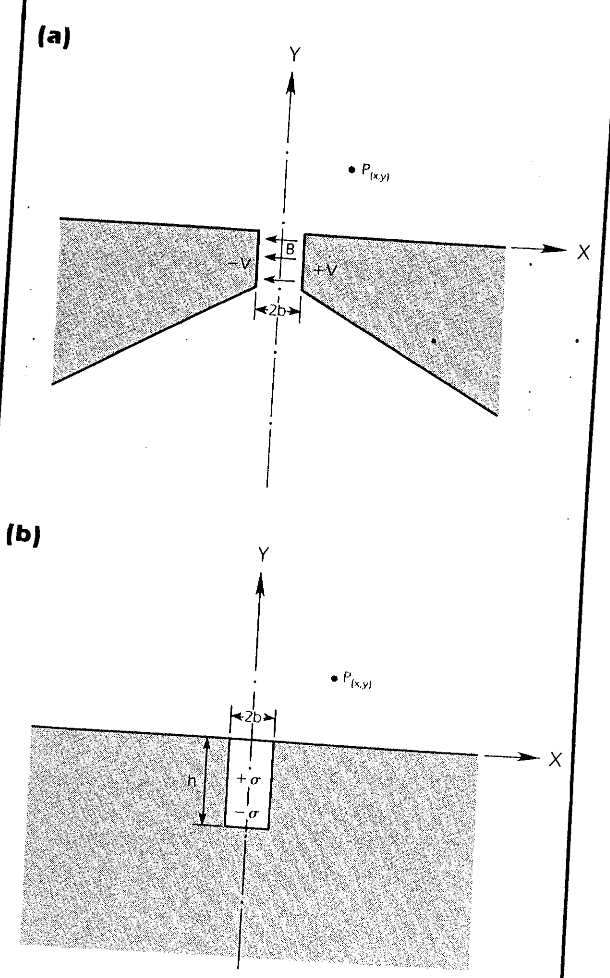
$$H_x = 2s \tan^{-1} \frac{h(x+b)}{(x+b)^2 + y(y+h)} - 2s \tan^{-1} \frac{h(x-b)}{(x-b^2) + y(y+h)} \quad \text{(Eq. 141)}$$

and

$$H_y = s \ln \{[(x + b)^2 + (y + h)^2] [(x - b)^2 + y^2]\} - s \ln \{[(x + b)^2 + y^2] [(x - b)^2 + (y + h)^2]\} \quad \text{(Eq. 142)}$$

In these equations, h is the depth of the discontinuity. As the depth of the discontinuity approaches infinity, the expressions in Eqs. 141 and 142 become:

FIGURE 15. Leakage field models: (a) Karlqvist model of a recording head; and (b) dipole model of a slot



$$H_x = 2s \left[\tan^{-1}\frac{x + b}{y} - \tan^{-1}\frac{x - b}{y}\right] \quad \text{(Eq. 143)}$$

and

$$H_y = s \ln \left[\frac{(x - b)^2 + y^2}{(x + b)^2 + y^2}\right] \quad \text{(Eq. 144)}$$

These relationships are only as good as the assumptions behind them. If infinitely long planes are assumed with charge distributed over them, then the solution is not capable of modeling short, tight discontinuities. In addition, these models exemplify the basic limitation of analytical models: it is often necessary to assume an oversimplified geometry (the infinite parallel planes) or even a nonphysical assumption (the *magnetic charge* idea). This oversimplification is at the root of two problems: (1) the inability to adequately solve the field equations analytically; and in turn (2) the inability to obtain an adequate model.

Many other methods for the solution of magnetostatic field equations exist and have found application. Because the magnetostatic field equation (Eq. 26) is either a Laplace equation for zero excitation or a Poisson equation for nonzero excitation, the classical methods for the solution of Laplace and Poisson's equations can be used. It is also reasonable to consider such well known solutions as the separation of variables, the method of images and conformal transformations. None of these methods is satisfactory in the general sense. Separation of variables can only be used with simple geometries and boundaries,[10] the method of images is only applicable to highly symmetric problems,[10] while conformal transformations are strictly two-dimensional methods that can be used for some simple boundaries.

Numerical Modeling

Numerical modeling is conceptually different from analytical modeling. For the purpose of modeling nondestructive tests, the most important advantage in numerical modeling is the fact that none of the simplifying assumptions made in the analytical approach are necessary in order to reach a satisfactory solution.

Starting with Maxwell's equations, it is possible to proceed in many different ways, each of which requires the formulation of these equations in some particular form.[11,12] Assumptions are made for the sake of simplicity and economics of the solution and not to render the equations solvable. Thus, a two-dimensional or axisymmetric solution may be assumed if the geometry is approximately two-dimensional or has axisymmetry. A two-dimensional solution is a special case of the more general three-dimensional solution which, if needed, can be used. Similarly, an axisymmetric solution is the solution of a three-dimensional problem in cylindrical coordinates. Other assumptions may be employed in order to shorten the solution process or to obtain insight into the problem before a more general solution is attempted. A linear formulation may be used as a first approximation or in cases where the problem is indeed linear.

As with analytical methods, there are many approaches and numerical methods available. Some are more accurate, more convenient, more economical or more suitable for the solution of a particular problem.

The successful application of a numerical process for obtaining a model is determined by three preliminary decisions: (1) choosing the appropriate numerical method; (2) making correct assumptions about the geometry and the nature of the solution; and perhaps most important (3) resolving the question of economics. Accuracy can be obtained regardless of the problem's geometry, linearity, nonlinearity or dimensionality, provided the necessary expenses associated with such a general solution are justifiable and that the computer resources are available.

A significant point and one of considerable practical importance is the fact that the numerical solution to many significant problems does not require large computers or highly trained personnel, despite the prevalent notion. Desktop computers may be used for the solution of many two-dimensional or axisymmetric problems. Some large scale models or specialized three-dimensional problems still require supercomputers but it is reasonable to assume that tomorrow's minicomputers will be more powerful than today's mainframes. The developments in computer technology favor numerical modeling approaches.

Numerical methods are generally far more powerful than analytical methods. At the same time, the solution is obtained as numerical data rather than as a closed form solution. As such, the result obtained for a particular problem is not usable for the analysis of a different, perhaps similar, problem. Parameter study requires repetitive solution and it is not always possible to deduce it from the solution, as is the case with analytical solutions. This is not a significant disadvantage because the same repetitive process allows study of parameters for which the analytical approach cannot be applied, including changes in the geometry of an arbitrarily shaped discontinuity.

Numerical modeling can be viewed as a special subset of the analytical methods because the goals are to solve the same system of equations; the methods do differ in approach. In analytical methods, there are attempts to simplify the geometry or the equations. Numerical methods rely on discretization of the solution space into subspaces, for which a good approximation to the solution can be obtained. At least in principle, the numerical methods suffer none of the limitations of the analytical methods and are capable of solving the governing equations with few, if any, approximations. The main difficulties with numerical methods are technical: large computer resources, nonclosed form solution, and so on.

Numerical modeling in nondestructive testing is an outgrowth of the failure of analytical models to reliably predict the necessary field discontinuity interactions with any degree of generality. A numerical model uses a digital computer to solve the governing equations directly without simplifying assumptions and this is enough to explain the significance of such models for the solution of field problems, including those related to active and residual leakage fields. It not only allows the solution of very complex problems but at the same time does not require the user to know the intricacies of electromagnetic theory or differential calculus. All that the user is required to do is input the problem variables and, if necessary, verify the results experimentally.

The Finite Difference Method

The finite difference method has been traced back to Gauss and has more recently found significant use as a general method for the solution of partial differential equations. There are many reasons for its widespread application, especially in the early days of computer modeling. The method is not only general but relatively easy to apply. It is equally applicable to direct current fields, quasistatic or transient fields and to linear and nonlinear problems. In its simplest form, the formulation of the field equations consists of simply replacing the partial derivatives by appropriate difference formulas. A solution can then be obtained for the dependent variable at discrete points within the solution region either by an iterative process or by the solution of a system of algebraic equations, depending on the finite difference formula chosen.

The application of the finite difference method is complicated by problems of convergence and stability of the solution as well as by restrictions on the discretization process. While regular sets of discretization points (grids) are easy to handle, irregular grids are not. Discretization of complex geometries into regular grids is not practical and irregular grids may in some cases render the solution nonconvergent. In field problems, the inability to properly discretize small areas (such as air gaps or discontinuities) is critical and is detrimental to the use of the method. In addition, the finite difference method is in effect a nodal method and cannot take into account distributed parameters such as current densities, conductivities and permeabilities. These have to be described as equivalent nodal quantities with all the associated errors. The solution is only valid at the nodal points.

Despite its limitations, the finite difference method has been applied successfully to a variety of electromagnetic field problems. The problems related to leakage fields are those applications that deal with electrical machines.[13-16] In those applications, the actual geometry, machine parameters, current densities and realistic material properties were modeled.

Nonlinearity of ferromagnetic materials is taken into account by iteration methods[14] to produce results that no analytical model can match either in accuracy or flexibility. While two-dimensional and axisymmetric models are sufficient in many applications, there are also three-dimensional models using the finite difference method. These models can be used for alternating current applications as well.

The Finite Element Method

The finite element method has a briefer history than the finite difference method. It evolved in the late 1950s as a numerical method in structural analysis[17] but has spread quickly to become a major analysis tool in diverse areas of engineering,[18-22] in the physical sciences and in medical research.[23]

Because of its success in modeling intricate geometries efficiently and accurately, the potential for its application to electric and magnetic fields was recognized in the early 1970s and has been applied with great success to the study of direct current and low frequency electromagnetic fields in electrical machines,[24] large magnet structures[25] and permanent magnet design.[26] The finite element method has considerable advantage over the finite difference method, including the ease of handling boundary conditions and the ability to follow awkwardly shaped boundaries.[27]

The method is by definition a volumetric method: various parameters are defined by their association with the volume or, in the case of two-dimensional and axisymmetric formulations, with the surface. The finite element method is therefore naturally suited to the modeling of continuum problems and is quite flexible in terms of the discretization process.

Being a discrete method, it requires discretization of the solution region but no restrictions are imposed on the shape, size or number of finite elements.[28] The solution process and the formulation are identical, regardless of the size and shape of the elements used. While the finite difference method assumes linear relations between the unknowns, the finite element method can handle higher order relations as well.[28] Problems with convergence have no meaning in the context of finite elements.

These factors are of particular importance for the simulation of electromagnetic nondestructive testing techniques and accordingly the method has received considerable attention. Numerical models based on the finite element method have been developed for two-dimensional[29-32] and three-dimensional[27,33-36] eddy current applications.

The advantages of the method come with a price. When compared to finite difference methods, problems solved by the finite element method generally require larger computer resources, especially for nonlinear and time dependent problems. In addition, the method does not lend itself well to the solution of transient problems because it cannot efficiently handle time discretization.

These two methods are complementary, each being suited to the solution of different problems. For example, time integration in finite element computer codes is usually handled by various forms of finite difference methods.[37]

The flexibility of finite element models has been demonstrated by diverse applications to the solution of a variety of leakage field problems. Both active[38] and residual[39] applications have been handled successfully in linear or nonlinear environments. The extension to three-dimensional problems is relatively simple,[27] although extensive computer resources are required, especially for nonlinear problems. Alternating current applications, either eddy current or general problems, have also been treated extensively in two-dimensional and axisymmetric geometries and in three-dimensional geometries.

PART 8
MATHEMATICS OF ELECTROMAGNETIC FIELD STUDIES

Vector Algebra and Calculus

The presentation and use of electromagnetic field relations requires the manipulation of vector and scalar quantities. The following text attempts to define the necessary quantities, relations and theorems. These should be viewed as a listing rather than as a mathematical treatment of any depth. Further reference to sources on fields or vector algebra and calculus are encouraged.

Gradient

The gradient of a scalar function U is defined as the steepest slope of the function at a given point and is denoted by ∇U where ∇ is called the *del operator*. In Cartesian coordinates this is:

$$\nabla U = \hat{x}\frac{\partial U}{\partial x} + \hat{y}\frac{\partial U}{\partial y} + \hat{z}\frac{\partial U}{\partial z} \qquad \text{(Eq. 145)}$$

In cylindrical coordinates, the gradient is written as:

$$\nabla U = \hat{r}\frac{\partial U}{\partial r} + \hat{\phi}\frac{\partial U}{r\partial \phi} + \hat{z}\frac{\partial U}{\partial z} \qquad \text{(Eq. 146)}$$

In spherical coordinates, the gradient is written as:

$$\nabla U = \hat{R}\frac{\partial U}{\partial R} + \hat{\theta}\frac{\partial U}{R d\theta} + \hat{\phi}\frac{1}{R\sin\theta}\frac{\partial U}{\partial \phi} \qquad \text{(Eq. 147)}$$

Note that the gradient is only defined as operating on a scalar function. The gradient of a vector is not defined.

Divergence

The divergence of a vector function is defined as:

$$\nabla \cdot \overline{A} = \lim_{\Delta V \to 0} \frac{\oint_s \overline{A} \cdot \overline{ds}}{\Delta V} \qquad \text{(Eq. 148)}$$

This can be interpreted as the total flux through an elemental volume. It is therefore a measure of the outward flow of flux per unit volume. The divergence can be written in terms of partial derivatives in Cartesian coordinates as:

$$\nabla \cdot \overline{A} = \frac{\partial A_x}{\partial x} + \frac{\partial A_y}{\partial y} + \frac{\partial A_z}{\partial z} \qquad \text{(Eq. 149)}$$

In cylindrical coordinates, the divergence is written as:

$$\nabla \cdot \overline{A} = \frac{1}{r}\frac{\partial}{\partial r}(rA_r) + \frac{\partial A_\phi}{r\partial \phi} + \frac{\partial A_z}{\partial z} \qquad \text{(Eq. 150)}$$

In spherical coordinate systems, divergence is written as:

$$\nabla \cdot \overline{A} = \frac{1}{R^2}\frac{\partial}{\partial R}(R^2 A_R) + \frac{1}{R\sin\theta}\frac{\partial}{\partial \theta}(A_\theta \sin\theta) + \frac{1}{R\sin\theta}\frac{\partial A_\phi}{\partial \phi} \qquad \text{(Eq. 151)}$$

Curl

The gradient and the divergence define important quantities relating to fields. There are however fields with special properties that cannot be defined in terms of these two properties alone. The circulation of a turbulent flow field, for example, has rotation properties that must be described. Rotation of a vector field can be described by the circulation of the vector.

$$C = \oint_c \overline{A} \cdot \overline{d\ell} \qquad \text{(Eq. 152)}$$

This definition relates the field to a contour around a specified area. It is helpful to envision a small area around which this contour integral can be evaluated. If a differential form of the circulation is needed, a point circulation vector should be defined. This is done by taking a limiting process as the area s tends to zero. The curl of the vector $\overline{A}$ is defined as the vector whose magnitude is the maximum circulation of $\overline{A}$ per unit area:

$$\nabla \times \overline{A} = \lim_{\Delta S \to 0} \frac{1}{\Delta S} \left[\hat{n} \oint_c \overline{A} \cdot \overline{d\ell} \right]_{max} \quad \text{(Eq. 153)}$$

In terms of partial derivatives in Cartesian coordinates, this is written as:

$$\nabla \times \overline{A} = \hat{x} \left(\frac{\partial A_z}{\partial y} - \frac{\partial A_y}{\partial z} \right) \quad \text{(Eq. 154)}$$

$$+ \hat{y} \left(\frac{\partial A_x}{\partial z} - \frac{\partial A_z}{\partial x} \right) + \hat{z} \left(\frac{\partial A_y}{\partial x} - \frac{\partial A_x}{\partial y} \right)$$

In cylindrical coordinates, it is written as:

$$\nabla \times \overline{A} = \hat{r} \left(\frac{\partial A_z}{r \partial \phi} - \frac{\partial A_\phi}{\partial z} \right) \quad \text{(Eq. 155)}$$

$$+ \hat{\phi} \left(\frac{\partial A_r}{\partial z} - \frac{\partial A_z}{\partial r} \right) + \hat{z} \frac{1}{r} \left[\frac{\partial}{\partial r} (r A_\phi) - \frac{\partial A_r}{\partial \phi} \right]$$

In spherical coordinate systems, it is written as:

$$\nabla \times \overline{A} = \hat{R} \frac{1}{R \sin \theta} \quad \text{(Eq. 156)}$$

$$\left[\frac{\partial}{\partial \phi} (\overline{A}_\phi \sin \theta) - \frac{\partial A_\theta}{\partial \phi} \right]$$

$$+ \hat{\theta} \frac{1}{R} \left[\frac{1}{\sin \theta} \frac{\partial A_R}{\partial \phi} - \frac{\partial}{\partial R} (R A_\phi) \right]$$

$$+ \hat{\phi} \frac{1}{R} \left[\frac{\partial}{\partial R} (R A_\theta) - \frac{\partial A_R}{\partial \theta} \right]$$

In these relations $\hat{x}, \hat{y}, \hat{z}, \hat{r}, \hat{R}, \hat{\theta}, \hat{\phi}$, are the unit vectors in the x, y, z, r, R, θ, ϕ directions respectively.

Vector Identities

In the following identities, all symbols without a bar are scalars while those with a bar are vectors. The operator is a vector. The identities listed here are those that are most often used.

$$\overline{A} \cdot \overline{B} \times \overline{C} = \overline{B} \cdot \overline{C} \times \overline{A} = \overline{C} \cdot \overline{A} \times \overline{B} \quad \text{(Eq. 157)}$$

$$\overline{A} \times (\overline{B} \times \overline{C}) = \overline{B} (\overline{A} \cdot \overline{C}) - \overline{C} (\overline{A} \cdot \overline{B}) \quad \text{(Eq. 158)}$$

$$\nabla(\phi V) = \phi \nabla V + V \nabla \phi \quad \text{(Eq. 159)}$$

$$\nabla \cdot (\phi \overline{A}) = \phi \nabla \cdot \overline{A} + \overline{A} \cdot \nabla \phi \quad \text{(Eq. 160)}$$

$$\nabla \times (\phi \overline{A}) = \phi (\nabla \times \overline{A}) + \nabla \phi \times \overline{A} \quad \text{(Eq. 161)}$$

$$\nabla \cdot (\overline{A} \times \overline{B}) = \overline{B} \cdot (\nabla \times \overline{A}) - \overline{A} \cdot (\nabla \times \overline{B}) \quad \text{(Eq. 162)}$$

$$\nabla \cdot \nabla \phi = \nabla^2 \phi \quad \text{(Eq. 163)}$$

$$\nabla \times \nabla \times \overline{A} = \nabla(\nabla \cdot \overline{A}) - \nabla^2 \overline{A} \quad \text{(Eq. 164)}$$

$$\nabla \times \nabla \phi = 0 \quad \text{(Eq. 165)}$$

$$\nabla \cdot (\nabla \times \overline{A}) = 0 \quad \text{(Eq. 166)}$$

These identities are used to put an expression in a particular form or to simplify the expression. For example, a vector triple product may be expressed as the sum of the gradient of the divergence of a vector K minus its vector Laplacian (see Eq. 164).

Vector Theorems

Like any other mathematical discipline, many important theorems can be derived from the basic properties of vectors and scalars. There are three theorems that are particularly important in field problems.

Stokes' theorem relates the line integral of a vector with the surface integral of its curl. It is an important tool that allows the use of simpler line integrals whenever the theorem can be applied.

$$\int_s (\nabla \times \overline{A}) \cdot \overline{ds} = \oint_c \overline{A} \cdot \overline{d\ell} \quad \text{(Eq. 167)}$$

The divergence theorem relates the volume integral of the divergence of a vector to the closed surface integral (or flux) of the vector.

Its importance lies in its abilities for simplification and derivation of field relations.

$$\int_v \nabla \cdot \overline{A} dv = \oint_s \overline{A} \cdot \overline{ds} \qquad \text{(Eq. 168)}$$

Helmholtz' theorem states that a vector field is defined (within a constant) if both its divergence and its curl are specified. Thus, the divergence specifies the solenoidal properties of the field while the curl specifies its rotational properties. A field is said to be solenoidal if its divergence is nonzero and rotational if its curl is nonzero. Similarly, nonsolenoidal and rotational fields can be defined, or fields with any combination of the two properties.

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SECTION 6

MAGNETIZATION METHODS

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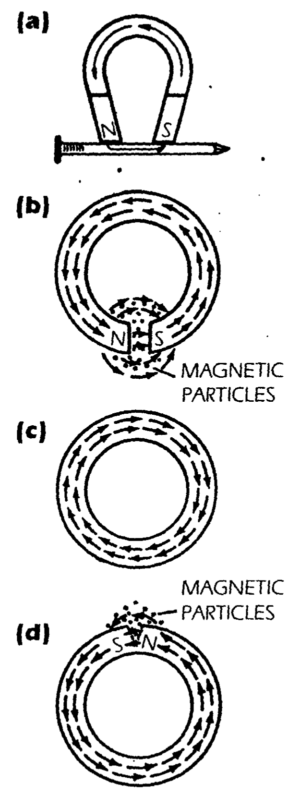
PART 1
DESCRIPTION OF MAGNETIC FIELDS

The magnetic particle testing method uses magnetic fields to reveal material discontinuities in ferromagnetic materials. The common horseshoe magnet attracts ferritic materials to its ends or poles. Magnetic lines of flux flow from the south pole through the magnet to the north pole as illustrated in Fig. 1a.

FIGURE 1. Magnetism in various shapes: (a) a horseshoe magnet; (b) a ring magnet with air gap; (c) a closed magnetized ring; and (d) magnetic particles attracted to a radial crack in a circularly magnetized object



Magnets only attract materials where the lines of flux leave or enter the magnet. When magnetic material is placed across the poles of a horseshoe magnet, the lines of flux flow from the north pole of the magnet through the material to the south pole. Magnetic lines of flux flow preferentially through magnetic material rather than nonmagnetic material or air.

Magnetized Ring

If a horseshoe magnet is bent so that its poles are close together (see Fig. 1b), the poles still attract magnetic materials. Iron filings or other magnetic materials cling to the poles and bridge the gap between them. In the absence of a slot, the magnetic flux lines are enclosed within the ring (Fig. 1c). No external poles exist, and magnetic particles dusted over the ring are not attracted to the ring even though there are magnetic flux lines flowing through it. Magnetized materials attract externally only when poles exist. A ring magnetized in this manner is said to contain a circular magnetic field which is wholly within the object.

Small changes in the cross section of the ring or in the permeability of its material may cause external flux and the attraction of magnetic particles.

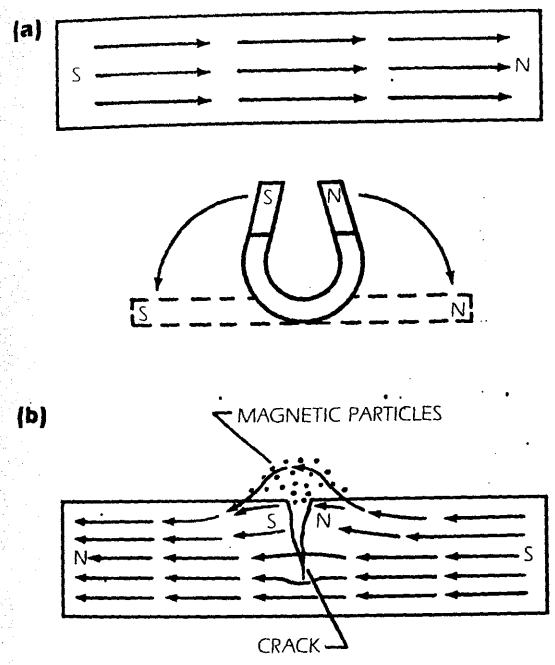
Effect of Cracks in a Magnetized Ring

A radial crack in a circularly magnetized object creates north and south magnetic poles at the edges of the crack. This forces some of the magnetic lines of force out of the metal path. These disrupted lines of force are called *magnetic leakage flux*. Magnetic particles are attracted to the poles created by such a crack, forming an indication of the discontinuity in the metal test object (Fig. 1d).

Bar Magnet

When a horseshoe magnet is straightened, it becomes a bar magnet with poles close to each end. Magnetic flux lines flow through the bar from the south pole to the north pole but the flux density is not uniform along the bar (Fig. 2a). Magnetic particles are attracted to any location where flux emerges and particularly to the ends of the magnet where the concentration of external flux lines is greatest. Since the

FIGURE 2. Straightening a horseshoe magnet results in a bar magnet: (a) lines of magnetic flux pass through the magnet from its south to its north pole; and (b) a crack in a bar magnet creates magnetic poles that attract magnetic particles outside the bar; magnetic lines of flux flow from north pole to south pole



magnetic flux within a bar magnet may run the length of the bar, it is said to be *longitudinally magnetized* or to contain a *longitudinal field*.

Effect of Cracks in a Magnetized Bar

A crack in a bar magnet (Fig. 2b) distorts the magnetic lines of force and creates poles on either side of the crack. These poles attract magnetic particles to form an indication of the crack. The strengths of poles formed at a crack depends on the number of magnetic flux lines interrupted. A crack at right angles to the magnetic lines of force interrupts more flux lines and creates stronger poles than a crack more nearly parallel to the flux lines. Test indications of maximum size are formed when discontinuities are at right angles to the magnetic lines of flux.

PART 2

MAGNETIZATION WITH ELECTRIC CURRENT

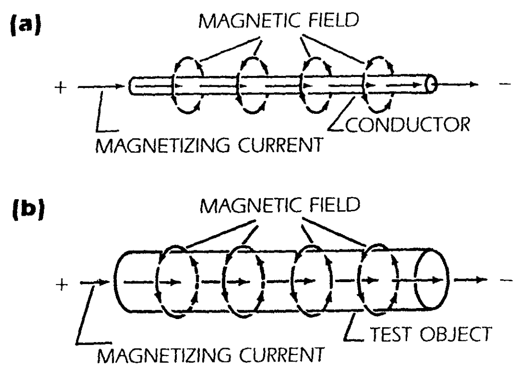
Electric currents are used to create or induce magnetic fields in electrically conducting materials. Since it is possible to alter the directions of magnetic fields by controlling the direction of the electrical magnetizing current, the arrangement of current paths is used to induce magnetic flux lines at right angles to expected discontinuities in the test object.

Circular Magnetization

Electric current passing through a straight conductor (a wire or bar, for example) creates a circumferential magnetic field around that conductor (see Fig. 3a). The magnetic lines of force are always at right angles to the direction of the current that induces the magnetic field.

To determine the direction taken by magnetic lines of force around a conductor, imagine that the conductor is grasped with the right hand so that the thumb points in the direction of the electric current. The fingers then point in the direction taken by the magnetic field lines, surrounding the conductor. This is known as the *Fleming right hand rule*.

FIGURE 3. Fields in circular magnetization: (a) circumferential magnetic field surrounding a straight conductor carrying an electric current; and (b) circular magnetization of a test object through which a magnetizing electric current passes

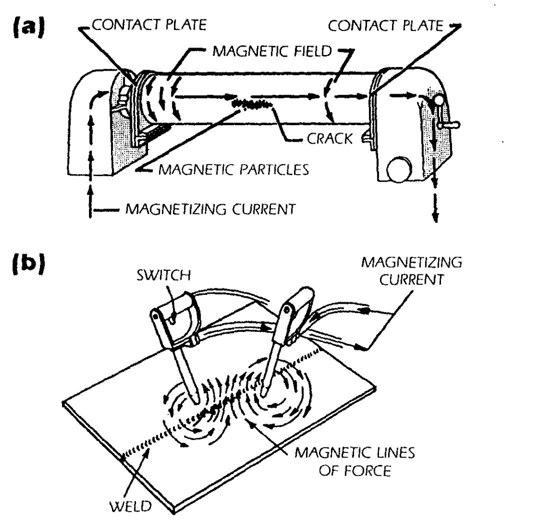


The passage of current induces a magnetic field strength in the conductor as well as in surrounding space. An object magnetized in this manner is said to have a *circular field* or to be *circularly magnetized* (Fig. 3b).

Circular Magnetization of Solid Test Objects

To induce a circular magnetic field in a solid test object, current may be passed through the object. This creates poles on both sides of discontinuities that are parallel to the length of the test object. These poles attract fine magnetic particles and form an indication of the discontinuity (see Fig. 4a). It is also possible to generate a circular field in

FIGURE 4. Circular magnetization of typical test objects: (a) circular magnetization caused by passing electric current from contact plates through the test object; and (b) production of a localized circular field by passing electric current between contact prods



localized areas of the object using prods to pass current through the area being tested (Fig. 4b).

The prod electrodes (generally solid copper or braided copper tips) are first pressed firmly against the test object. The magnetizing current is passed through the prods and into the area of the object in contact with the prods. This establishes a circular magnetic field in the test object around and between each prod electrode.

The use of alternating current limits the prod technique to the detection of surface discontinuities. Half-wave rectified direct current is more desirable here because its greater particle mobility helps detect surface and near surface discontinuities with greater particle mobility.

The prod technique generally is used with dry magnetic particle materials because of increased particle mobility on rough surfaces and better penetration. In the United States, wet magnetic particles are not normally used with the prod technique because of electrical and fire hazards. In Europe, wet particles are regularly used with prods to achieve higher sensitivity. Care should be taken to maintain clean prod tips, to minimize heating at the point of contact and to prevent arc strikes and local heating of the test surface. Aluminum or copper braided tip prods or pads (rather than solid copper tips) are recommended because of the possibility of copper penetration if arcing occurs.

A remote control switch should be built into the prod handles to permit control of the current after positioning and before removing, to minimize arcing.

Circular Magnetization with Prods

In circular magnetization with prods, the field strength is proportional to the current used but varies with prod spacing and the thickness of the section being tested. A magnetizing current of 90 to 110 A for each 25 mm (1 in.) of prod spacing is recommended for material under 20 mm (0.75 in.) thick. A magnetizing current of 100 to 125 A for each 25 mm (1 in.) of prod spacing is recommended for material over 20 mm (0.75 in.) in thickness. Prolonged energizing cycles may cause localized overheating. Prod spacing should not exceed 200 mm (8 in.).

Prod spacing less than 75 mm (3 in.) is usually not practical because the particles tend to band around the prods, making interpretation difficult.

Circular Magnetization with Direct Contact

Figure 5 shows the direct contact method for producing circular fields in a ring to indicate circumferential cracks. To achieve a reliable examination of the entire cylindrical surface, two magnetizations are required.

This is done because the points of contact (where the current enters and leaves the ring) are not adequately magnetized for discontinuity indication. The ring must therefore be turned 90 degrees and then retested.

Circular Magnetization with Induced Current

A current flowing circumferentially around the ring can be induced by making the ring a single-turn, short circuited secondary transformer (Fig. 6b illustrates this effect). To accomplish this effect, a standard magnetizing coil can be used.

The ring is placed inside the coil with its axis parallel to that of the coil. When the coil is energized with alternating current, the arrangement constitutes an air core transformer; the magnetizing coil is the primary and the ring is the single-turn secondary. The total current induced in the ring is greatly increased by inserting a laminated core of ferromagnetic material through the ring.

For materials with high magnetic retentivity, direct current can be applied in the method known as *quick break* and the objects may then be tested by the residual method. Quick break is when a direct current field is caused to collapse suddenly due to an abruptly interrupted magnetizing current. The circular field generated by the induced current leaves the test object with a strong residual induction. A bearing race is a good example of the type of object that can be tested advantageously by this method.

For test objects made of soft material, with little retentivity, the continuous method must be used and the collapsing direct current field method is not applicable. By using alternating current (or half-wave direct current) in the magnetizing coil, the current may be left on and an alternating current (or half-wave direct current) of the same frequency as the magnetizing current is induced in the ring. This current should be allowed to flow long enough to produce indications by the continuous method.

FIGURE 5. Direct contact method of magnetizing ring shaped test objects to locate circumferential discontinuities

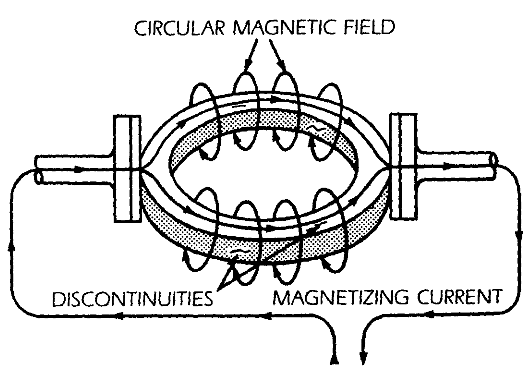


FIGURE 6. Magnetizing with the induced current method to locate circular discontinuities in ring shaped objects

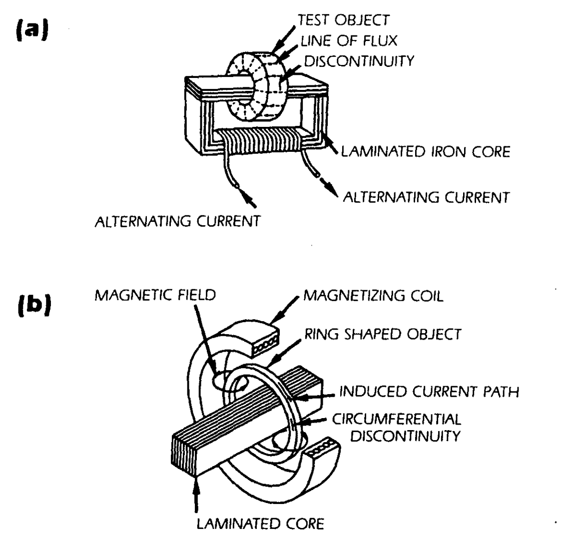
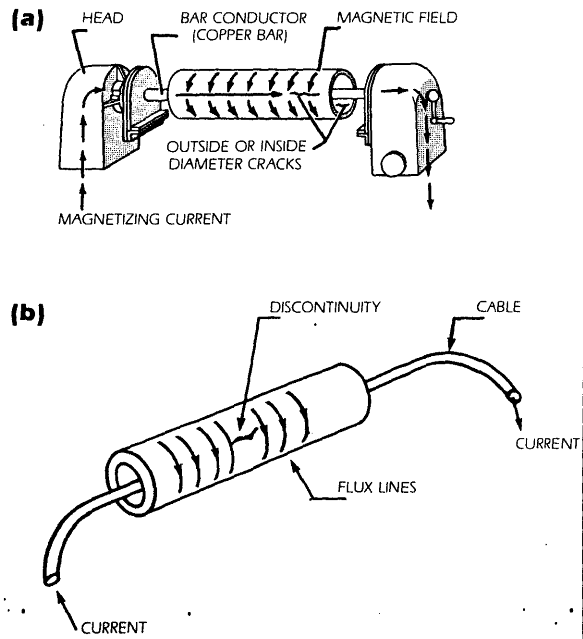


FIGURE 7. Circular magnetization of cylindrical objects using an internal current carrying conductor: (a) internal bar conductor and (b) internal cable conductor



Circular Magnetization of Hollow Test Objects

With hollow objects or tubes, the inside surfaces may be as important for testing as the outside surfaces. When such an object is circularly magnetized (by passing the magnetizing current through it), no magnetic flux is produced on the inside surface.

Since a magnetic field surrounds a current carrying conductor, it is possible to induce a satisfactory magnetic field by sliding the test object onto an internal conducting bar (Fig. 7). Passing current through the bar induces a circular magnetic field throughout the volume of the test object.

When a conducting bar is not available, an electrical cable may be passed through the test object and connected to receptacles in the magnetic particle unit (Fig. 7b). For large diameter cylinders, the cable can be brought back on the outside of the test object, then threaded through again — each pass through increases the effective field by a factor of two. For long finished tubes, uninsulated conductors are not permitted because of arc burns.

Longitudinal Magnetization

Electrical current can be used to create a longitudinal magnetic field in magnetic materials. When electric current is passed through a coil, a magnetic field is established lengthwise or longitudinally within the coil (Fig. 8).

The nature and direction of this field are the result of the field around the conductor which forms the turns of the coil. Application of the right hand rule to the conductor at any point in the coil (Fig. 8a) shows that the field within the coil is longitudinal.

Coil Magnetization

When magnetic material is placed within a coil, most of the magnetic lines of force created by the electric current concentrate themselves in the test object and induce longitudinal magnetization (Fig. 8b).

Testing of a long cylindrical object with longitudinal magnetization is shown in Fig. 8c. With a transverse discontinuity in the test object, magnetic poles are formed on both sides of the crack. These poles attract magnetic particles to form an indication of the discontinuity. Figure 8c shows that a magnetic field has been induced at right angles to the discontinuity.

Test objects too large to fit in a fixed coil can be magnetized longitudinally by making a coil from several turns of flexible cable (see Fig. 8b). The use of portable magnetizing equipment with cables and prods or clamps has broadened the use of magnetic particle testing — there is no theoretical limit to the size of the object that can be tested in this manner.

Field Flow Magnetization

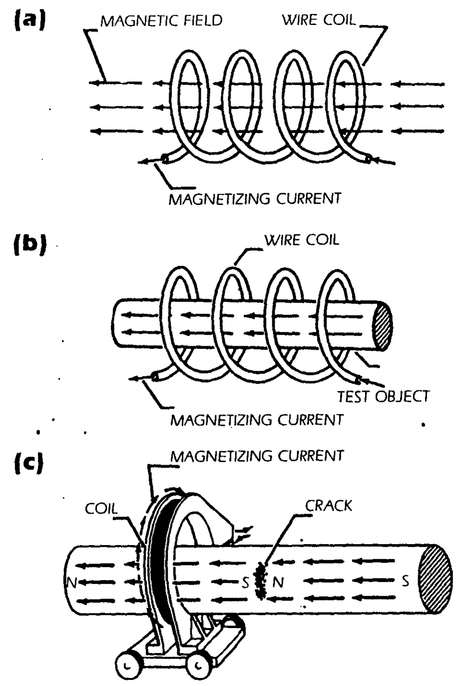
Another means of producing a longitudinal field in a test object is the field flow method. Here, the field is produced by electromagnets and passed through objects as if they were the keepers in a yoke. The field is almost wholly contained within the test object.

While there is theoretically no limit to the length of a test object that can be magnetized this way, as a practical matter with an alternating current source, power requirements limit the effective length to about 1.3 m (4 ft). However, special techniques using direct current have accomplished longitudinal magnetization in one step for lengths over 3 m (10 ft).

The field flow (or yoke) method may have some advantages over the current flow (coil) method in some production applications because: (1) moving a magnetizing coil several times may be impractical and time consuming; (2) test objects with length-to-diameter ratios less than 3:1 require no special handling; (3) a consistent field wholly contained within a test object may be required. Frequently the field flow method is indicated in multidirectional magnetization.

A reference standard containing known artificial discontinuities should be located in the center of the test object during setup to ensure adequate field strength along its entire length.

FIGURE 8. Longitudinal or coil magnetization: (a) longitudinal magnetic flux within a current carrying magnetizing coil; (b) longitudinal magnetization with a coil; and (c) typical arrangement of coil and test object for longitudinal magnetization



PART 3

FACTORS CONTROLLING MAGNETIZATION

Factors that should be considered when selecting a method of magnetization include: (1) alloy, shape and condition of the test object; (2) type of magnetizing current; (3) direction of the magnetic field; (4) sequence of operations; (5) value of the flux density; (6) desired throughput; and (7) type of discontinuities anticipated. Material properties and current type are considered below. Direction of the magnetic field is covered in the next part of this Section.

Material Properties

The alloy, its heat treatment, cold working and other conditioning treatments determine the magnetic permeability of a test object. It is necessary to consider these when selecting the sequence of operations, the value of flux density or the magnetic field strength. They, in turn, affect selection of the magnetization method.

The size and shape of the test object determine the most practical method of magnetization with the available equipment. The surface condition of the test object influences the selection of particles as well as the magnetization method. Surface coatings such as paint, chemical conversion or lacquer coatings are poor electrical conductors and affect testing because it is difficult or impossible to pass magnetizing current through such coatings. Whenever a test object can be properly magnetized with an induced method, coating thickness is the main concern for the inspector.

Types of Magnetizing Current

Many types of magnetizing current can be used for each type of testing (see Fig. 9)[1] Full-wave rectified alternating current with three-phase bridge circuitry is shown in Fig. 9a. With a ripple of 5 percent, nearly the entire cross section can be magnetically saturated. This means that the probability of detecting subsurface discontinuities may be improved over other forms of current. Because only ohmic resistance is involved, large lengths can be tested at high current values.

Half-wave rectified alternating current with a single-phase circuit is shown in Fig. 9b. The direct current proportion amounts to about 30 percent of the peak value.

Figure 9c shows full-wave rectified alternating current with a single-phase bridge circuit. The direct current proportion amounts to about 64 percent of peak value.

Alternating current with a frequency of 50 to 60 Hz (Fig. 9d) shows excellent uniform magnetization of the surface even with large changes of cross section. Penetration depth is frequency dependent and equals about 2 mm at 50 Hz (skin effect). There is rapid reduction in indication sensitivity with increasing depth when using alternating current magnetization.

Pulsed current is illustrated in Fig. 9e. Because of the pulse train at predetermined intervals, the danger of heating from current flow at the contact points is minimized. Thin walled test objects can therefore be tested using higher currents.

Impulse current is normally used with the residual method (Fig. 9f). The magnetization effect results from a high intensity single-current pulse of short duration (millisecond range).

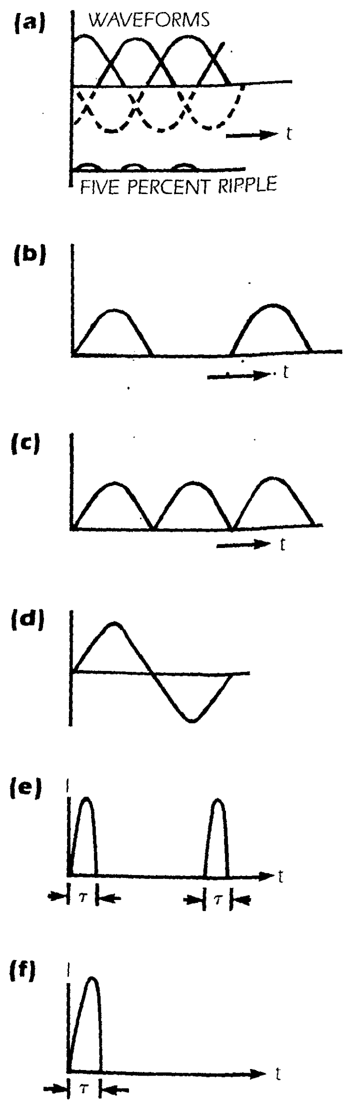
Direct Current Magnetization

Direct current obtained from storage batteries was first believed to be the most desirable current to use for magnetic particle testing because direct current penetrates more deeply into test specimens than alternating current. The big disadvantage of storage batteries as a source of current is that there is a definite limit to the magnitude and duration of current that can be drawn from a battery before recharging. Battery maintenance is costly and can be a source of trouble.

Direct current obtained through dry-plate rectifiers from alternating current power lines is similar to battery current and has the advantage of permitting an almost unlimited number of magnetizing shots. Today, nearly all direct current is produced with silicon diode rectification. Current obtained by passing three-phase alternating current through special rectifiers is called *three-phase rectified alternating current*.

Single-phase full-wave rectified alternating current has the advantage of greater particle mobility when compared to the three-phase bridge circuit. There is no detectable difference in discontinuity detection capability between the

FIGURE 9. Types of current used for magnetic particle testing: (a) full-wave rectified alternating current with a three-phase bridge circuit; (b) half-wave rectified alternating current with single-phase circuit; (c) full-wave rectified alternating current and single-phase bridge circuit; (d) alternating current at a frequency of 50 to 60 Hz; (e) pulsed current; and (f) impulse current



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methods. However, a three-phase circuit demands lower power consumption to achieve an equivalent current density.

Half-Wave Rectified Magnetizing Current

Half-wave rectified alternating current is the most effective current to use for the detection of subsurface and surface discontinuities when dry magnetic particles are used. This type of current is produced by putting single-phase alternating current through a rectifier. The rectifier is a nonlinear electronic component that permits unimpeded current flow in one direction and thus simulates direct current characteristics for purposes of testing. Half-wave rectified current imparts a very noticeable pulse to the particles. This gives them mobility, aids in the formation of indications and helps prevent the formation of nonrelevant indications.

Alternating Current Magnetization

Alternating current at line frequency is the most effective current to use for the detection of surface discontinuities, particularly fatigue cracks. It is important that alternating current testing equipment be built to include proper current controls.

An advantage of alternating current testing is the ease with which test objects can be demagnetized.

Choosing Alternating or Direct Current[2,3]

A direct current is distributed uniformly across the entire cross section of the test object. The field and flux density it creates are maximum at the outer surface and zero along the object's central axis, as required by Ampere's law. An alternating current field is forced to the surface because of the skin effect. This fact has technical consequences for the current flow in a billet of square cross section, for example. Figure 10 shows the difference in field strength distribution along the test object surface in cases of alternating and direct current.

For direct current flow, the magnetic field near the billet corners is considerably lower than in the middle of each side; it is nearly constant in the case of an alternating current field. For corner cracks to be accurately indicated by direct current fields, an overmagnetization in the center area of each side may be unavoidable. With the alternating current method, the same field strength is obtained across the surface of the billet at half the current density.

Figure 11 shows the distribution of field strength on the surface of a stepped sample. The difference in magnetic field strength for the largest and smallest cross section is much greater in the case of direct current magnetization.

For the same value of direct current, the field strength is inversely proportional to the square of the diameter; an

FIGURE 10. Magnetic field strength in kiloamperes per meter on the surface of a current flow in square billets (f = 50 Hz); current flow is through the length of the billet

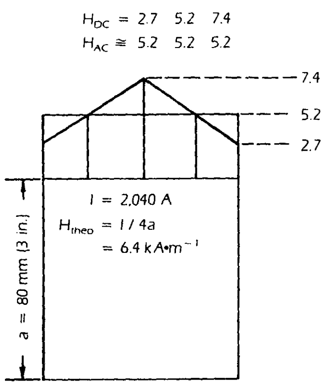

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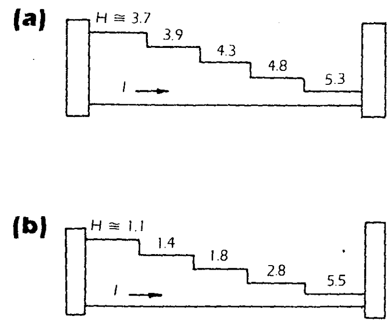
FIGURE 11. Distribution of field strength in kiloamperes per meter on the surface of a stepped sample: (a) alternating current field and (b) direct current field



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alternating current field is inversely proportional only to the diameter. When maximum and minimum field strengths for a specimen are given in test specifications, a complicated test object can often be inspected only in sections, if the test is carried out with a direct current magnetic field.

More obviously, this effect can be seen on objects with sudden enlargements in cross section. In camshafts, for example, the alternating current field (in accordance with the skin effect) follows the contour; the direct current field follows a more complex path. As a consequence, alternating current systems are often found at airline and automotive overhaul stations, where surface fatigue cracks can occur at various locations on complex shapes such as landing gear and actuating mechanism components.

Furthermore, the magnetic pole areas at the ends of a test object are much smaller with an alternating current field. The indications of cracks near the contacting area, are much better with an alternating current field.

An advantage of the direct current field is its increased depth of penetration. This provides the ability to test for subsurface cracks with magnetic particle techniques. Such tests are generally used to find cracks under chromium plating; subsurface cracks in flash welds; lack of root penetration or lack of fusion in weldments.

Extensive research has shown that the depth effect not only depends on the distance of the crack from the surface but also on the crack's shape, size and its relations to the test object dimensions. The indications from subsurface cracks are relatively blurred and indefinite and can be recognized safely only on a sufficiently smooth surface.

Direct current field magnetization cannot guarantee the ability to indicate all subsurface discontinuities, particularly as depth increases. The application of magnetic particle testing methods should be for detecting surface or near surface discontinuities. Wet method indications of discontinuities below 0.25 mm should be relied on only when other nondestructive testing methods cannot be used.

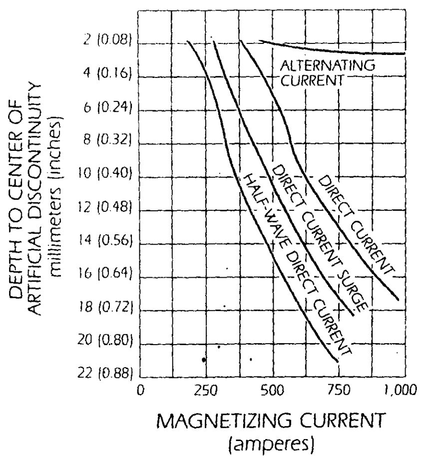
Depth of Penetration

Figure 12 is a plot of threshold values for the magnetizing currents necessary to produce a readable indication of holes in a tool steel ring standard. Holes parallel to the cylindrical surface are drilled 1.8 mm (0.07 in.) in diameter at increasing depths below the surface. The depths vary from 1.8 to 21 mm (0.07 to 0.84 in.), in 1.8 mm (0.07 in.) increments, from hole-1 to hole-12.

The results plotted in Fig. 12 were obtained using the dry continuous testing method with an internal conductor using 60 Hz alternating current, and three forms of direct current: (1) direct current from batteries; (2) three-phase rectified alternating current with surge; and (3) half-wave rectified single-phase alternating current.

The alternating current test required about 475 A to indicate hole-1 and over 1,000 A to indicate hole-2. Hole-3 could not be shown at any available alternating current value. Hole-2 was indicated with 475 A straight direct current, with 275 A full-wave rectified alternating current preceded by a surge of double this amount, and by 175 A using half-wave rectified alternating current. Half-wave

FIGURE 12. Comparison of the sensitivity of alternating current, direct current, direct current with surge, and half-wave rectified current for locating discontinuities wholly below the surface of a test object; threshold indications produced using dry particles and continuous magnetization on an unhardened tool steel ring with an artificial discontinuity diameter of 1.8 mm (0.07 in.)



rectified alternating current of 750 A indicated hole-12, while 975 A of direct current from batteries was needed to indicate hole-10.

These comparisons verify the importance of choosing the right current for producing the best indications. The comparisons also show how current should vary, depending on the nature and location of the discontinuities.

PART 4
DIRECTION OF THE MAGNETIC FIELD

The proper orientation of the magnetic flux in relation to the direction of a discontinuity is the most important factor affecting discontinuity detection, even more than the magnitude of the magnetizing current.

For reliable testing, the magnetic flux should be at right angles to the discontinuity. If the magnetic flux is parallel to the discontinuity, there is little magnetic leakage; if an indication is formed at all, it is likely to be extremely small or indefinite. To ensure that proper field direction exists at the desired magnitude, reference standards containing artificial discontinuities are needed.

Circular Magnetization

Fundamentals of Circular Magnetization

The magnetizing method that is easiest to control is circular magnetization. This is the method in which the magnetizing current is passed directly through the test object, setting up circular magnetic field lines at right angles to the direction of current flow (see Fig. 4a).

A good way to circularly magnetize the outer regions of a test object is to place the object between the contact plates of a stationary magnetic particle testing system. Care should be taken to clamp the test object firmly between the soft lead contact plates. Enough of the object's surface area must contact the plates to permit passage of the magnetizing current without burning. As the area of the surface decreases, the probability of burning increases.

On irregular test objects, it may be helpful to use copper braid contact pads between the objects and plates to prevent overheating. When testing objects with irregular cross section, it may be necessary to circularly magnetize with a low current to inspect the thin areas. A method specific to the application must be devised to pass a higher current through the heavier sections for testing of those areas.

Prod Magnetization of Large Test Objects

When an object is too big to fit into available test equipment, the test object (or areas of it) can be circularly magnetized by either of two methods.

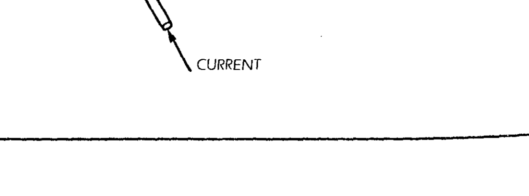
One method is to use prod contacts with cables to transmit the magnetizing current from the source to the test object (see Fig. 4b). Prods are attached to the ends of the cables so that magnetizing current can be passed through the test object or through an area of it. Portable equipment should have a remote control switch on the prods, enabling the operator to control the current while moving the prods or viewing the test indications.

Another means of local magnetization is to use contact clamps with cables, particularly when the test objects are relatively small in diameter. Tubular structures can be tested this way by positioning the clamps so that the current passes through the area of interest and along the line of suspected discontinuities (Fig. 13).

Internal Conductor Magnetization

In a tubular test object, a circular magnetic field may be set up by passing current through the tube itself; no field is induced on the inside surface of the tube. If the test object is hollow or has holes through which an internal conductor can be passed, it is best to induce a circular magnetic field in the object by passing the magnetizing current through the conductor. Circular magnetization with an internal conductor has the following advantages over passing current through the test object itself:

FIGURE 13. Current carrying clamp electrodes used for testing tubular objects with small diameters



1. it induces flux at the inside diameter of the test object, permitting testing of inner as well as outer surfaces;
2. direct electrical contact is not made with the test object, thereby eliminating the likelihood of burning; and
3. several small test objects (washers or nuts, for example) can be suspended on the same conductor and tested in groups (see Fig. 14).

Capacitor Discharge Circular Magnetization

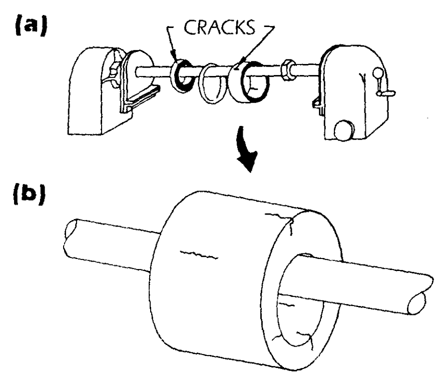
Capacitor discharge methods are used for the circumferential magnetization of oil field pipes. The technique is discussed in detail under *Circumferential Magnetization of Pipe* later in this Section.

Limitations of Parallel Magnetization

A circular magnetic field surrounds any electrical conductor and this is the magnetic principle underlying circular magnetization with an internal conductor. Knowing this, some operators have assumed that they can induce a circular field in a test object by placing it next to instead of around a conductor. This is not true.

Some field is induced in the test object by such a procedure, but since a portion of the magnetic flux path is in air, the field in the object is greatly reduced, distorted and unevenly distributed. This procedure is sometimes called *parallel magnetization*. It is not dependable and should not be used.

FIGURE 14. Internal conductor method used to produce circular magnetization: (a) several ring shaped test objects magnetized simultaneously; and (b) close-up of a ring with cracks in several locations and orientations



Longitudinal Magnetization

A longitudinal field can be induced in a test object by placing the object in a fixed current carrying coil, mounted on the rails of a stationary unit or attached by cables to a portable unit (Fig. 8). The effective magnetic field induced by a coil extends from 150 to 220 mm (6 to 9 in.) beyond either end of the coil. Depending on fill-factor, if the test object is long, it is necessary to magnetize and test it in sections along its length.

Longitudinal magnetization with portable equipment is accomplished by wrapping current carrying cable in a coil around the test object.

Important Considerations in Coil Magnetization

To induce an adequate longitudinal magnetic field with a coil, the long dimension of the test object should be at least twice as great as its short dimension or end pieces should be added and the long axis of the test object should be parallel to the coil axis. This is especially true in the case of irregularly shaped test objects, because the shape of the object affects the direction of the induced flux.

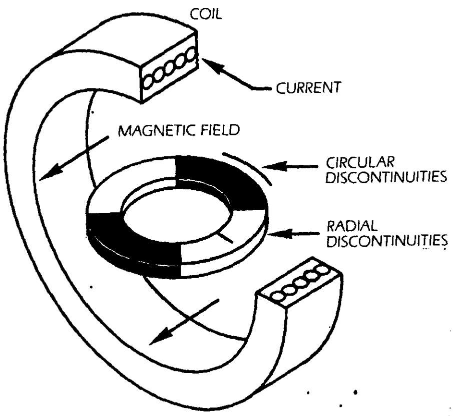
When a wheel, smaller in diameter than a coil, is placed in the coil (as shown in Fig. 15), a field is induced in the white areas of the test object in such a direction that radial discontinuities create indications. However, radial cracks in the shaded areas of the test object are parallel (or nearly so) to the induced magnetic field, so that few or no indications are formed. Furthermore, magnetic poles and attractive forces occur in these areas. To indicate radial discontinuities in the shaded areas, it is necessary to rotate the test object through 90 degrees and remagnetize it, although this technique is not recommended.

The detection of radial cracks in a test object of this shape is more accurately and rapidly done using an internal conductor (see Fig. 14). Better methods for finding circumferential discontinuities in ring shaped test objects are shown in Figs. 5 and 6. Ring shaped objects, disks, wheels or races are best checked for circumferential cracks using the induced method of Fig. 6. An iron core, for example, is used with a coil surrounding it to produce a toroidal field. This method has an advantage over the direct contact method (Fig. 5) in that no danger of arcing or burning exists, and the field is constant throughout the test object.

Yoke Magnetization

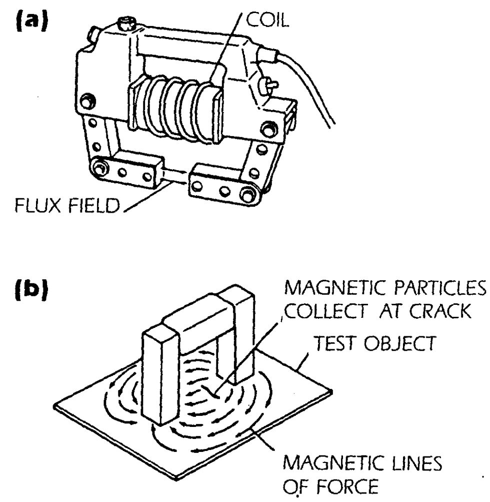
A longitudinal magnetic field can be induced in a test object or in a limited area of an object by using a handheld yoke. A yoke is a *U* shaped piece of soft magnetic material, either solid or laminated, around which is wound a coil carrying the magnetizing current (Fig. 16).

FIGURE 15. Coil magnetization of a circular shape; radial discontinuities will be indicated only in white areas (to reveal radial discontinuities in the dark areas, the test object must be rotated 90 degrees and remagnetized); circular discontinuities will be indicated in the shaded areas (to reveal circular discontinuities in the white areas, the part must be rotated 90 degrees and remagnetized)



When a test object is placed across the opening of the *U* shape and the coil is energized, the object completes the path of the magnetic lines of force. This sets up a longitudinal field in the test object between the ends of the yoke. Permanent magnetic yokes can also be used to create a longitudinal magnetic field (Fig. 16a). Such yokes are often specified by their lifting power or by the tangential field strength midway between the legs.

FIGURE 16. Longitudinal lines of force induced by a yoke magnet: (a) electrically energized yoke magnet and (b) permanent magnet yoke



Combined Circular and Longitudinal Magnetization

Complete testing for discontinuities in different directions requires that two or more magnetizations and tests be performed. The test object should first be circularly magnetized and examined for indications, then longitudinally magnetized and inspected. Demagnetization is the final step.

It is critical to remember that discontinuities are best detected when they are at right angles to the magnetic lines of force.

PART 5
MULTIDIRECTIONAL MAGNETIZATION[1,2,3]

With all magnetizing methods, discontinuities perpendicular to the magnetic flux are optimally indicated. However, discontinuity detection depends heavily on material permeability, flux density and the properties of the testing medium (see Table 1).

It is true that magnetic excitation also permits the detection of discontinuities that are not exactly perpendicular to the flux direction. In this case, the line of flux can be decomposed into two components, one of them parallel and the other perpendicular to the direction of the crack. The perpendicular component contributes to the indication of the discontinuity. In some cases, even cracks appearing to be parallel to the flux direction may be weakly indicated. The reason is that most cracks are ragged in outline (intercrystalline cracks) so that some sections may be properly oriented for detection. However, at best cracks can only be detected when the angle between them and the direction of magnetization is more than 30 degrees.

Combined Direct Current Fields

When a direct current magnetic field of a certain direction and strength is superimposed on one of a different direction and strength, both fields can be combined to form another field as shown in Fig. 17. Physically, the resulting field is formed by the addition of the two magnetic field vectors (something like the combination of forces in a parallelogram). The resulting field has a direction and strength different from either of the primary fields, and is therefore very difficult to predict, especially when induced in complex shapes.

Two or three field directions may be superimposed by sequencing. If the fields vary in strength with time, a swinging vector field is created. It is essential that multiple imposed fields be balanced.

Combined Direct Current and Alternating Current Fields

For combined direct and alternating current magnetic particle testing, two perpendicular magnetic fields are superimposed in such a way that the resulting field changes its direction with time (generally in rhythm with the alternating frequency). The direction change again occurs in such a way that, for at least a short time, some field component is perpendicular to any existing crack direction. This in turn causes a magnetic particle accumulation and subsequent detection.

In the case of a combination of direct current yoke (or coil) with an alternating current flow (Fig. 18), the resulting field swings around the axis of the test object (Fig. 19). This combination of static and dynamic fields results in a vector swinging over an angle. The magnetic vector swings around the position of the direct current field and, in any given position, a sufficient component of it is at right angles to a possible discontinuity. If both fields have the same strength, a total angle range of ±45 degrees (totally 90 degrees) is covered.

The disadvantages of direct current yokes are: (1) stray fields may form at the rounded ends of the test objects or at

FIGURE 17. Superimposition of direct current magnetic fields: (a) addition of field vectors and (b) relationship of field directions

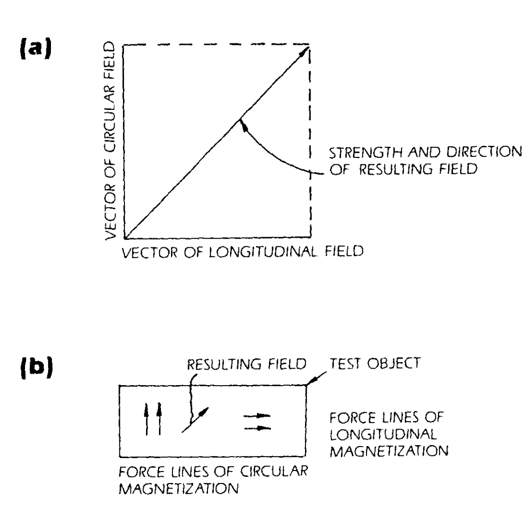


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FIGURE 18. Complete discontinuity detection by the traditional swinging field method (combination of direct current yoke and alternating current head current flow)

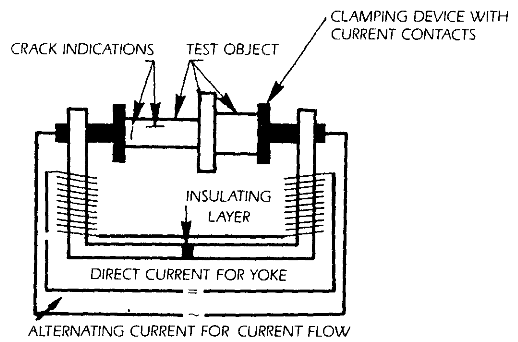

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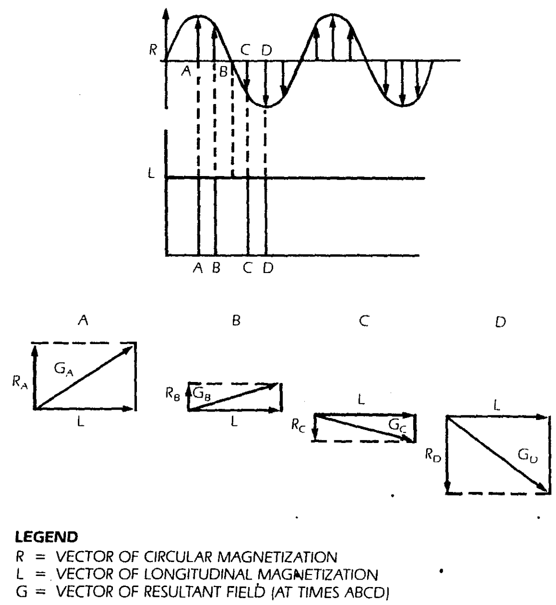
FIGURE 19. Combined crack detection by a circular alternating current and a longitudinal direct current field



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cross-sectional differences between the yoke and the object; and (2) considerable field reduction occurs with large cross-sectional changes of the test object. Similar situations can also occur with coil magnetization.

Combined Alternating Current Fields

It can be advantageous to magnetize in two directions with alternating current fields. An effective combination for periodic alteration of the resulting field vector cannot be realized if the two fields are in phase or in counter phase.

At a phase shift between 50 and 130 degrees, a rotating magnetizing vector of sufficient uniformity can be obtained. At a phase shift of 90 degrees and for equal field strengths, a circularly rotating vector is generated, as illustrated in Fig. 20. When three-phase current from the mains of a phase shift of 120 degrees is used, the behavior is similar (elliptical rotation).

Yoke for Combined Alternating Current Fields

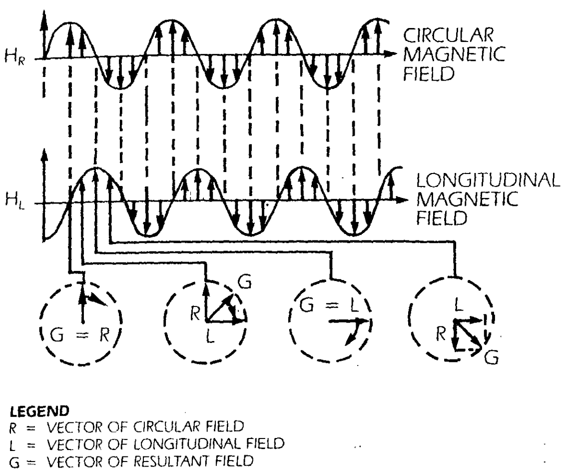
For structural reasons, a direct current yoke of solid steel has been used for many years to indicate transverse cracks. Alternating current yokes have recently been used but they must be assembled from laminated transformer sheet to prevent eddy current losses. These constructions are more expensive than direct current yokes.

Alternating current yokes are usually built to operate over limited clamping lengths, because a longitudinally oriented alternating current field is reduced with increasing clamping lengths.

The advantages of an alternating current yoke are:[1]

1. uniform field distribution, even over test objects with geometrically complicated shapes and over changes of cross section;
2. the possibility of induced field flow;
3. simple and rapid demagnetization of the test object; and
4. short testing times.

FIGURE 20. Alteration of the magnetic field by combination of two phase shifted alternating current fields (rotating vector)



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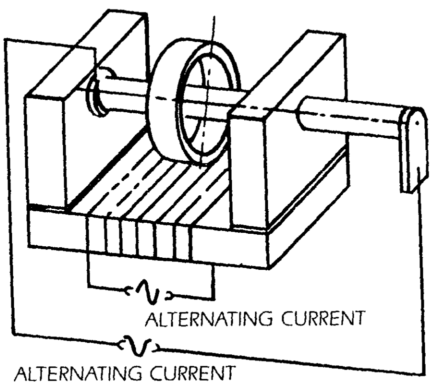
With clamping lengths from 900 mm to 1,200 mm (36 to 48 in.), longitudinal magnetization may better be achieved using a movable alternating current coil.

Testing Procedures with Multidirectional Magnetization[2]

With multidirectional magnetization methods, the resulting magnetic field changes its direction in the rhythm of the alternate frequency of the current application, becoming alternately perpendicular to certain cracks. However, the direction of such a vector is also parallel to a particular crack for a very short time. For this reason, when using the multidirectional method, the application of the testing medium must always take place during magnetization. An indication previously established cannot be held by magnetic force and could theoretically be flushed away by the testing fluid. The procedure does possess a certain inertia; the magnetic vector has already left the parallel direction when the particles begin to move away.

Experience in Germany and more recently in the United States indicates two advantages for the multidirectional magnetization method. The technique can detect very small discontinuities because at some period in the magnetization cycle the field vector is normal to the discontinuity direction. Also, in comparison with the single magnetization procedures (head and coil magnetizations), the combined current method presents considerable economic advantages since it requires only one processing step instead of two or more.

FIGURE 21. Combined auxiliary magnetization by a combination of alternating current flow and current induction methods



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Combined Auxiliary Magnetization

An exceptional variation of the multidirectional magnetization method is called *combined auxiliary magnetization*, used for cylindrical test objects. Here, the auxiliary alternating current flow method is combined with the alternating current induction method (Fig. 21). A magnetizing bar is put through the hole of the test object and this laminated steel, copper coated bar serves as both a current conductor and a phase shifted magnetic field conductor.

This reliable technique is noncontacting, pole free and can indicate cracks of any direction on inside surfaces, outside surfaces and face areas of cylindrical test objects. Combined auxiliary magnetization can be carried out only by systems equipped with an alternating current yoke — contributing still further to the trend toward alternating current yoke techniques (see Table 1).

TABLE 1. Techniques for multidirectional magnetization

Circular magnetization: • current flow method (for solid and tubular test objects) • internal conductor method (recommended for tubular test objects)
Longitudinal magnetization method: • yoke or coil magnetization
Current induction method: • circulating current induced in a ring using a laminated core and the influence of the fluctuating longitudinal alternating current yoke field (Fig. 6)
Combinations of methods for overall coverage in one test mode: • yoke or coil magnetization with current flow or internal conductor method • internal conductor method with current induction method

PART 6

CIRCUMFERENTIAL MAGNETIZATION OF PIPE

The drilling and production of natural hydrocarbons generally require that the tubular product (casing, tubing and drill pipe) be tested for discontinuities. Magnetic flux leakage methods are the most commonly used tests for detection of outer and inner surface discontinuities. Ultrasonic methods are used for testing regions difficult to inspect with magnetic flux leakage techniques.

A common form of testing for longitudinally oriented, surface breaking, tight discontinuities (seams, laps and cracks) involves magnetization of the tube circumferentially by the internal conductor method, followed by testing with some form of magnetic flux leakage sensor. The use of ferroprobes, coils and solid state sensors for this application is summarized in Volume 4 of the *Nondestructive Testing Handbook* series: *Electromagnetic Testing*. The text below deals with the magnetization of oil field tubes and treats magnetic particles as the sensor.

Specifications for Testing Oil Field Tubulars

Specifications and recommended practices for the testing of oil field materials are written by both the American Petroleum Institute (API)[5] and by oil companies.[6] Table 2 summarizes the API documents that pertain to the testing of oil field tubular product by magnetic particle techniques. A more detailed description of these documents is given in the Section titled *Codes, Standards and Specifications for Magnetic Particle Testing.*

Magnetization Methods for Oil Field Applications

Two distinct methods[7] are used for the circumferential magnetization of tubes up to 14 m (45 ft) long (see Fig. 22). Both methods use an insulated rod (generally made from aluminum although this is not required) which passes through the bore of the tube. In Fig. 22a, the rod is reasonably well centered in the bore and fed with some form of direct current. In mill installations, this might be full-wave or half-wave rectified alternating current with the subsequent test being done using wet fluorescent magnetic particles.

In field operations, banks of batteries have been used for current. When the magnetizing current is pure direct current, the magnetic field strength H at the outer surface of the tube, when the conductor is centered within the bore, is given in amperes per meter by:

$$H = \frac{I}{2\pi R_o} \qquad \text{(Eq. 1)}$$

Where:

I = the current (amperes); and
R_o = the outer radius of the tube (meters).

Figure 23 illustrates some of the values used in this discussion. In Eq. 1, the field strength is given in amperes

TABLE 2. American Petroleum Institute specifications and recommended practices for magnetic particle testing of oil field tubular products

Specification 5CT	Specification for Casing and Tubing (first edition, 1988)
Specification 5D	Specification for Drill Pipe (first edition, 1988)
RP 5A5	Recommended Practice for Field Evaluation of New Casing, Tubing and Plain-End Drill Pipe
RP 7G	Recommended Practice for Drill Stem Design and Operating Limits

FIGURE 22. Two methods for establishing circumferential magnetization in elongated tubes: (a) the central conductor method with a battery pack to provide high current; and (b) the internal conductor method with a capacitor discharge system (a peak and duration meter may be used to measure pulse amplitude and duration)

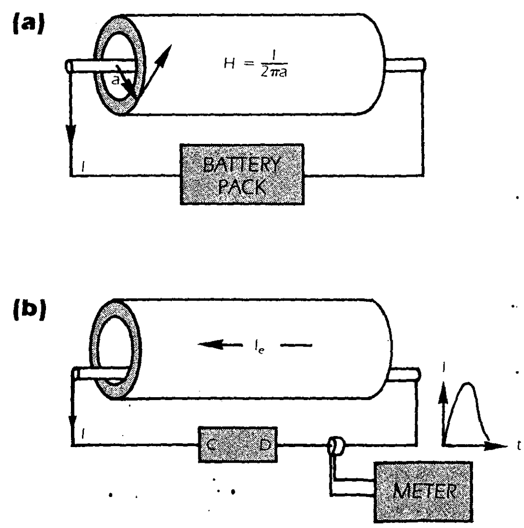
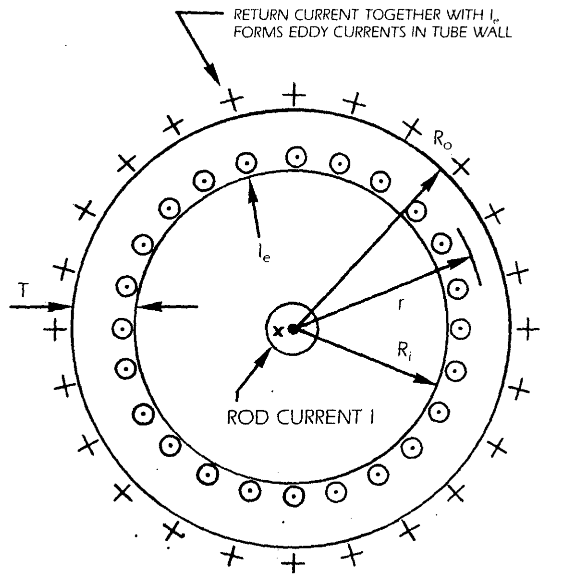


FIGURE 23. The eddy current I_e created in a steel tube at the beginning of a pulse I in a rod centered within the bore of the tube; the direction of I_e on the inner surface opposes that of I; the outer surface forms the return path



per meter since R_o is expressed in meters. However, this field strength is sometimes measured with a Hall element gaussmeter, and since one gauss is numerically equal to one oersted in air, conversion to gaussian units yields:

$$H = \frac{2I}{10R_o} \qquad \text{(Eq. 2)}$$

where I is in amperes and R_o is in centimeters.

The second magnetization method is shown in Fig. 22b. The motive force is provided by a capacitor discharge unit[8] and the necessity for rod centralization is eliminated. Magnetization by this method obeys no scientifically simple rules because the rapid rise of rod current during magnetization causes the induction of an eddy current in the tube and this detrimentally affects penetration of the magnetizing field strength into the material.

The direction of the induced eddy current I_e with respect to the rod current I is shown in Fig. 23 for a centered rod. By Lenz's law, the eddy current induced on the inner surface of the tube must create a field within the material which opposes the field caused by the rod current I. The field strength at some radius r at some instant while the rod and eddy current fields are finite, is given in amperes per meter by:

$$H = \frac{I}{2\pi r} + H_e \qquad \text{(Eq. 3)}$$

The H_e term is the field strength created by the eddy current itself.

The Eddy Current Effect

In considering Fig. 23, Ampere's law indicates that the field at the radius r is caused by the currents inside that radius (rod current and inner wall eddy current). The outer wall eddy current is the return loop for the inner wall eddy current, and plays no role in the theory so far outlined. However, since it does represent an unwanted current flowing in the tube, its presence does lead to two very practical considerations.

First, pipes being magnetized before testing should be insulated from each other by an air gap. If this does not occur, then the outer surface eddy current can jump from protrusions in the pipe being magnetized to the next pipe in the string. The resulting arc can cause burns on both tubes. This in turn can cause hard spots on the materials at which corrosion might preferentially occur. This is particularly to be avoided with corrosion resistant materials, some of which require a hardness less than 22 on the Rockwell C scale for longevity in sour environments.

Secondly, the material should be insulated from the metal racks that carry it. If pipe racks are not insulated with a layer of nonconductive material (rubber or wood, for example), then the outside diameter surface eddy current can flow to ground through the rack and there is a real possibility of arc burn at the point of contact.

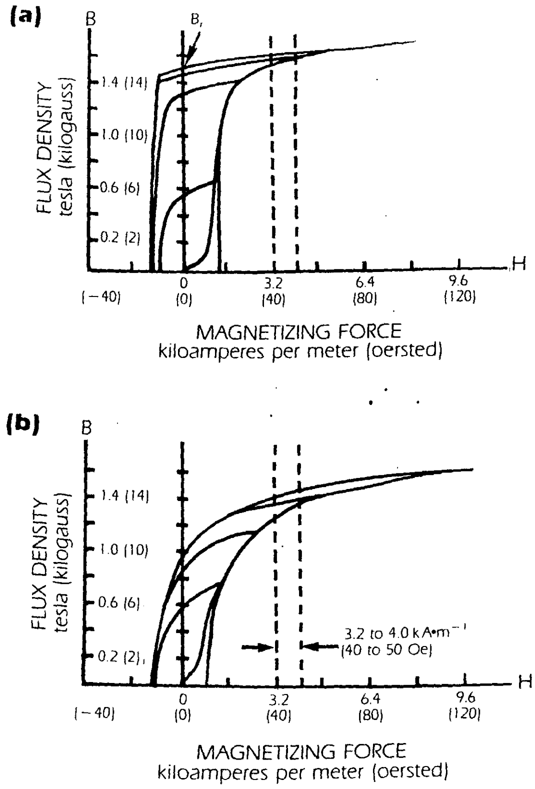
Use of B-H Curve in Setting Specifications

There is an important fact about the magnetization of test objects by the capacitor discharge, internal conductor method: the ring sample *B-H* curve governs the flux density value in the material. In effect, knowing the *B-H* properties of the material from a ring sample investigation allows field strength levels to be set. Figure 24 shows the *B-H* properties of two typical oil field tubular materials: a 620 MPa (90,000 psi) proprietary material (DSG-90) and a 390 MPa (55,000 psi) K-55 casing material.

The important point that can be made from these curves is that after application of about 3,200 $A{\cdot}m^{-1}$ (40 Oe), the materials are effectively saturated.[9] It is generally true of oil field tubular materials that 3,200 to 4,000 $A{\cdot}m^{-1}$ (40 to 50 Oe) are required within the material to magnetize to a level sufficient for subsequent residual induction testing. It is required that this field strength level be reached at each point in the tube wall, despite the demagnetizing effect of the eddy current.

This requirement does not lead to a simple current equation that can be used by a typical operator in the field (experimental specifications found effective in saturating tubes are presented later in this Section).

FIGURE 24. Magnetizing force versus flux density (B-H) curves: (a) high strength (DGS-90) tubular; material is a sour gas grade of special chemistry and heat treatment; and (b) a lower strength (K-55) oil field casing; the dashed lines indicate that the materials are magnetized almost to saturation by application of 3.2 to 4.0 kA•m^{-1} (40 to 50 Oe)



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Typical Requirements for Direct Current Magnetization

If the central conductor method is used for the magnetization of tubes, then the values given in Table 3 reflect the magnetizing field at the outside diameter of either 3,200 $A{\cdot}m^{-1}$ (40 Oe) for I_1 or 4,800 $A{\cdot}m^{-1}$ (60 Oe) for I_2 for typical pipe sizes. Since the magnetization method is direct current, then the wall thickness, mass per meter (weight per foot) and tube grade — which affect the magnetic and electrical properties of the material — do not affect the field strength. The actual value used is often determined by specifications, as agreed between the manufacturer of the material and the user. A typical specification[6] is given by:

$$I = 12{,}000\ D \qquad \text{(Eq. 4)}$$

where D is the tube diameter in meters, and:

$$I = 300\ D$$

TABLE 3. Current requirements for direct current magnetization of oil field tubes; direct current or long pulse (> 0.5 s) only; not valid for capacitor discharge magnetization

Tube Diameter millimeters (inches)	I_1* (amperes)	I_2** (amperes)
60 (2.4)	600	910
73 (2.9)	730	1,100
89 (3.5)	890	1,340
102 (4.0)	1,020	1,530
114 (4.5)	1,150	1,720
127 (5.0)	1,280	1,910
140 (5.5)	1,400	2,100
168 (6.6)	1,690	2,530
178 (7.0)	1,790	2,680
194 (7.6)	1,940	2,920
219 (8.6)	2,200	3,300
244 (9.6)	2,450	3,680
273 (10.8)	2,740	4,110
298 (11.8)	3,000	4,500
340 (13.4)	3,410	5,120

* 3.2 kA•m^{-1} (40 Oe) AT OUTSIDE DIAMETER
** 4.8 kA•m^{-1} (60 Oe) AT OUTSIDE DIAMETER

where D is the tube diameter in inches. This *amperes per diameter unit* specification is equivalent to 3,760 A•m^{-1} (47 Oe) at the tube surface. It can be seen from Fig. 24 that such a field strength raises the value of the flux density in the tube to a high level, so that after the field has fallen to zero, the flux density in the material is at a value close to remanence (B_r).

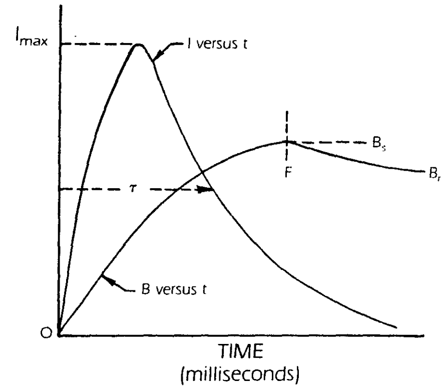
Full-Wave and Half-Wave Rectified Alternating Current

For the central conductor method outlined above, some form of rectified alternating current is often used. It should be noted that such current waveforms induce eddy currents in the test object. The field strength waveform at the outer surface can be seen by positioning a Hall element to detect the field and feeding the output of the gaussmeter to an oscilloscope.

Pulsed Current Magnetization

Internal conductor magnetization (using single pulses of current) differs from direct current or continuous magnetization by the central conductor method because account must be made for the fact that the induced eddy current may not have time to die away before the field strength from the conductor current dies away. Figure 25 shows two time variations that are measurable for single pulses, such as are provided by capacitor discharge units. The first variation is that of the magnetizing current (I versus t). In this variation, a relatively rapid rise of current to its maximum value I_{max} is followed by a much slower fall toward zero, the entire pulse length being on the order of 200 ms. This time variation is the response to the discharge of a capacitor C, initially charged to V_o volts through a resistor R in a circuit containing inductance L. A simple mathematical analysis is provided later.

FIGURE 25. Plots of the capacitor discharge internal conductor current (I versus t) and the average flux density induced (B versus t) in a tube; I_{max} and τ are measured with a peak and duration meter; note that the flux density peaks well after the current



The second variation is that of the average bulk flux density within the material (B versus t). This quantity rises at a much slower rate than $I(t)$ due to the shielding effect of I_e. A high level of magnetization is reached when the flux density at the point F is close to the material's saturation value B_s. The consequences of conditions shown in Fig. 25 are that deep magnetization of the tube only occurs when the detrimental effect of the eddy current is overcome by elongating the electrical pulse in time so that the magnetizing current is still effective as the eddy current is dying away.

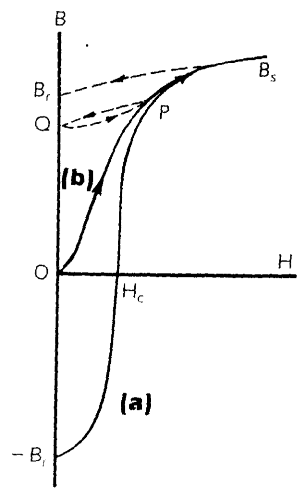
The fall in induction from F to B_r is that which is normally expected when the magnetizing field strength falls to zero, as it does after the passage of a pulse. This is determined by the B-H curve for the material undergoing magnetization. Should the point F not represent saturation (B_s), then the material reaches some average bulk flux density lower than B_r. This is often not a problem: while the surfaces are magnetized sufficiently for longitudinally oriented discontinuities to hold magnetic particles, no information of the interior condition is required. However, in the case where relatively thin elongated tubulars can be tested from the outside diameter surface only, saturation of the material is necessary for inside diameter discontinuities to produce magnetic flux leakage at the outside diameter.

Practical Testing Situations

Commonly encountered testing situations for the magnetization or remagnetization of tubulars are discussed below, including: (1) material at unknown induction; (2) material at zero induction; and (3) material not saturated by pulse.

The magnetic condition in which a sample arrives is often not known to the inspector, who must assume the worst possible case: the material is at saturation in a direction directly opposed to that caused by the magnetic particle test equipment. This is resolved by taking the material from an unknown value of remanence in one direction to remanence in the other direction as is shown in the schematic *B-H* curve for the material (Fig. 26).

FIGURE 26. Possible paths taken by circumferentially magnetized material from various initial magnetization conditions to saturation B_s and then remanence B_r in a known direction: (a) material at remanence in the opposite direction; (b) material at zero induction; point P indicates weak pulse followed by a second pulse



A material might also arrive with an induction between zero and $-B_r$ and it is desired to perform testing at $+B_r$. During magnetization, the material should take the path $-B_rH_cPB_sB_r$. That is, through saturation B_s to remanence B_r.

In the case of material initially at zero induction, the tube is at 0 on Fig. 26 and during magnetization takes the path OPB_sB_r.

In cases where the pulse is insufficiently strong, the material may follow a magnetization path such as $-B_rH_cPQ$ or OPQ. It is then essential to pulse more than once. A possible magnetization path during a second pulse is QB_sB_r. The net final induction is raised as shown.

Analysis of Pulse Current Magnetization

In the text below, an analysis of the pulse current internal conductor method for magnetizing elongated tubulars is presented. Simplified equations are given for the types of current pulses available for magnetization. From the theoretical viewpoint, the current pulse time dependence (I versus t of Fig. 25) is discussed and then formulas are presented for the inductance experienced by the magnetizing circuit.

These formulas illustrate the dependence of such inductances (1) on the average value of the differential permeability (dB/dH) of the object under magnetization; and (2) between the field strength and flux density limits imposed by the exciting current and *B-H* properties of the material.

Current Pulse Time Dependence

For *LCR* circuits, the time variation of the current pulse obeys the equation:

$$\frac{d(LI)}{dt} + IR + \int I \frac{dt}{C} = 0 \qquad \text{(Eq. 5)}$$

The three terms on the left of Eq. 5 represent the instantaneous voltages across the inductance, the resistance and the capacitance in the circuit (Fig. 22b). The inductance in the circuit is mainly that of the rod tube system, since by careful design the presence of additional inductance between cables and ground can be minimized. Because inductance is time dependent, it is included in the derivative term. The resistance is the combined resistance of the rod, cables and their connection, and any internal resistance in the capacitor discharge box. Resistance in the discharge box may be due to the forward resistance of a silicon controlled rectifier included to eliminate the possibility of current oscillation. The capacitance of the system is generally in the region of 2 to 8 F.

Equation 5 has three solutions if the time dependence of L is ignored. These solutions depend on the relative values of L, C and R.

$$I = \frac{2V_o}{\sqrt{\frac{4L}{C} - R^2}} \exp(-\beta t) \sin\sqrt{\frac{4L}{C} - R^2}\, t \qquad \text{(Eq. 6)}$$

$$I = V_o C(\beta^2 t) \exp(-\beta t) \qquad \text{(Eq. 7)}$$

$$I = \frac{2V_o}{\sqrt{R^2 - \frac{4L}{C}}} \exp(-\beta t) \sin h\sqrt{R^2 - \frac{4L}{C}}\, t \qquad \text{(Eq. 8)}$$

Where:

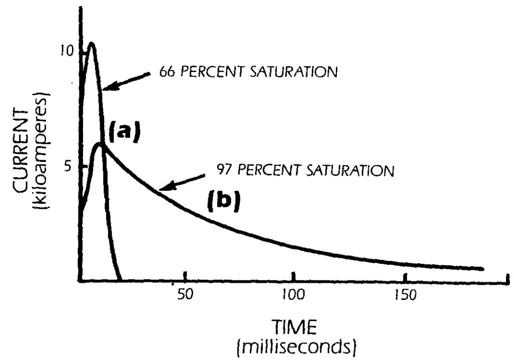
V_o = the voltage to which the capacitor bank is charged; and
β = $R/2L$.

The solution to Eq. 6 is oscillatory, but the presence of the *SCR* limits the pulse to only the first positive-going peak. This is shown in Fig. 27. In this example, the pulse has a length of 17 ms and reaches 10,500 A. Such pulses are ideal for magnetizing objects of low electrical conductivity, such as ferrite magnets. However, with highly conducting materials such as steel tubes, the initial rapid current rise (up to millions of amperes per second) induces a shield of eddy currents that does not permit field penetration into the bulk of the material. The net effect of this is a magnetized outer layer only.

The exponential solution (Eq. 7) is known in its mechanical analog as *critical damping*. It is difficult to achieve in this situation because it depends on the value of L which in turn is dependent on the physical and magnetic parameters of the test object. The formula for the inductance of a tube is given below.

The sin h solution (Eq. 8) leads to the longest pulses because there is no oscillation. Pulses of full length up to 160 ms are commonly used in the oil tube testing industry (Fig. 27b).

FIGURE 27. Typical pulses from capacitor discharge systems; the longer pulse is more effective in magnetizing a tube sample (line pipe): (a) short pulse and (b) long pulse



Definition of Pulse Length

It has become commonplace to define the length of such pulses as the time taken for the pulse to reach 0.5 I_{max} during decay τ (Fig. 25). Both I_{max} and τ are measurable with an inductive ammeter or peak and duration meter (Fig. 22b). Such pulses are effective in magnetizing tubular test objects because the field strength from the rod current is still high as the eddy current in the test object dies away, so that penetration of the field into the bulk of the material occurs.

Since the inductance is a function of time, a full solution for the variation of the pulse current $I(t)$ can only be obtained by modeling the effect that the induced eddy current has on the instantaneous value of L. Experimental evidence indicates that, at least for elongated tubulars, the physics of the magnetization process can be illustrated by a discussion of the constant L case.

Typical Values for L, C and R

In the design of a capacitor discharge pulsing system, it is essential to aim at a pulse that has sufficient length to deeply magnetize the material. There are two reasons for this. First, the material to be tested may arrive at the test site in a longitudinally magnetized condition and it may be necessary to remagnetize it circumferentially prior to testing. Second, some specifications call for relatively low emergent longitudinal field strengths at the ends of such elongated test objects. Rotation of the bulk flux density into the circumferential direction may be simplest way to achieve this.

An additional consideration unrelated to the physics of the magnetization of the test object is the safety of the system in both installed and field situations. The National Electric Code should be consulted for details. However, it appears essential for field use to limit the charging voltage of the capacitor bank to 50 V. The tendency of this restriction is to add capacitance to the system.

The resistance of the magnetization system is a factor in permitting high currents to flow. It is minimized for field use by employing parallel strands of AWG 0000 copper welding cable for the connections between the rod and the capacitance discharge box. The rod is made of aluminum (mainly because of the continued need to make and break the rod) but any highly conductive material would work equally well. The requirement of elongating the pulse length to ensure the presence of its field after eddy currents have died away far outweighs the requirement of minimizing the overall resistance of the magnetizing circuit. Typical values, which might include that of 5 m (16 ft) of cable and 15 m (49 ft) of rod, are 1 to 5 milliohms.

The capacitance within the capacitance discharge supply is generally within the range of 2 to 8 F, which is comparatively large. This occurs because of the need to maintain relatively low voltages around the circuit and to elongate the pulse.

While the values R and C can be controlled by the manufacturer, the value of L cannot, mainly because it depends on the test object undergoing magnetization. In the case of tubulars, the inductance is given by:

$$L = \frac{\ell}{2\pi}\left(\frac{dB}{dH}\right)\ln\frac{R_o}{R_i} \qquad \text{(Eq. 9)}$$

Where:

ℓ = the length of the tube;
dB/dH = the differential permeability;
R_o = the outer radius; and
R_i = the inner radius (see Fig. 23).

It often occurs that the wall thickness T is much smaller than the average radius of the tube. Under these circumstances, Eq. 9 may be converted to:

$$L = \frac{\ell}{2\pi}\left(\frac{dB}{dH}\right)\ln\frac{r+\frac{T}{2}}{r-\frac{T}{2}} \qquad \text{(Eq. 10)}$$

which reduces to:

$$L \sim \frac{\ell T}{2\pi r}\left(\frac{dB}{dH}\right) \qquad \text{(Eq. 11)}$$

Using the International System of Units (SI), Eq. 11 becomes:

$$L \sim 0.16\left(\frac{\ell T}{r}\right)\left(\frac{dB}{dH}\right) \qquad \text{(Eq. 12)}$$

where r is $0.5(R_o + R_i)$. All lengths are in meters and dB/dH is dimensionless (see Fig. 29).

The inductance of thin walled tubes is seen from Eq. 11 to be proportional to the length (ℓ) and wall thickness (T) of the tube, and inversely proportional to its radius or diameter. Neither of these physical parameters nor the value of dB/dH can be controlled by the designer of the magnetizing equipment.

For much of the tubular product used in oil fields, the value of T/R does not vary a great deal, perhaps only by a factor of two. The average value of dB/dH encountered during magnetization can be seen from Fig. 26 to vary widely, depending on (1) the point (P) reached on the B-H curve by the material during magnetization; and (2) the starting point for magnetization (anywhere from $-B_r$ to Q on the B axis). Examples of typical inductances follow.

Example 1: pipe magnetized to saturation following the path $-B_rH_cPQ$.

B_r = 1.2 T (12 kG)
P = 1.2 T (12 kG)
ℓ = 10 m (33 ft)
T = 12.6 mm (0.5 in.)
r = 136.5 mm (5.4 in.)
dH = 2,400 A•m^{-1} (30 Oe)

Here dB is 24,000 G, so dB/dH = 800, and

L = (2 × 10^{-7})(10 m)(12.6 mm)(800)/(136.5 mm)
= 148 μH

Example 2: same tube as example 1, taken from Q through P and B_s to B_r by a second pulse.

Q = 1.0 T (10 kG)
B_s = 1.5 T (15 kG)
dH = 4,000 A•m^{-1} (50 Oe)

The average value of dB/dH is now only 100. Dividing the value obtained in example 1 by 8, the ratio of the two values of dB/dH exhibited by the steel yields:

L = 18.5 μH

Example 3: pipe initially unmagnetized follows path OPB_sB_r with:

$$
\begin{aligned}
B_s &= 1.5\ T\ (15\ \text{kG}) \\
&= 9.09\ \text{m}\ (30\ \text{ft}) \\
T &= 4.83\ \text{mm}\ (0.2\ \text{in.}) \\
R &= 27.7\ \text{mm}\ (1.1\ \text{in.}) \\
dH &= 3{,}200\ \text{A}\bullet\text{m}^{-1}\ (40\ \text{Oe})
\end{aligned}
$$

So that:

$$
\begin{aligned}
L &= (2 \times 10^{-7})(9.09\ \text{m})(4.83\ \text{mm})(15{,}000/40)/(27.7\ \text{mm}) \\
&= 119\ \mu\text{H}
\end{aligned}
$$

The relatively large change in inductance exhibited by the tube in examples 1 and 3 affects the shape of the pulse waveform, notably the easily measurable parameters of peak current I_{max} and pulse duration τ. These parameters are shown in Fig. 25.

Design Considerations

Good equipment design must include user input about the material being magnetized. The worst case for the internal and external resistances of the magnetizing system should be known to the manufacturer and worst values of inductance should be investigated. Under no circumstances should peak currents be stated for the purpose of magnetization withc.t an electrical and magnetic load being used for the system evaluation.

Depending on the use of the equipment, the relevant regulations should be consulted with regard to insulation, isolation, explosion proofing, intrinsic safety and purging. Such regulations are found in a variety of places, depending on the use of the product. Notable among these are the Occupational Safety and Health Administration (OSHA), the National Institute of Occupational Safety and Health (NIOSH), Code of Federal Regulations (CFR) and a variety of foreign specifications, many of which are a great deal more stringent than those in the United States.

Equipment designers should particularly note the requirements of the CSA when designing for Canada; the requirements of the United Kingdom, Norway and West Germany are applicable when designing for the North Sea.

Magnetization Recommendations

Tubular product has such wide limits of diameter and wall thickness that it is difficult to provide a universal specification for the measurable parameters of current pulses for a high level of residual induction. However, broad guidelines based on research with a variety of tubes indicate that the values given in Table 3 provide adequate magnetization.

Pulse Duration

In Table 4, pulses are classified by duration. Long duration pulses are those in excess of 100 ms. For such pulses, the induced eddy current can be assumed to have died away while the magnetizing field strength is still high enough to cause saturation. Moderate duration pulses are those between 40 and 100 ms. For magnetization, the longevity of the induced eddy current is acknowledged by its effect on the tube (shown through the use of the lineal mass of the tube rather than the outer diameter). Short pulses are those below 40 ms. The maximum current requirement for the single short pulse compared to that for the single moderate pulse is higher for the same lineal mass of tube. In effect, the higher current causes a larger magnetizing field strength in an attempt to overcome the eddy current.

Should it be necessary to use two such pulses, the peak current requirement falls because the material is partially magnetized. If the peak current can only reach I_{max} = 180 (W), then two such pulses are required. Should the pulse be of insufficient magnitude to magnetize the tube with two pulses, then a third pulse is necessary so that the three pulses meet the requirement of I_{max} = 145 (W).

These requirements are designed to ensure that the bulk induction following the pulses is at least 90 percent of the remanence value. In most cases it is higher.

TABLE 4. Pulse classification by duration with current requirement

Magnetization System	Duration (milliseconds)	Current Requirement Equation
Long pulse	> 100	I = 11.8 (D_1)
		I = 300 (D_2)
Moderate pulse	40 to 100	I = 74 (W_1)
		I = 110 (W_2)
Single short pulse	0 to 40	I = 161 (W_1)
		I = 240 (W_2)
Double short pulse	0 to 40	I = 121 (W_1)
		I = 180 (W_2)
Triple short pulse	0 to 40	I = 97 (W_1)
		I = 145 (W_2)

I = CURRENT IN AMPERES
D_1 = OUTER DIAMETER IN MILLIMETERS
D_2 = OUTER DIAMETER IN INCHES
W_1 = TUBE WEIGHT IN KILOGRAMS PER METER
W_2 = TUBE WEIGHT IN POUNDS PER FOOT

Current Pulse Effectiveness

There are two methods used to evaluate the effectiveness of a current pulse. A third technique, which detects surface fields only, is also outlined here. The first method is a variation on the Rowland ring technique for the evaluation of the magnetic parameters of magnetizable materials, and involves the measurement of magnetic flux. The second method is an indirect technique using an inductive ammeter (peak and duration meter). The third method uses simulated contact discontinuities.

The Fluxmeter Method

Magnetic fluxmeters measure the total magnetic flux threading an area defined by a search coil. In the case of circumferential magnetization of a hollow product by the internal conductor method, the search coil can be a single-turn coil through the test object. Flux changes are given by:

$$\Delta\Phi = A\Delta B \qquad \text{(Eq. 13)}$$

Where:

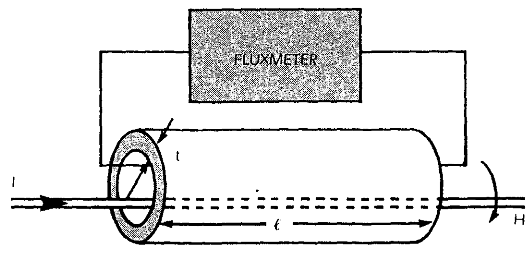
$\Delta\Phi$ = changes in flux;
A = the area of the test object perpendicular to the search coil ($A = t\ell$); and
ΔB = the change in flux density of the test object induced during magnetization.

Commercially available fluxmeters can generally be compensated for the test object area so that the device can be made to read the average flux density directly. The problem with this approach to the measurement of the final flux density is that the initial flux density in the test object, with respect to the vector direction of the search coil, must be zero. This problem occurs because, when flux changes are to be measured, the initial value must be known. However, if the tube shown in Fig. 28 is initially unmagnetized or the prior magnetization is longitudinal, then the fluxmeter reads the average density of induced circumferential magnetization.

Should the output of the fluxmeter be presented on an oscilloscope, it should be noted that flux values (caused by the passage of a pulse) between the beginning and the end of the magnetization process represent the flux linked by the single turn coil and contain the effect of the flux in the air between the terminals of the fluxmeter.

During the pulse, the air field caused by the current I in the rod and eddy currents I_e in the test object affects the instantaneous fluxmeter reading. When these currents have died away, only flux perpendicular to the single-turn coil affects the final result. If the operator has time to wind more than one turn around the test object, the resulting error in final bulk flux can be reduced. However, for the purpose of establishing the presence of a residual induction in the test object to excite magnetic flux leakage from discontinuities, this procedure is not necessary.

FIGURE 28. Measuring the flux density induced in the circumferential direction by the methods shown in Fig. 22



The Inductive Ammeter Method

Figure 29 shows an inductive ammeter or peak and duration meter.[9] As shown in Fig. 22b, the pickup coil of the device is threaded onto any convenient part of the magnetizing circuit and when the pulse is fired the meter reads the peak current (I_{max} of Fig. 25) and the duration of the pulse (τ of Fig. 25).

Saturation of the material occurs when successive readings on the ammeter are identical. This can be explained as follows. When the first pulse is fired, the material exhibits its highest value of dB/dH because of the inclusion of the steep part of the B-H curve into the value of L (Fig. 27). The average value of dB/dH is effective in determining the value of the inductance in Eqs. 6, 7 and 8. This value is relatively large compared to what the material might exhibit during a second pulse. High values of dB/dH for a first pulse (0.001 $T{\cdot}m{\cdot}A^{-1}$ in the SI system or 800 in the gaussian system) correspond to lower values during the second pulse (1/8,000 $T{\cdot}m{\cdot}A^{-1}$ in the SI system or 100 in the gaussian system). In effect, the second pulse experiences a lower inductance than the first pulse.

The effect of the lowered inductance experienced by a second pulse is to permit the peak current I_{max} to reach a higher value than it reached on the first pulse — in effect, the material is different — but the system response is also to lower the duration τ. By monitoring I_{max} and τ, it is possible for inspectors to determine the relative degree of magnetization of the test object.

FIGURE 29. Inductive ammeter or peak and duration meter; measures the peak current I_{max} in kiloamperes and pulse duration τ in milliseconds for magnetizing current pulses

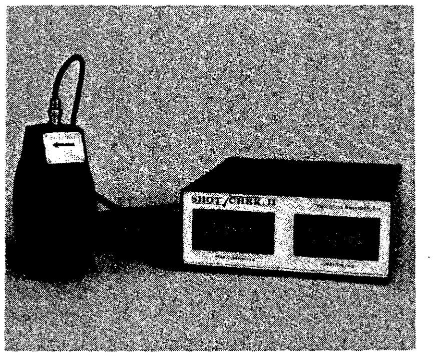


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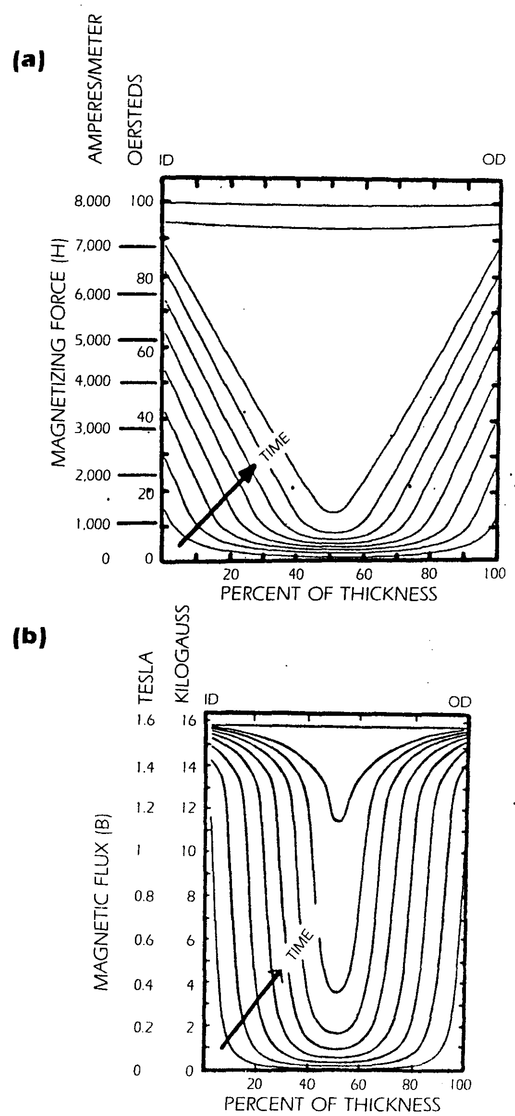
FIGURE 30. Plots of tube wall thickness versus: (a) magnetizing force; and (b) resultant flux density; the lower lines represent field and induction at the beginning of the pulse (time proceeds up the figures); the central regions are the last to be magnetized



The Simulated Test Discontinuity

Strips of high permeability material are commercially available and these may be placed in intimate contact with the test object after magnetization. Such strips contain three test discontinuities encapsulated in brass so that the lift-off between the test object and the strip is minimized to that of the brass encapsulation.

Under such circumstances, the magnetized material shares flux with the strip and, if the test discontinuities give an indication with magnetic particles, then so will a similarly sized discontinuity in the test object.

Use of Inductive Ammeters

When magnetizing with pulse techniques, the value of the material's field strength H and flux density B both change with time. In Fig. 30, the horizontal axes show the percent distance from the inside diameter surface to the outside diameter surface. The vertical axes show either the fraction of H required to saturate the material or the flux density B. The lowest lines indicate time from the very start of the pulse. The uppermost lines indicate the field strength and flux density levels at later time increments.

It can be seen from Fig. 30 that three phenomena occur during pulse magnetization: (1) both inner and outer surfaces are rapidly magnetized; (2) the midwall region is the last part of the material to be magnetized; and (3) the midwall region can be left with a low state of magnetization if the pulse field strength is insufficient to saturate the material.

This last phenomenon contributes to magnetic fields from discontinuities at one surface, producing no leakage field at the other surface, when the material is not saturated. The leakage field into the midwall section of the material merely raises the local magnetization level to a higher degree.

During magnetization, if parts of the material do not reach a field strength level that ensures saturation (the point P in Fig. 26), then the ensuing bulk residual flux density is low and the material requires additional pulses to saturate it. The magnetization process calls for the highest values of the inductance L in Eqs. 5 through 12 during the first pulse and lower values during subsequent pulses. The general effect of a high value of inductance is to lower the value of I_{max} and elongate the value of τ.

In order to show that this is the case, and to limit the necessary mathematical computation, Eq. 7 is selected and from it the closed form results for I_{max} and τ are found. First, the time t (in seconds) at which I_{max} occurs is found by differentiation of Eq. 7 to be:

$$t = \frac{2L}{R} \qquad \text{(Eq. 14)}$$

Where:

L = self inductance (henrys); and
R = resistance (ohms).

When this value is used in Eq. 7, the result for I_{max} is:

$$I_{max} = V_o C \frac{R}{2Le} \qquad \text{(Eq. 15)}$$

Where:

V_o = voltage; and
C = capacitance (farad).

This result indicates that the value of I_{max} is inversely proportional to that of L (the greater is L, the lower is I_{max}). In order to find τ, $I(t)$ must be set at 0.5 I_{max}. The result in seconds is:

$$\tau = 5.36 \frac{L}{R} \qquad \text{(Eq. 16)}$$

In this case, the pulse duration as defined by τ is proportional to the value of L. Larger values of L, such as are found for the initial pulse, lead to the longest pulse durations.

The B-H curve indicates that the lowest value of inductance that can occur under these magnetization conditions is that exhibited by saturated material, when the value of dB/dH is at its lowest (see Eq. 11). If two identical readings are obtained from an inductive ammeter as shown in Fig. 22, the material must be exhibiting its lowest inductance to the magnetizing circuit and must therefore be at remanence B_r.

Operation of Inductive Ammeters

The inductive ammeter is a microprocessor based instrument that employs an inductive pickup coil. This coil contains a large number of turns wound onto a nonconducting nonmagnetic ring shaped core. It is threaded onto the cables from the capacitor discharge system or onto the rod itself. When a pulse is fired, the flux caused by the current surge links with the ring and the voltage induced in the coil (see Fig. 31) is given by:

$$E = (2 \times 10^{-7}) N d \frac{dI}{dt} \ln \frac{b}{a} \qquad \text{(Eq. 17)}$$

Where:

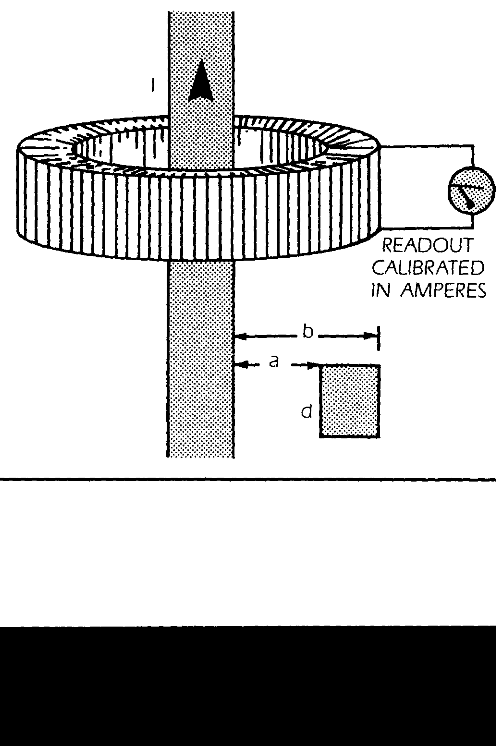
N = the number of turns in the ring;
d = the axial length of the ring;
b = the outer radius of the ring;
a = the inner radius of the ring; and
dI/dt = the rate of change of the current.

This equation is derived from Faraday's law of induction. In order to provide a signal related to the current itself, Eq. 17 must be integrated. The result is:

$$e = \int E \cdot dt = \left[(2 \times 10^{-7}) N d \ln \frac{b}{a} \right] I \qquad \text{(Eq. 18)}$$

Here, e is the output voltage of the integration circuit. Since all the terms in the brackets are known, the output of the integration of the induced voltage is proportional to the instantaneous current, and the instrument can be calibrated to read current. Electronic circuits are used to measure the peak current I_{max} and the pulse duration τ.

FIGURE 31. Diagram of an inductive pickup coil (dimensions used in Eq. 17)



PART 7

MAGNETIC FLUX IN TEST OBJECTS WITH COMPLEX SHAPES

When a discontinuity lies perpendicular to the magnetic field and is at or near the surface, a leakage field occurs which attracts and holds magnetic particles applied to the test object surface. The capturing and holding power of the leakage field is determined by both the size of the discontinuity and the magnitude of the magnetic flux in the test object.

There are rules used to define the current needed and how it is applied to produce the desired direction and flux density in the test object. Those rules, along with recommended particle concentrations, are specified in military and commercial specifications. Unfortunately, many complex ferromagnetic aircraft components have varying cross sections, large cutouts and protruding extremities. With these, it is difficult to apply empirical rules that guarantee effective testing of the object in its entirety.

The testing of the object shown in Fig. 32 has been detailed in the literature.[11] The direction and intensity of the external flux fields are measured using circular and longitudinal magnetization by means of a transverse Hall probe gaussmeter. The magnitude of the current pulse is determined from empirical rules in order to ascertain the validity of the rule in each case. The determination of the field direction and magnitude does not reveal the field level required for crack detection but does uncover problem areas caused by part geometry. Locations having cross-sectional areas significantly larger than those where the current enters the test object exhibit fields whose magnitudes are extremely low compared to those at the entry area (points 5, 6 and 7 in Fig. 32).

FIGURE 32. Complex shape of steel forging for aircraft

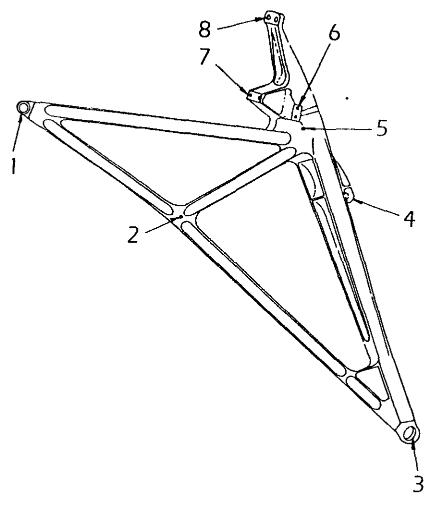
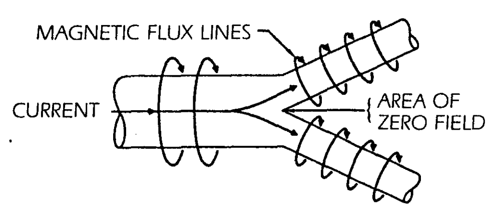


FIGURE 33. Typical geometry problem in magnetic particle testing



Magnetization was performed using full-wave direct current techniques. Low fields were also observed in deep cutouts (between points 6 and 7 of Fig. 32) and at the extremity areas not directly in the path of the current flow (points 4, 6 and 7 of Fig. 32). Any area producing a field of less than 10^{-3} T (10 G) was deemed inadequately magnetized. It was also determined that when the current branched into different directions at an intersection, the field at this intersection was zero (see Fig. 33 and points 1, 2, 3 and 5 of Fig. 32). These particular areas required additional tests using portable electromagnetic yokes.

When dealing with complex test objects, initial investigations concerning the direction of the flux field and adequacy of field strength should be determined using calibrated artificial discontinuity shims placed at a sufficient number of locations on the test object. Special techniques are required to establish adequate field strength and direction in some areas of the test object. The techniques should be documented for future reference when identical objects are to be tested. In cases of high production rates, special magnetizing tools may need to be fabricated to achieve reliable testing of the entire test object. This is important because areas containing changes in shape or thickness are likely locations for development of cracks during fabrication or service.

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SECTION 7

MAGNETIC LEAKAGE FIELD MEASUREMENTS

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PART 1

FUNDAMENTALS OF MAGNETIC FLUX LEAKAGE FIELDS

Magnetic particle testing is not an isolated technical discipline. It is a combination of two distinct nondestructive testing techniques: magnetic flux leakage testing and visual testing. The basic principle of the magnetic particle technique is to magnetize an object to a flux density that causes magnetic flux leakage from a discontinuity. Powdered ferromagnetic material is then passed through the leakage field and those held over the discontinuity are visually interpreted by the operator.

From a theoretical point of view, the only difference between magnetic flux leakage testing and magnetic particle testing is the use of iron or iron oxides as a sensor. In effect, magnetic particles may be considered a commonly used form of sensor for the detection of magnetic flux leakage (sometimes called *stray fields*).

The key to ideal magnetic particle testing is to provide the highest sensitivity to the smallest discontinuities by a careful combination of: (1) applied magnetic field strength. $H(t)$; (2) flux density $B(t)$ in the test object; (3) particle size and application method; and (4) optimal viewing conditions. In order to do this, experiments are necessary with all of the parameters. The best combination is then chosen for a particular application.

Writers of specifications have often over-generalized this empirical process in order to provide the magnetic particle test operator with a set of rules that govern all situations. This generalization can lead to inappropriate specifications for certain magnetic particle tests.

There are many forms of magnetic field sensors, including the Hall element, the magnetodiode, the ferroprobe and the sensor coil.[1,2] Tape recorder heads are magnetic sensors, as are the triaxial flux gate magnetometers that are orbited above the Earth to detect very small changes in magnetic fields. The purpose of this chapter is to provide details about the use of sensors in measuring and detecting fields for magnetic nondestructive tests.

Inducing Magnetic Flux Leakage

The essence of all magnetic flux leakage testing is to induce a magnetic flux density $B(t)$ around a discontinuity. The flux density may or may not be time dependent but should be at such a level that some of the flux is displaced by the discontinuity's higher magnetic reluctance. The displaced flux is forced out of the object's surface into the surrounding environment (air or water), where it can be detected (see Fig. 1).

Magnetizing Current

To induce flux leakage, magnetizing current can be passed through the test object by direct contact. This is commonly done but because of the danger of arc burns, it is not always recommended (see Fig. 2). Insulated current carrying rods or cables may be used, by passing them through holes in the test object. Other alternatives are the use of coils to carry the current around the test object and the use of electromagnets or permanent magnets applied to the test object.[3]

When current is present, there is an associated field strength $H(t)$ that raises localized areas to various flux density $B(t)$ values, based on the B-H properties of the test material. Figure 1 shows a computer simulation of field lines in and above a material at some value below magnetic saturation, as can be seen from the bending of the field lines under the discontinuity.[4]

FIGURE 1. Field lines around, through and above a discontinuity (an oblique slot), as computed by a finite element computer model; note the asymmetry of the magnetic flux leakage field

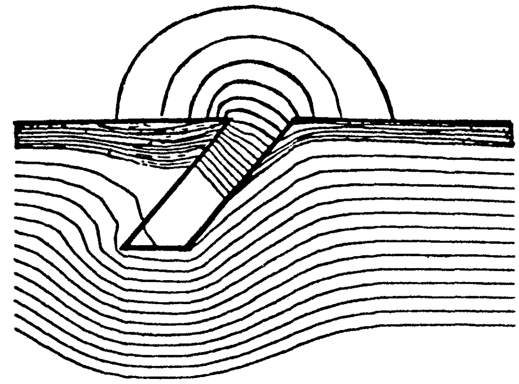

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FIGURE 2. Typical arc burn caused by direct contact magnetization

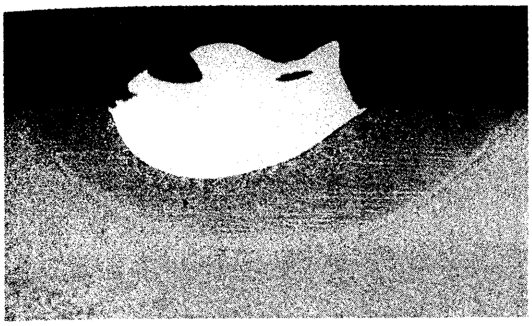


FIGURE 3. Minor surface flux leakage from variations in local magnetic permeability may be the source of false test indications

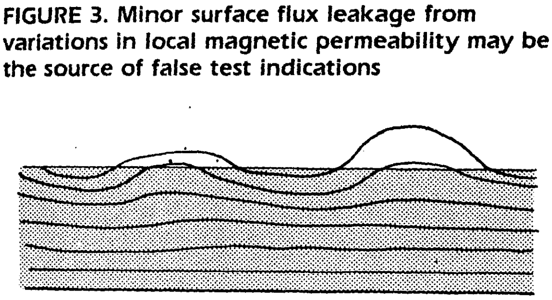
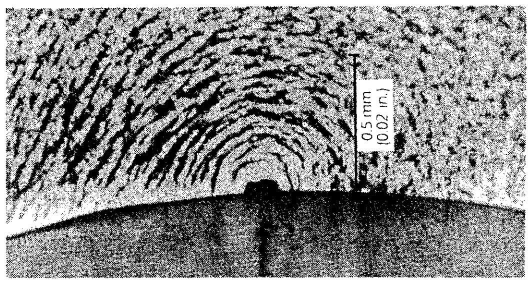


FIGURE 4. Highly curved magnetic field from a narrow surface breaking discontinuity



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Effect of Flux Leakage on False Indications

In a magnetic particle test, it is important to raise the field strength and flux density in the object to a level that produces magnetic flux leakage sufficient for holding particles in place over discontinuities. On the other hand, excessive magnetization causes particles to stick to minor surface leakages not caused by discontinuities.

If such surface leakage occurs (Fig. 3) and attracts large numbers of particles, the result is a false indication and the test object is said to be over magnetized for this inspection. It may then be necessary to verify the test results with shear wave ultrasound or another nondestructive testing method. Such false indications may result from local permeability changes which are caused by local stresses in the test object. In some cases, the magnetic flux leakage field might be caused by a subsurface material discontinuity and it may not be possible to distinguish the cause of the leakage without the use of additional nondestructive testing technology.

One way around this problem of excessive magnetization is to localize magnetizing fields at the object surface. This can be done using alternating current fields and the corresponding skin effect. As a rule, skin depth (also called *standard depth of penetration*) for 60 Hz alternating current fields is 1 mm (0.04 in.). The field strength falls to $1/e$ of its surface value, or 37 percent, at this depth. At two skin depths, field strength falls to $(1/e) \times (1/e)$ or 13 percent of its surface value. Magnetic flux leakage from discontinuities depends on the value of $H(t)$ and, in turn, on how large a $B(t)$ value the field strength causes around the discontinuity.

Why Particle Indications Form

Surface-breaking discontinuities best detected by magnetic particle tests are those that expel the optimal magnetic flux leakage for the technique. In order to gain a clearer insight of this, it is necessary to understand three sets of variables:

1. how discontinuity parameters affect the external magnetic flux leakage;
2. how magnetic field parameters affect the external flux leakage field; and
3. how the sensor reacts to passing through such fields.

Discontinuity Parameters

The discontinuity characteristics that are critical to the formation of magnetic particle indications include depth, width, and angle to the object surface. The effects of discontinuity width on the topography of the magnetic flux leakage field has been described in what might be termed classical approaches[5-7] where the discontinuity may be replaced by arrays of poles. Higher ambient field strengths or flux densities are included within such models by increasing the pole densities that give rise to the magnetic flux leakage fields. More recently, computer models have been developed[4,8] to explain how magnetic flux leakage fields are related to discontinuity parameters (Fig. 1 is an example of such work).

In cases where the discontinuity is narrow and surface breaking (seams, laps, quench cracks and grind tears), the magnetic flux leakage field near the mouth of the discontinuity is highly curved (Fig. 4). The activating field strength may be quite small (a few amperes per meter) or, after saturating the test object, inspection can be performed with the resulting residual induction.

In the case of subsurface discontinuities (inclusions and laminations), the magnetic flux leakage field at the inspected surface is much less curved (Fig. 5). Relatively high values of field strength and flux density within the object are required for testing. This lack of leakage field curvature greatly reduces the particles' ability to stick to such indications.

Magnetic Field Parameters

The properties of the magnetic field that most affect flux leakage include the field strength, local B-H properties and the angle to the discontinuity opening. The leakage field's ability to attract magnetic particles is determined by several additional factors. These include:[9]

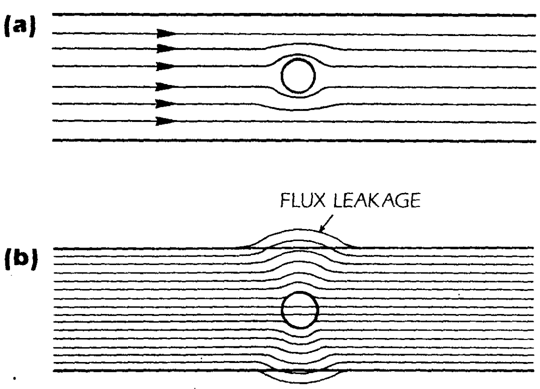
1. the magnetic forces between the magnetic flux leakage field and the particle;
2. image forces between a magnetized particle and its magnetic image in the surface plane of the test object;
3. gravitational forces that may act to pull the particle into or out of the magnetic flux leakage field; and
4. surface tension forces between the particle vehicle and the object surface (wet method tests).

Some of these forces may in turn vary with: discontinuity orientation; the Earth's gravitational field; particle shape and size (in effect, with particle effective permeability); and with the particles' containing medium.

The magnetic force F_m (newtons) that holds a single particle to a magnetic flux leakage field is determined by the vector relation:

$$F_m = K(\overline{H} \cdot \nabla\overline{H}) \qquad \text{(Eq. 1)}$$

FIGURE 5. Effects of induction on flux lines in the presence of a discontinuity: (a) compression of flux lines at low levels of induction around a discontinuity, so that no surface flux leakage occurs; (b) lack of compression at high induction, showing some broad surface magnetic flux leakage



Where:

K = a mathematical constant [(N•m³)•A⁻²];
$\overline{H}$ = the ambient leakage field strength (A•m⁻¹); and
$\nabla\overline{H}$ = the vector gradient of the field (A•m⁻²).

It can be seen from Eq. 1 that F_m is dependent on the local field strength $\overline{H}$ and how it changes over the length of the particle $\nabla\overline{H}$. For surface discontinuities, $\nabla\overline{H}$ is large (because the field is highly curved), while $\overline{H}$ itself need not be large. For subsurface discontinuities, $\nabla\overline{H}$ is relatively small and $\overline{H}$ itself must be raised to compensate for the small change. Unfortunately, raising $\overline{H}$ will also raise surface noise.

In other forms of magnetic flux leakage testing, the flux density is raised to a higher level than is common with magnetic particle testing and nonrelevant indications (noise) are in some way recognized. For example, the signals that noise induces in flux sensitive detectors may be filtered out. Magnetic flux leakage testing is therefore not limited by a human inability to distinguish real from apparent discontinuities. It is limited by an electronic inability to perform the same function.

PART 2
FLUX SENSITIVE DEVICES

Described below are flux sensitive devices used in magnetic nondestructive testing. The sensors detailed here measure either magnetic fields or their gradients.

The inability to measure magnetic fields has seriously hampered progress in magnetic particle testing. Recent research[10] indicates that the lack of discontinuity detection can be blamed on the magnetizing method, the particles used, and the capability of the inspector. The important question that must be answered before beginning any magnetic particle test is: *what is the best possible combination of magnetizing method, particle shape, type and size, and operator training that will reliably detect a discontinuity of a specific size every time?* Commonly accepted magnetization methods may not always be the best. Flux measurement devices can help provide more accurate information about the test procedure.

Commonly used magnetic flux sensitive devices include: (1) a long straight wire passing through a magnetic field, (2) the search coil, (3) search coil derivatives such a C and E cores, (4) the Hall element, (5) the magnetodiode, (6) the ferroprobe and (7) the flux gate magnetometer. For sensors in categories 1 through 3, the output signal depends on some form of time variation for the ambient field strength. Sensors in categories 4 through 7 are not time dependent.

A long straight wire passing through a magnetic field is not used for nondestructive testing, but it is a crucial concept for understanding the signal developed in coil sensors as they pass through magnetic flux leakage patterns.

Voltage Developed between the Ends of a Straight Wire

As shown in Fig. 6, two conducting wires PQ and RS are placed at right angles to a magnetic field (shaded area) of constant flux density (B) directed towards the reader. Let another free wire AA' be moved to position CC', a distance Δx away. The area swept out by the wire is then:

$$dA = L\Delta x \qquad \text{(Eq. 2)}$$

Where:

dA = the area swept out by the moving wire (square meters);

L = the length of the wire between PQ and RS (meters); and

Δx = the distance between position AA' and CC' (meters).

The magnetic flux interrupted by the wire is:

$$\Phi = \overline{B} \cdot \hat{n} dA \qquad \text{(Eq. 3)}$$

Where:

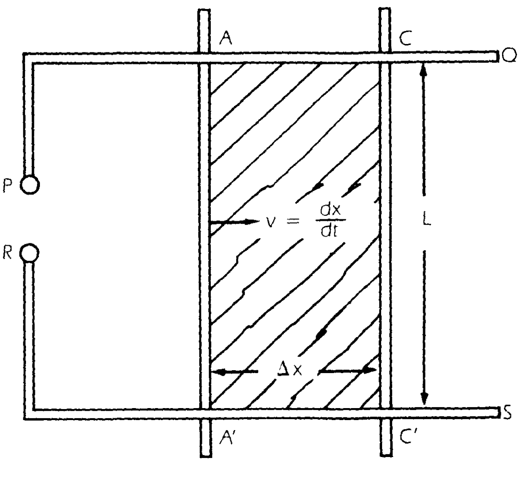
Φ = the interrupted magnetic flux (weber);
$\overline{B}$ = the magnetic flux density (tesla); and
$\hat{n}$ = the unit vector for the area dA.

The two equations together give:

$$\Phi = L\overline{B} \cdot \hat{n}\Delta x \qquad \text{(Eq. 4)}$$

Faraday's law of induction states that an electromotive force e will be induced in the wire and its magnitude is given by the relation:

FIGURE 6. Wire cutting magnetic flux between AA′ and CC′



$$e = -\frac{d\Phi}{dt} \qquad \text{(Eq. 5)}$$

This is the rate at which the magnetic flux is cut. Eliminating the flux between Eqs. 4 and 5, and taking the component of B perpendicular to ndA gives:

$$e = -BL\frac{dx}{dt} \qquad \text{(Eq. 6)}$$

Finally, since dx/dt is actually the velocity v of the wire, the induced electromotive force becomes:

$$e = -BLv \qquad \text{(Eq. 7)}$$

As an example calculation, consider a truck traveling north at 100 km•h^{-1}. If the length of the truck's axle is 2 m (6.6 ft) and the vertical component of the Earth's magnetic field strength is 3×10^{-5} Wb•m^{-2} (0.3 G), then from Eq. 7 the electromotive force between the ends of the axle is:

$$e = (3 \times 10^{-5}\ \text{Wb}\cdot\text{m}^{-2})\ (2\ \text{m})\left(\frac{100{,}000}{60 \times 60}\ \text{m}\cdot\text{s}^{-1}\right)$$

$$e = 1.7 \times 10^{-3}\ \text{volt}$$

This example indicates the magnitude of voltages induced when metal objects move in relatively small magnetic fields. As another example, compute the electromotive force generated between the ends of a 10 mm long wire when moving at 500 mm•s^{-1} through a field of 1.6×10^{-3} Wb•m^{-2} (16,000 G).

$$e = (1.6 \times 10^{-3}\ \text{Wb}\cdot\text{m}^{-2})\ (0.01\ \text{m})(0.5\ \text{m}\cdot\text{s}^{-1})$$

$$e = 8 \times 10^{-6}\ \text{volt}$$

It is unusual for B to be at right angles to v and under such circumstances a more general form of Eq. 7 is required:

$$e = -\int (v \times B)dl \qquad \text{(Eq. 8)}$$

where $v \times B$ is the vector cross product of the wire velocity and the flux density through which it passes. Numerically, this is $(vB) \sin \theta$, where θ is the angle between v and B. The integral is taken along the length of the wire because the local value of B through which each segment of wire is passing may vary.

In magnetic nondestructive testing, wires in the form of coils are moved in a controlled fashion over a test surface so that the value of v is known and Eq. 8 can then be written as:

$$e = -v\int B_{\perp}dl \qquad \text{(Eq. 9)}$$

where $B_{\perp}$ is the perpendicular component of the magnetic field, such as the magnetic flux leakage field shown in Fig. 1.

The tangential flux density B_t plays no role in the development of the electromotive force in the conductor since $\sin \theta$ is zero for this field component.

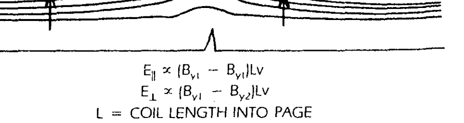
The electromotive force developed between A and A' appears across PR (Fig. 6) and can be measured with a sensitive voltmeter. No current flows if P and R are not connected. Furthermore, in the general case of conductor motion through magnetic fields, the variation of B along the conductor must be known so that the integral of Eq. 9 can be computed.

Example of a Straight Wire Signal

The electromotive force generated in the leading edge of the coil shown in Fig. 7 is deduced from the perpendicular field component of a tight crack. The simplest approximation for this magnetic flux leakage field is:[5,6]

$$B_t = \left(\frac{B_g L_g}{\pi}\right)\frac{y}{x^2 + y^2} \qquad \text{(Eq. 10)}$$

FIGURE 7. Parallel and perpendicular coils cutting magnetic flux leakage fields from a discontinuity at a speed v; for discontinuity fields longer than the coil, the output of the coils is given by the formulas shown



and

$$B_{\perp} = \left(\frac{B_g L_g}{\pi}\right) \frac{x}{x^2 + y^2} \qquad \text{(Eq. 11)}$$

Where:

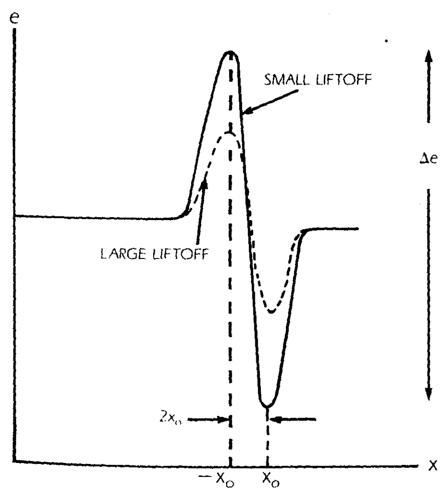
B_g = the flux density deep within the discontinuity (weber per square meter);
L_g = the width of the discontinuity (meter).

The origin of coordinates is the mouth of the discontinuity. If the length of the wire L is parallel to and shorter than the discontinuity opening, then the electromotive force developed between the ends of the wire is taken from Eqs. 10 and 11 as:

$$e = -\left(\frac{B_g L_g L v}{\pi}\right) \frac{x}{x^2 + y^2} \qquad \text{(Eq. 12)}$$

In traditional magnetic flux leakage testing equipment (see *Nondestructive Testing Handbook* Volume 4 on electromagnetic testing), the value of y is maintained at some constant value h (liftoff of the sensor). The form of the electromotive force is shown in Fig. 8 for increasing value of liftoff h. From Eq. 12, the magnitude of the electromotive force is shown to depend linearly on:

FIGURE 8. Electromotive force developed between the ends of a conductor passing at constant speed through a leakage field such as Equations 11 and 12



1. the value of $B_g L_g$ (the magnetomotive force of the discontinuity);
2. L (the length of the wire, provided that the aforementioned conditions are met); and
3. v (the relative velocity between the object and the conductor).

The dependence on liftoff can be seen by differentiating Eq. 12 for the turning points ($x_o = \pm h$) and using these values to compute the swing Δe in e. The result is:

$$\Delta e = \frac{B_g L_g L v}{\pi h} \qquad \text{(Eq. 13)}$$

In this field approximation, the swing in voltage as the conductor passes through the magnetic flux leakage field is inversely proportional to the liftoff.

Simple Pickup Coils

Figure 7 shows two commonly used pickup coils: parallel and perpendicular. In some cases, the turns of these coils are wound onto small blocks of ferrite to increase the value of $B_{\perp}$ above its air value ($B_{\perp}$ is the flux leakage component perpendicular to the test surface). Air core coils are discussed below.

Perpendicular Coil

With a one-turn coil passing at speed v through the same magnetic flux leakage field as above, the signal electromotive force is the difference between the two electromotive forces developed in the upper and lower branches:

$$e = -\frac{B_g L_g L v}{\pi}(x)\left[\frac{1}{x^2 + h_1^2} - \frac{1}{x^2 + h_2^2}\right] \qquad \text{(Eq. 14)}$$

where h_1 and h_2 are the liftoffs of the two branches.

If the coil has N turns and a width of $2b$, then $h_1 = H + b$ and $h_2 = H - b$ (the liftoff is measured to the center of the coil). The electromotive force then becomes:

$$e = -\frac{B_g L_g L N v x}{\pi}\left[\frac{1}{x^2 + (H + b)^2} - \frac{1}{x^2 + (H - b)^2}\right] \qquad \text{(Eq. 15)}$$

The results of varying h and b are shown in Fig. 9 where the electromotive force is similar in form to that of the

FIGURE 9. Form of the voltage signal developed in a perpendicular coil when passing at constant speed through a leakage field of the form given by the simple Foerster relation

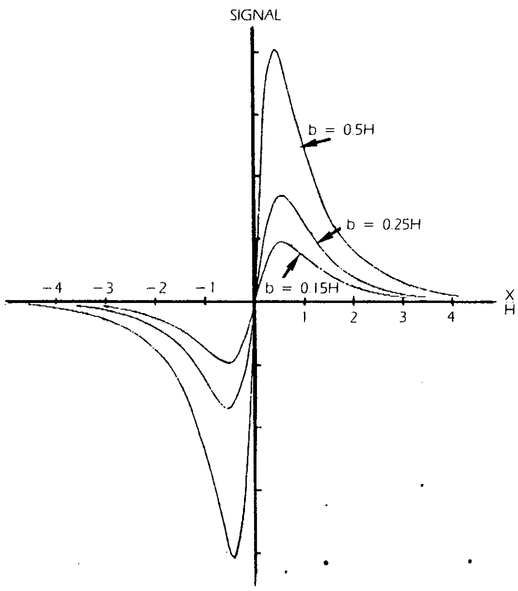


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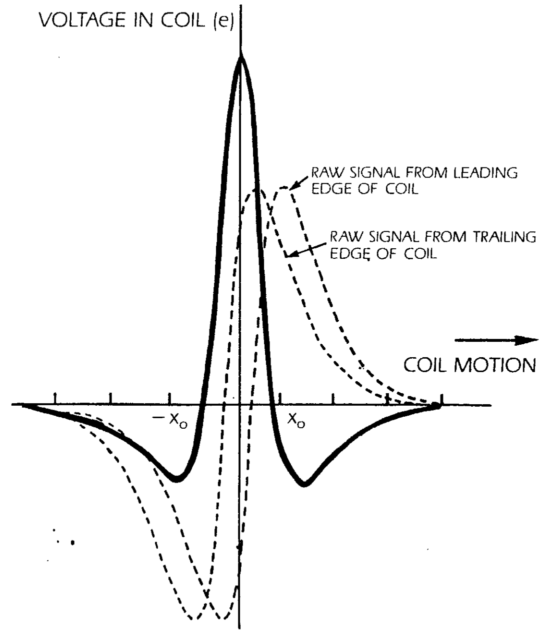
FIGURE 10. Voltage induced in a parallel coil by passing it through a magnetic flux leakage field such as in Equation 11; the coil voltage is the difference between leading and trailing edge signals



straight wire. The turning points in the electromotive force are given by the solution to Eq. 16.

$$x_0^2 = \frac{1}{3}\sqrt{2H^4 - (Hb)^2 + b^4 - (H^2 + b^2)^2} \quad \text{(Eq. 16)}$$

For example, when $b = H/2$, then the turning points are $x_o = \pm 0.74H$ and $2x_o$ (the distance between the turning points) is $1.49H$. The swing in signal e is difficult to compute in closed algebraic form.

Parallel Coil

When the coil is oriented so that one set of wires follows another, then the output signal is the difference between the signals developed in the leading and trailing branches:

$$e = -[B_{\perp L} - B_{\perp T}]Lv \quad \text{(Eq. 17)}$$

Using Eq. 11 for the leading and trailing edge fields ($B_{\perp L}$ and $B_{\perp T}$), substitute $x_L = x - b$ and $x_T = x + b$ for the leading and trailing edge distances from the center of the coil:

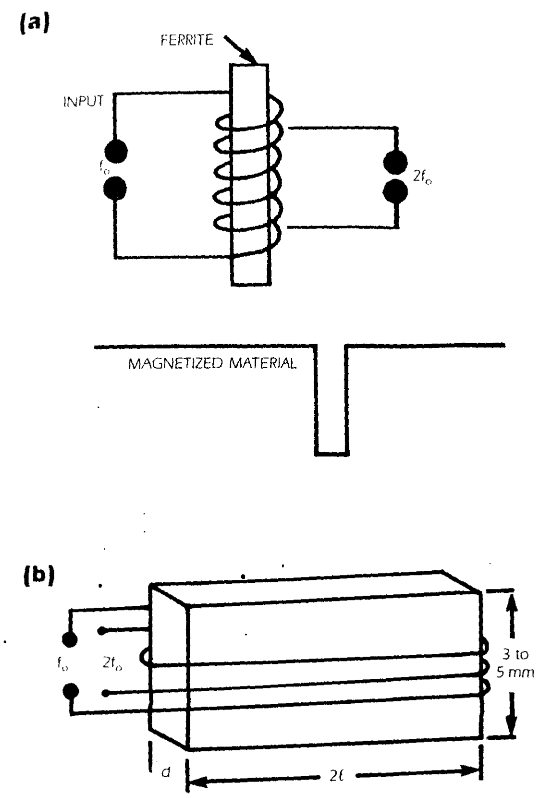
$$e = \left(\frac{2bNB_gL_gLv}{\pi}\right) \quad \text{(Eq. 18)}$$
$$\cdot \left(\frac{h^2 + b^2 - x^2}{[(x + b)^2 + h^2][(x - b)^2 + h^2]}\right)$$

The form of Eq. 18 is shown in Fig. 10. The dashed lines are voltages induced in the leading and trailing edges. The solid line is their difference or the form of the electromotive force. The signal consists of a major peak at $x = 0$ and two smaller side peaks. The roots of Eq. 18 occur at $x_o = \pm(h^2 + b^2)^{1/2}$ so that the distance between the points at which $e = 0$ is given by:

$$2x_o = 2\sqrt{h^2 + b^2} \quad \text{(Eq. 19)}$$

The maximum value of the coil signal occurs at $x = 0$ and is proportional to $b/(h^2 + b^2)$. Differentiation with respect

FIGURE 11. Ferrite cored magnetic flux leakage detector coil systems



to b indicates that the coil signal is maximized when $b = h$. Thus when the half-width of the coil is equal to the liftoff, the coil output voltage is maximized with respect to the magnetic flux leakage from the discontinuity. This argument also indicates that this type of coil discriminates against relatively long range material surface noise such as might be caused by local permeability variations.

Ferrite Cores in Coils

Ferrites are useful in pickup coils because they not only provide support for the wire turns but they also amplify the flux density through the coil windings by a value equal to the effective permeability of the ferrite.

For small pieces of ferrite (Fig. 11) where the dimensional ratio is small, the effective permeability of the ferrite may vary from the low teens to the thousands. The advantage of using ferrite occurs not only in this amplification but also in the fact that ferrites have very low electrical conductivities, minimizing detrimental eddy current effects in them.

Electronic Considerations for Coil Voltages

It is essential that pickup coils are used to generate voltages and not currents. Once a current is allowed to flow in a coil, it creates its own magnetic field, one that can interfere with the field under investigation. The output of such coils is therefore generally fed to a high resistance operational amplifier.

Coil Applications and Derivatives

Examples of the use of coils as detectors for magnetic flux leakage are presented in the *Nondestructive Testing Handbook* on electromagnetic testing. Such coils can be connected in series adding, series opposing (a figure eight), overlapping and many other configurations.

Search coils are often wound on ferrite cores to increase the flux through them (Fig. 11 shows two common configurations). A detailed discussion of such sensors is given in the electromagnetic testing volume.

Hall Element Sensors

Hall elements are crystals of semiconductor material. When a current is passed through them and they are placed in a magnetic field, then a voltage develops across two of the faces of the crystal. The voltage is proportional to the strength of the magnetic field.

A solid state gaussmeter is made up of the electronic components needed to supply current to a Hall element, to detect and measure the resulting voltage and to then convert it to the measured field value (see Fig. 15).

Theory of Hall Element Operation

Electrically conducting solids are almost transparent to the flow of conduction electrons, since the ions in the crystal lattice do not deflect conduction electrons as might be expected from a typical billiard ball model. As current is fed into one end of a crystal (see Fig. 12), electrons are deflected toward one another or toward the other side of the crystal, in accordance with the Lorentz force F:

$$\overline{F} = -e(\overline{E} + \overline{v} \times \overline{B}) \qquad \text{(Eq. 20)}$$

Where:

e = electronic charge (coulombs);
E = electric field strength (volts per meter) on particle;
v = velocity of particle (meters per second); and
B = applied flux density (tesla).

The term $v \times B$ is a vector cross product and is itself a vector at right angles to both v and B. Its direction determines which side of the crystal the electrons are deflected toward. The theory of solid state physics provides a voltage V_h across the crystal[1] of:

$$V_h = \frac{R_h I B_z}{b} \qquad \text{(Eq. 21)}$$

Where:

I = the applied current (amperes);
B_z = the component of the applied field at right angles to the current (webers per square meter);
b = the thickness of the crystal in the direction of the magnetic field (meter); and
R_h = the Hall coefficient ($A^{-1} \cdot s^{-1}$).

FIGURE 12. Magnetic flux, drive current and Hall effect voltage relationship

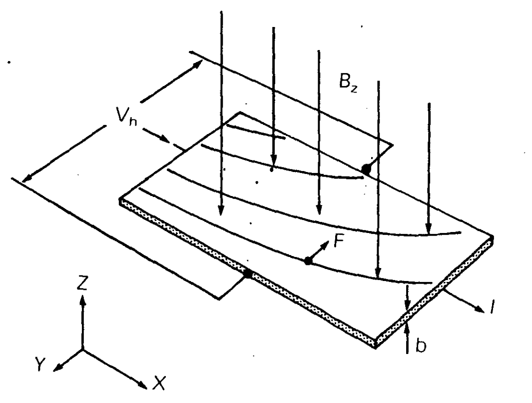


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FIGURE 13. Typical Hall element probes: (a) flat, (b) high linearity, (c) miniature, (d) subminiature and (e) axial (see Table 1)

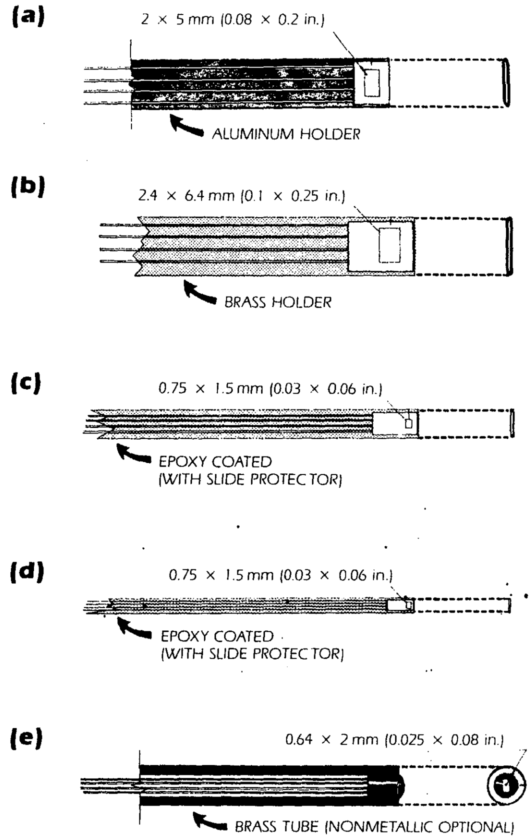

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TABLE 1. Specifications of typical Hall element probes (see Figure 13)

Probe Type	Hall Output Voltage (millivolts)	Nominal Current Control (milliamperes)	Temperature Coefficient (°C)	Operating Temperature (°C)
Flat or transverse	340	200	−0.1	−65 to 85
High linearity	350	350	−0.1	−65 to 85
Miniature	200	25	−0.25	−65 to 85
Subminiature	200	25	−0.25	−65 to 85
Axial	100	100	−0.1	−65 to 85

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In general, if the crystal is placed at an angle to the field B, such that $B_z = B \cos \theta$, then the cosine of the angle must be found. Normally, the crystal is rotated until the maximum gaussmeter reading is found. At that point, θ is 0 since $\cos \theta$ is 1.

The value the Hall coefficient R_h is determined by the interaction of charge carriers with the crystal lattice. In metal crystals, it is given by:

$$R_h = -\frac{1}{ne} \quad \text{(Eq. 22)}$$

Where:

n = the electron concentration; and
e = charge on the electron (-1.6×10^{-19} coulombs).

Metals do not make the best Hall sensors because their Hall coefficients are often relatively low. As can be seen in Eq. 21, the larger the Hall coefficient, the larger the Hall voltage. Investigations of Hall coefficients for many substances have shown that combinations of elements from groups III and V of the periodic table give the highest Hall voltages and have the least sensitivity to changes in temperature. Also, the charge carrier for these groups is more likely to be a hole rather than an electron.

Excitation of Hall Elements

Where contacts occur between two dissimilar metals such as the current and voltage attachments on the Hall crystal, thermoelectric electromotive forces are generated.

If direct current is used to excite the crystal, the voltage read by circuitry following the voltage contacts is the sum of the Hall voltage *and* the thermoelectric voltage. For this reason, Hall element crystal excitation is usually performed with 25 to 350 mA alternating current with frequencies in kilohertz.

Manufacture of Hall Elements

Bulk Hall elements are generally bismuth doped semiconductors such as indium antimonide (InSb). These are produced by solid state crystal growth technology, cut into small rectangular blocks and have current and voltage leads attached before being encapsulated. Typical sizes are as small as 0.8 mm (0.03 in.) long by 0.4 mm (0.015 in.) wide by 0.5 mm (0.02 in.) thick.[2]

Vapor deposited Hall elements have been reported for use in the testing of ball bearings by the magnetic flux technique.[11] In this application, bismuth was evaporated onto an alumina substrate. A newer development is to combine the Hall sensor, its power supply and an amplifier on one chip. Figure 13 and Table 1 show configurations of typical Hall sensors and their specifications.

FIGURE 14. Hall element configurations: (a) sensor at a fixed distance from wire; (b) ferrite core; (c) free-standing flux concentrator; (d) symmetrically positioned contacting concentrator; and (e) asymmetric contacting concentrator

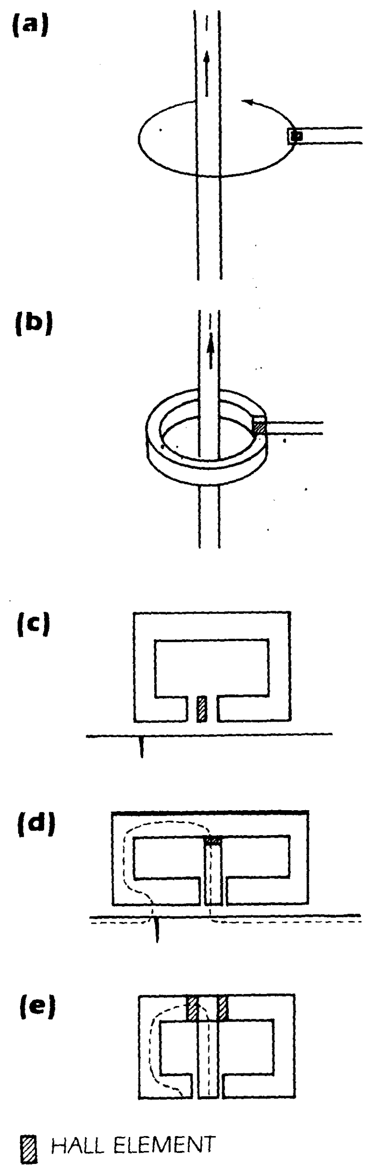
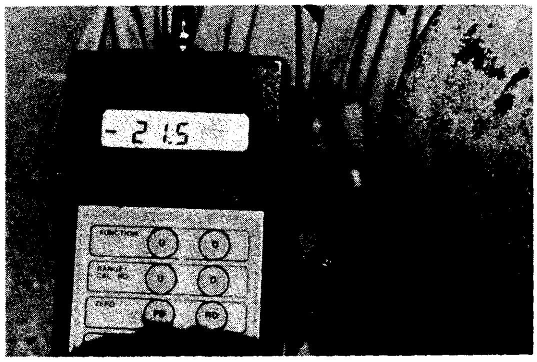


FIGURE 15. Checking external field level with a meter after partial demagnetization



Applications of Hall Elements

Hall elements are used in conjunction with gaussmeters or other devices to detect or measure magnetic fields. Typical configurations are shown in Fig. 14. In Fig. 14a, the Hall sensor is held a fixed distance from a current carrying wire and the gaussmeter measures the field strength created by the current. In the case of pulsed currents, the peak current can be measured with a peak reading gaussmeter.

In Fig. 14b, a ferrite ring is added to measure small fields or currents. The high permeability of the ferrite aids in creating a high B value in the vicinity of the sensor's active area. Figure 14c, 14d and 14e show combinations of Hall elements and ferrite flux concentrator configurations used in magnetic flux leakage testing.

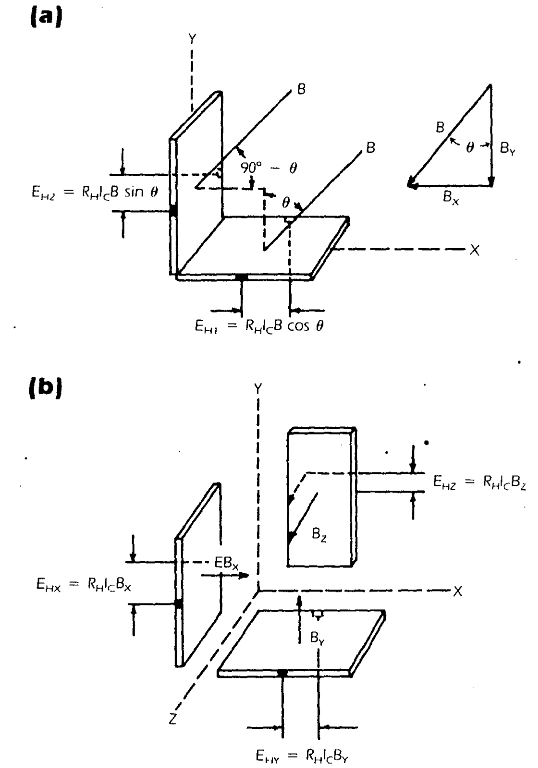
The level of external field just outside a partially demagnetized material may best be measured with a Hall element meter. Figure 15 shows an inspector checking the external field level with a gaussmeter after partial demagnetization of the test object, a 270 mm (10.75 in.) diameter steel tube.

Crossed Hall elements can also be used, as shown in Fig. 16. Such configurations are used to check welds or to reconstruct the total field from the measured components.[12]

Magnetodiodes

The magnetodiode is a solid state device whose resistance changes with field strength.[13] The device consists of p and n zones within a semiconductor, separated by a region of material that has been modified to create a recombination zone (Fig. 17). Its frequency response (Figs. 18 and 19) is flat from direct current to 3 kHz and the device is stable without temperature dependence from − 10 to 50 °C (15 to 120 °F).

FIGURE 16. Multidimensional arrays of Hall elements used to measure directional components of magnetic field intensity: (a) two-dimensional array of Hall detectors; components of magnetic field in XY plane are sensed individually; (b) three-dimensional array of Hall magnetic field detectors; each detector senses the magnetic field component perpendicular to the face of the semiconductor



Applications of Magnetodiodes

Figure 20 shows the use of magnetodiodes for detecting magnetic flux leakage from discontinuities in tubes.[2] The magnetic flux leakage is excited by alternating current electromagnets arranged to detect either internal or external surface breaking discontinuities. The system illustrates the general principles of magnetic flux leakage testing.

Sensors are connected differentially to eliminate signals from the applied field and from relatively long range variations in surface field strength. This system and magnetic flux leakage systems like it are used to rapidly evaluate the surface condition of tubes and can detect tight discontinuities with a depth of only 0.1 mm (0.004 in.).

FIGURE 17. Diagram of the magnetodiode showing p-zones and n-zones in semiconductor material along with intrinsic and recombination zones

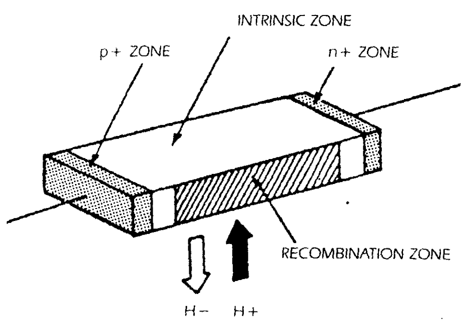


FIGURE 18. Typical characteristic curve showing that the response of a magnetodiode is linear to about a 40 kA•m⁻¹ (500 Oe) field

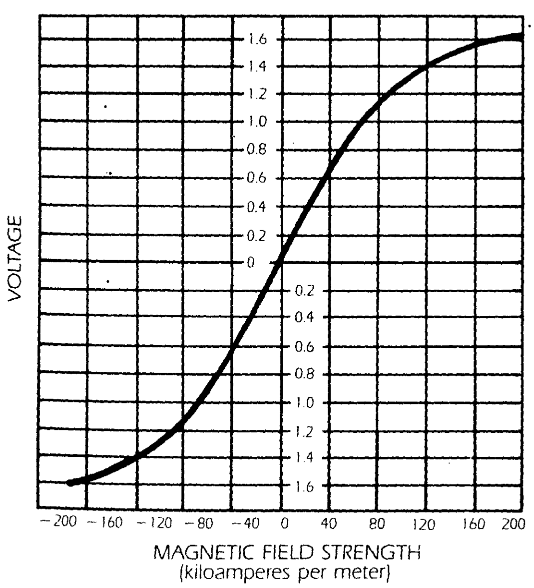
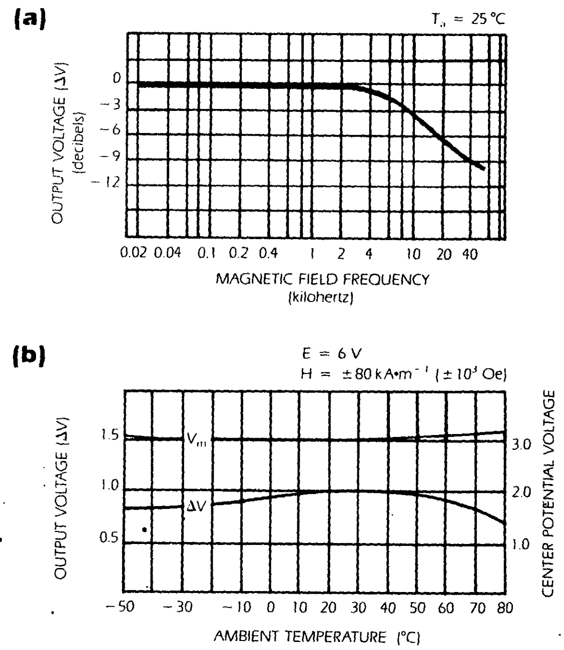


FIGURE 19. Characteristics of the magnetodiode: (a) frequency response and (b) temperature dependence



Magnetic particle testing is often used to inspect such tubes but while it is extremely sensitive to outer surface, tight discontinuities, its use for inner surface discontinuities requires the use of a viewing device.

Ferroprobes

Ferroprobes (also called *Foerster microprobes*) take many forms but for the purposes of nondestructive testing they generally consist of cylindrical or rectangular ferrite upon which one or two coils are wound (Fig. 11).

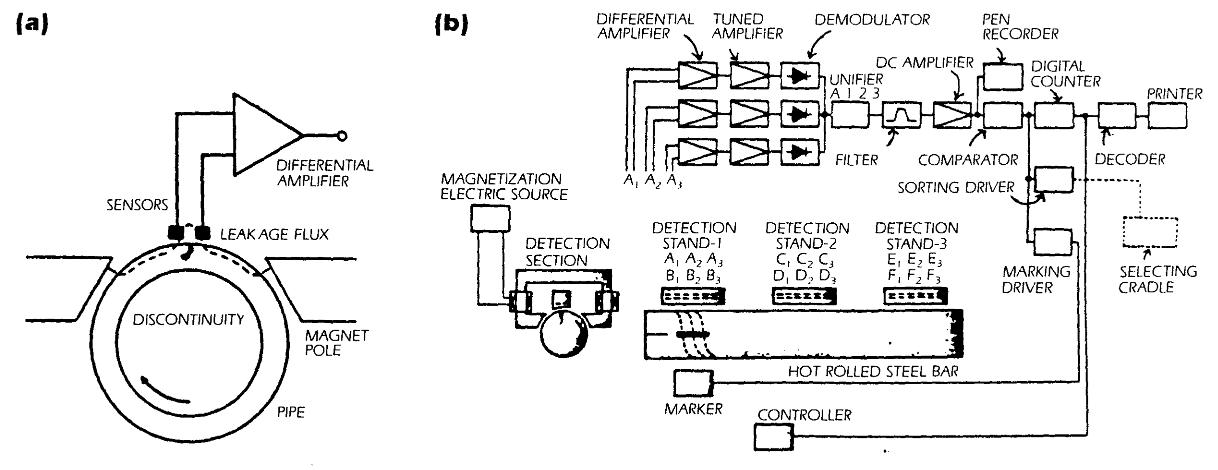
Flux gate magnetometers are used to detect small changes in the Earth's magnetic field. As might be used by geophysical prospectors, these devices consist of ferrite rings carrying many coil configurations.

Both of these devices are based on the same physical laws as a tape recorder head or any other ferrite cored magnetic field pickup. The difference between the two is that ferroprobes are activated at high frequency.

Typically, one coil is excited with alternating current at a frequency f. The voltage induced in a second coil at frequency $2f$ is then detected. This secondary signal carries information about the scanned magnetic flux leakage field. Figure 21 is an example of the tangential magnetic flux leakage field taken with such a probe over an angle slot in residual induction at a liftoff of 1 mm (0.04 in.).

Ferrite cores might be solid or hollow, to reduce eddy currents in the ferrite.

FIGURE 20. A magnetodiode testing system for tubes: (a) alternating current magnetizing method and (b) electrical block diagram



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Large Volume Magnetic Field Indicators

Bulk Field Indicators

The field measurement systems discussed above are designed and used for the assessment of magnetic leakage fields from material discontinuities. In all cases, the active sensing area of such a device is very small. In the case of the Hall element, which is rectangular in shape, it is possible to integrate the field over the active area of the Hall crystal, and so compensate for it. Then, by taking measurements at controlled distances above a magnetized surface, it is possible to extrapolate the field values to that at the surface. Once this is done, the electromagnetic boundary conditions indicate the magnetic field strength just inside the surface.

The following text relates to the detection or measurement of magnetic fields over much larger areas, since the active area of the sensor is larger than that used for leakage field testing. The instruments are handheld, moving magnet sensors used to measure bulk external fields at a relatively high liftoff from the test object. They are often used as a practical check on the external demagnetization state of an object. Their use to detect magnetic field strength within coils should be discouraged, since the coil field may remagnetize the moving magnetics. Note that these devices do not measure leakage fields from discontinuities.

A bulk magnetic field indicator can be used to measure the value of a uniform magnetic induction field in air. Because the relative magnetic permeability of air is 1, this reading is also the numerical equivalent of the magnetic field strength of air.

The magnetic field indicator is also used to determine the existence of a magnetic field external to a ferromagnetic object. To do this, the indicator is oriented against the object's surface and moved until it registers the maximum external field reading.

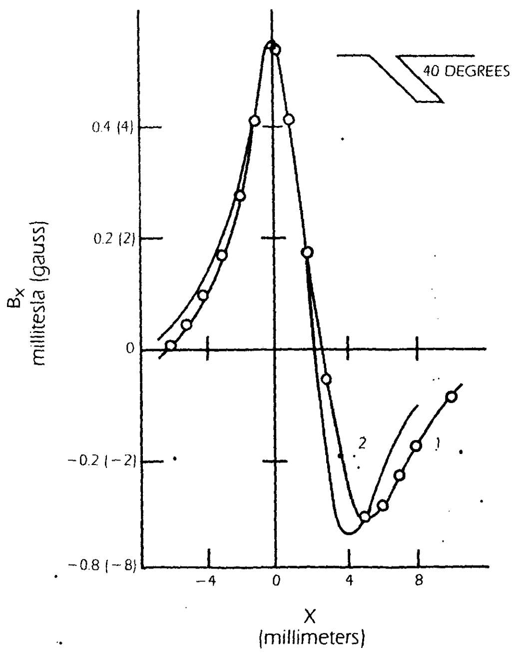
Bulk Field Indicator Construction

Many magnetic field indicators are round (see Fig. 22), about 64 mm (2.5 in.) in diameter with thicknesses of 13 to 25 mm (0.5 to 1 in.). The indicators commonly used for checking external field levels after magnetic particle tests have a range of about 1 to 2 mT (10 to 20 G) in divisions of 0.05 to 0.1 mT (0.5 to 1 G). Positive readings are north and negative readings are south.

A key component of the magnetic field indicator is a small movable field sensing magnet. The magnet is mounted so it is free to rotate. Its angular deflection is shown by the movement of a pointer.

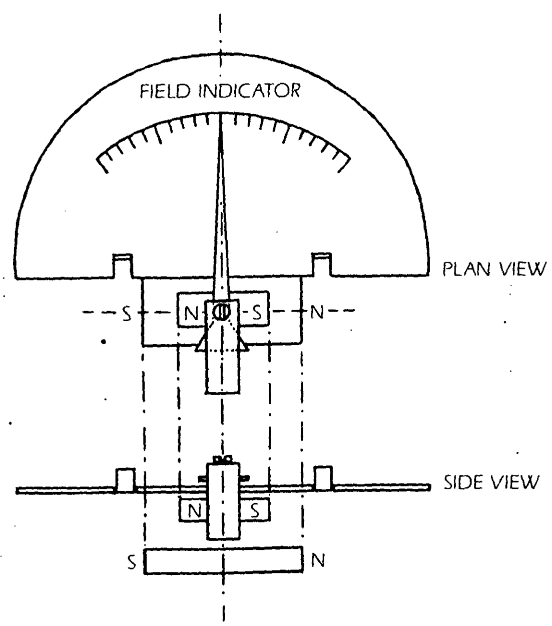
A second key component is a fixed permanent magnet. Its magnetic field strength limits the useful range of the unit by providing a restraining force to prevent the sensing magnet from rotating freely. With no external magnetic field, these two magnets stay antiparallel to each other and the pointer remains in a neutral position, registering a zero reading (Fig. 22).

FIGURE 21. Tangential magnetic flux leakage fields in saturated residual induction over a 40 degree slot; curve 1 is from experimental data at 1 mm (0.04 in.) liftoff; curve 2 is a model with increased charge on acute face of slot



AFTER ZATSEPIN AND SHCHERBININ.[7]

FIGURE 22. Diagram of a typical magnetic field indicator; distance from the pivoting point of the sensing magnet to the closest point on the edge of the casing is about 18 mm (0.75 in.); the size, shape, material, magnetic field strength and relative positions of the sensing magnet and the reference magnet vary with manufacturer



The field indicator is designed so that the net magnetic field from these two magnets is weak outside the device. Placing the indicator on an unmagnetized object does not induce poles on the object sufficient for causing inaccurate meter readings.

In principle, magnetic field indicators could use a coiled spring instead of a calibrated magnet to return the pointer to zero once the external field is removed. However, slight changes in the sensing magnet's strength would then require recalibration of the unit. Also, a strongly poled sensing magnet, when placed very close to an unmagnetized object, could induce localized poles and cause inaccurate readings.

Principles of Field Indicator Operation

A fixed magnet inside the device's housing sets up a reference magnetic field. A small movable sensing magnet is mounted inside this field. If a nearby object also sets up a magnetic field in the same area, the field sensing magnet rotates into a direction parallel to the resulting, combined magnetic field.

The instrument's pointer is attached to the sensing magnet and correspondingly rotates into a direction perpendicular to the resulting field. If the external field changes polarity, the pointer rotates in the opposite direction and the reading's algebraic sign changes. If the magnetic field indicator is rotated through 180 degrees about its pointer's zero direction, there is no algebraic sign change in the reading (the scale is also rotated 180 degrees).

However, in practice a reverse of polarity or rotation of the indicator often produces a change in a reading's magnitude unless the external field is perpendicular to the reference field.

FIGURE 23. Pointer deflection θ in first calibration type; B is perpendicular to B* and $\tan \theta = B/B^*$

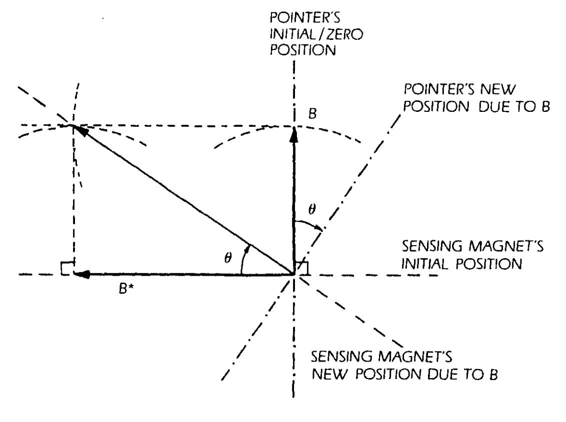
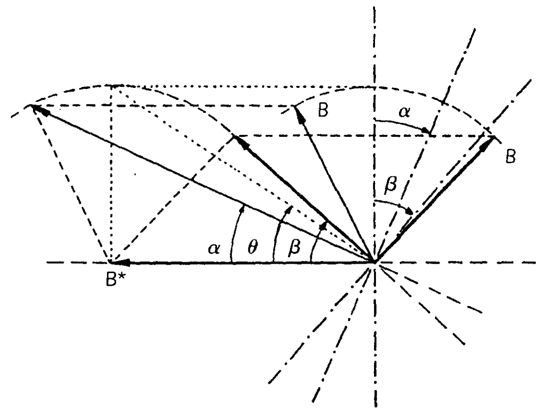


FIGURE 24. Pointer deflection α and β when B is not perpendicular to B* ($\alpha < \theta < \beta$)



Calibration and Use of Field Indicators

Generally, there are two ways to calibrate magnetic field indicators. These calibration methods provide two distinct ways of using the devices.

The most common calibration method correlates the angular deflection θ of the indicator's pointer with the magnitude B of a uniform external field whose direction is parallel to the zero direction of the pointer. To measure a uniform field, the field indicator is positioned so that the zero direction of the pointer is parallel to the field.

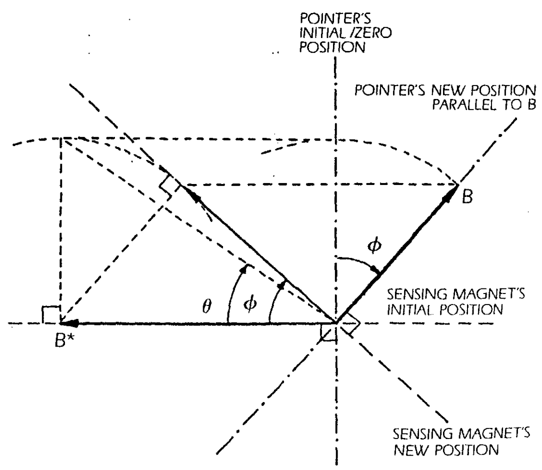
Used in this manner, the field B from an external object is perpendicular to the reference field B^* inside the magnetic field indicator. Or as depicted in Fig. 23:

$$B = B^* \tan \theta \qquad \text{(Eq. 23)}$$

For a small deflection, B^* may be considered uniform and a large θ indicates a relatively strong B. To keep within a practical calibrated scale when θ is between +45 and −45 degrees, the measured field must be weaker than the reference field (B less than B^*).

In many applications, B may not be perpendicular to B^*. For example, the direction of B may be unknown or the field could be nonuniform. In a case like this, the magnetic field indicator is positioned against the object's surface and oriented in such a way that the directional marking on the device's casing is near to and perpendicular to the object's surface. Because the field is not necessarily normal to the object's surface, the reading can be less or greater than the actual value, depending on whether the field makes an acute or obtuse angle with the reference field (see α and β in Fig. 24).

FIGURE 25. Pointer deflection ϕ in second calibration type; B and the pointer are parallel and ϕ is at a maximum. ($B^* > B$ and $\phi > \theta$)



The alternate way of calibrating correlates the uniform field value B with the maximum deflection ϕ of the magnetic field indicator's pointer. The value of ϕ is obtained by orienting the instrument inside the field B. As shown in Fig. 25, the field vector B changes its direction relative to the field vector B^* and their resulting vector traces out a circular path of radius B centered at the tip of B^*.

For B less than B^* and for a maximum deflection ϕ, the resulting field vector is tangential to this circular path. It follows that the field B is actually parallel to the pointer (Fig. 25). When $B < B^*$, Eq. 24 is valid.

$$B = B^* \sin \phi \qquad \text{(Eq. 24)}$$

Note the differences between Eqs. 23 and 24. When measuring very weak fields, these two calibration methods are about the same and the pointer's angular deflection is approximately linear with the uniform field's magnitude ($\theta = B/B^* = \phi$ for a small B/B^*). In general, for the same uniform field B:

$$\phi > \theta \qquad \text{(Eq. 25)}$$

As a consequence of this inequality, the scale of the second type of calibration is generally wider if marked on the same arc inside the same magnetic field indicator. When using an instrument that is calibrated in the second way, the unit is often rotated to verify that the readings are maximized. Sometimes this is inconvenient for objects with complicated geometry because a rotation of the device may move its sensing magnet away from the area of interest.

If magnetic field indicators of the first type are used as if they had the second type of calibration (maximizing their readings by rotation) then the resulting maximum values are actually greater than the true field values. Sometimes, in this way, an estimate can be made for the size of a uniform or nearly uniform field, even though its direction is unknown.

When measuring a nonuniform field, the reading of a magnetic field indicator is at best the average field value over the area covered by the sensing magnet. For example, assume that the flux lines from an external magnetic source are almost parallel with the special directional marking on the magnetic field indicator. The two ends of the magnetic field indicator's field sensing magnet may still experience deflection forces of different magnitudes because of different field values and the resulting pointer deflection is an average of the two field values.

Measuring Residual Fields

The primary function of a field indicator is to measure the external magnetic field strength close to an object, but not every kind of residual magnetism can be detected by these instruments.

In a circularly magnetized object, where residual flux lines are circumferential and form closed loops inside the material, the induction is significantly different from zero but the field may not produce poles outside the object. Such a circular field does not produce significant readings in magnetic field indicators. Circularly magnetized objects do not attract or deflect magnetic materials during normal use unless surface discontinuities occur, producing strong external poles.

Consider a cylinder with flat ends that has been longitudinally magnetized. A magnetic field indicator is placed against the cylinder's end surface and the directional marking on the indicator's casing is lined up with the length of the test object. The indicator is aligned normal to the cylinder's surface and a reading is taken.

If a demagnetization procedure has been properly performed, the indicator reading will be 0.1 mT (1 G) or less. Similar readings obtained on the side of the cylinder (with the directional marking perpendicular to the side surface) should be about zero. Sometimes, if residual magnetism is high, a nonmagnetic spacer is placed between the object and the magnetic field indicator and relative readings are obtained.

For a cylinder that is large compared to the indicator's size, measurements made at the center of the end surface are close to the actual values immediately beneath the surface of the object. The reason for this accuracy is that the magnetic fluxes immediately inside and outside the cylinder's end are perpendicular to the end surface and the perpendicular component of the magnetic induction field across the boundary surface is continuous, according to electromagnetic field theory.

However, the same accuracy is not possible for geometries with sharp corners or for objects that are small compared to the size of the indicator. In these instances, the measured field may not be uniform (the direction and density of the flux lines vary across a small distance) and a tangential component exists. It is known from electromagnetic field theory that the tangential component of magnetic induction may not be continuous when crossing the boundary surface between two media of different permeabilities. Therefore, the magnetic induction inside and outside the object may not be the same.

When the test object has an irregular shape or the residual field readings are large, one way to test external magnetism is to scan the entire surface of the object with a magnetic field indicator. Maximum readings occur at locations where significant external poles exist.

At such maximum reading locations, the field indicator can be used to determine if the field is normal to the object's surface. The field indicator is positioned against the object and oriented with its directional marking normal to the surface. The device is rotated through 180 degrees about the directional marking (normal to the object's surface). During rotation, variations of the indicator reading are noted.

If the rotation does not affect the indicator reading, then the reading is the true field value and the true field is normal to the object's surface at this location. If the field is not perpendicular to the object's surface, it is likely that, at a certain time during rotation, the actual field vector will have no projection along the direction of the indicator's reference field, and the reading at that time will be exactly the component of the field normal to the object's surface. In other words, the normal component of the field at this location will be no greater than the largest value observed in the rotation. More precisely, it is in between the readings obtained at the beginning and at the end of the rotation and is no greater than the average of these two values. If the same value appears twice during rotation, then it must be the normal component of the field.

In most applications, the purpose of external residual field measurement is to ensure that the objects are free of magnetic poles that detract from serviceability. The exact value of the external residual magnetism is not critical, so long as it is lower than a limit predetermined by the user's empirical data.

Checking Indicator Reading Accuracy

If inconsistent results occur in different sets of magnetic field indicators, it is likely that some of the devices are malfunctioning. Certain indicator malfunctions are easy to detect, such as an imbalanced or damaged pointer, or mechanical failures at the support of the sensing magnet and pointer assembly. High mechanical impact or sudden exposure to a strong magnetic field are among the less obvious causes for erratic readings.

A magnetic field indicator can also become inaccurate if its magnetization is changed by exposure to a strong direct current or a decaying alternating current field. If the fixed reference magnets become partially demagnetized, the unit can give readings much larger than a good unit's results (smaller B^* in Eq. 23). If an indicator's magnetic components are totally demagnetized, its pointer may not return to the zero position, remaining virtually anywhere on the scale.

Two different field indicators may give different results at the same location on the test object. However, these differences alone do not indicate that one of the field indicators is malfunctioning. The sensing magnets of different devices may have different sizes and their location inside the units may be different. They may therefore not be measuring the field at exactly the same location. In addition, reference fields inside the units may also differ.

In a highly nonuniform field, readings may not vary in the same ratio as varying measurement locations. As a result, it may not be possible to verify the accuracy of a magnetic field indicator by comparing its readings to a known reference unit (other field measurement devices may be equally inaccurate in the nonuniform field). The best way to test the accuracy of a particular device is to perform reference comparisons in uniform or nearly uniform magnetic fields.

To set up a uniform magnetic field for calibration, a Helmholtz coil may be used. This device contains two parallel coils separated at a distance equal to their radius and connected in series-aiding mode. In about 30 percent of the volume between the two coils, there is a very uniform magnetic field parallel to their axes. The field value can either be measured with an appropriate meter or calculated from the coils' dimensions and the value of applied direct current (in Eq. 26, x/R is 0.5 and B_o is replaced with $2B_o$).

TABLE 2. Nearly uniform magnetic field values for a five-turn coil carrying direct current, compared to the linear distance from the coil center

Distance from Coil Center meters (feet)	Measured Value millitesla (gauss)
0	31 (309)
0.45 (1.5)	1.0 (9.8)
0.9 (3.0)	0.14 (1.4)
1.0 (3.3)	0.1 (1.0)

In addition to the Helmholtz coil or commercial calibration fixtures, an approximately uniform magnetic field may be established using a large direct current coil. Over a small distance along the coil's axis, a magnetic field can be considered nearly uniform. As examples, Table 2 shows a set of magnetic field values for a five-turn coil of 300 mm (12 in.) diameter carrying 1,500 A direct current. The table values were calculated using the following equations.

$$B = \frac{B_o}{\left[1 + \left(\frac{x}{R}\right)^2\right]^{3/2}} \qquad \text{(Eq. 26)}$$

Where:

B_o = magnetic field at the center of the coil (millitesla);
x = distance from the center of coil along the axis (meters); and
R = coil radius (meters).

$$B_o = \mu_o\left(\frac{NI}{2R}\right) \qquad \text{(Eq. 27)}$$

Where:

μ_o = the permeability constant ($4\pi \times 10^{-7}$);
N = number of turns in the coil; and
I = applied direct current (amperes).

Sometimes, the Earth's magnetic field can indicate a meter's accuracy: the Earth's field is about 0.05 mT (0.5 G). If the indicator's accuracy is within ± 0.03 mT (0.3 G), then with proper north/south and horizontal orientations, the device should be able to register an approximate reading of the Earth's field, provided there are no other magnetic objects nearby.

The best magnetic field indicators are precision calibrated. Their accuracy may also be less susceptible to the influence of a strong magnetic field. In some applications, less costly magnetic field indicators may be used to do measurements. Precision calibrated units are then used as reference standards, verifying the readings of the less costly devices. Periodically, the reference devices are returned to the manufacturers for calibration.

Conclusion

A magnetic field indicator is a convenient low cost tool for measuring the residual external field strength of ferromagnetic objects. To measure a uniform field, these units are often calibrated in a way that requires the operator to align a special directional marking (line or arrow on the device's casing) with the field's known direction.

For an external flux measurement, the field indicator is positioned against the object with its directional marking near to and perpendicular to the object's surface. This positioning is based on the fact that flux lines are expected to be perpendicular to the object's surface at the location of significant poles.

In cases where the field direction is uncertain, the indicator may be rotated about its directional marking, which is in turn positioned normal to the object's surface. The rotation moves through 180 degrees to get a maximum reading. The component of the magnetic field normal to the object's surface is no greater than the maximum value registered during rotation and no greater than the average of the readings at the beginning and the end of rotation. If the rotation does not affect the reading, then the field is perpendicular to the object's surface and the reading is the field's true value.

For a nonuniform field, the reading of the magnetic field indicator is an average value (at the spot where the indicator's field sensing magnet is located).

Good magnetic field indicators have sound mechanical supports for their reading pointers and these supports cannot be easily damaged. Their magnetic components cannot be easily demagnetized by strong external fields. Also, they do not induce significant magnetic poles on the objects they test.

For an accurate calibration of a field indicator, a uniform magnetic field may be provided by a Helmholtz coil. For a quick check of calibration, various approximate uniform field values along the axis of a large direct current coil may be used.

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SECTION 8

MAGNETIC PARTICLES AND PARTICLE APPLICATION

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INTRODUCTION

The magnetic particle technique provides a test indication that is located very near actual material discontinuities, describing their size and shape on the test object surface. In this important way, the magnetic particle method differs from most other nondestructive tests. In other techniques, test indications are typically produced in a medium separate from the test object, as an oscilloscope trace, through an acoustic transducer or on radiographic film, for example. By outlining and precisely locating the discontinuity, magnetic particle indications are comparatively simple to interpret.

The magnetic particle method is best used for locating small surface discontinuities on ferromagnetic test objects. The technique may also indicate the presence of certain linear discontinuities slightly below an object's surface. The absolute sensitivity of the magnetic particle method has not been firmly established, although this text discusses several applications that demonstrate how fine a crack may be reliably detected with careful testing procedures. In practical situations, absolute sensitivity is not as important as the *probability of detection*. This probability is a product of the magnetic particle characteristics, the magnetization method, the level of magnetization, test environment lighting intensity and inspector training.

This chapter focuses on: the importance of the magnetic particle's characteristics, test indication contrast, maintenance and handling, and specification requirements. There are two types of magnetic particles in general commercial use: dry particles and wet particles. Dry particles are applied to the test surface as a solid suspension or as a cloud in air. Wet particles are applied as a suspension of particles in a liquid vehicle, either oil or water. Each method is discussed here, with details of their contrast, color type, fluorescence and some general information about the appropriate industry standards.

Note that the Nondestructive Testing Handbook *uses SI units of measure followed by American standard units. When quoting from US testing specifications, the SI units are often provided for consistency in the text but are not necessarily part of the original document's language. Conversions are typically rounded.*

PART 1
DRY METHOD TESTING MATERIALS

Dry Method Particle Characteristics

Particles used in dry method magnetic particle testing are manufactured to emphasize three sets of physical properties: (1) magnetic characteristics, (2) size and shape and (3) visibility.

Magnetic Properties

Nearly all dry magnetic powders are finely divided iron particles coated with pigments. These ferrous materials are chosen to provide the characteristics critical to magnetic particle test procedures. Primary among these are low coercive force, low magnetic retentivity and high magnetic permeability.

Low retentivity increases the dry powder's ability to clearly indicate discontinuities. If the particles retain magnetism (high magnetic retentivity), they adhere to each other and cannot be properly applied. When such particles reach the test object, they adhere to its surface and cause an intense background, masking discontinuity indications.

High magnetic permeability also increases the powder's ability to indicate discontinuities. Particles with high permeability are easily attracted to the small magnetic leakage fields from discontinuities, where they are trapped and retained for interpretation.

The concentration of the magnetic material in dry powders is a fourth critical consideration. Increasing the amount of magnetically inert pigment in a dry powder composition naturally lowers its magnetic sensitivity. Dry magnetic powders are therefore manufactured as a compromise between the primary need for sensitivity and the secondary need for high visibility.

Size and Shape

Particle size and shape are to some extent more critical than magnetic permeability for achieving sensitivity and ease of use in a dry powder. Magnetic powders are not simply an aggregate of metallic filings. The particles are made from carefully selected magnetic materials of specific size, shape, magnetic permeability and retentivity. They are designed to be used in air, not to be mixed with a liquid vehicle. Reclaiming dry powders is not recommended.

Fine dry particles that can pass through a US Standard 270 mesh sieve of 50 μm (0.002 in.) show much greater sensitivity to small discontinuities and their small leakage fields when compared to 100 mesh particles of 150 μm (0.006 in.). The coarser particles, nearly three times the diameter of the 270 mesh particles, are more than twenty times heavier and are too large to be held by weak leakage fields.

However, for two reasons, a dry testing powder cannot be made exclusively of small magnetic particles: (1) small particles adhere to all surface anomalies (traces of oil, dampness, fingerprints or roughness), producing dense particle backgrounds; and (2) the testing environment becomes extremely dusty and unsafe for the inspectors. As a result, a practical dry magnetic powder contains a range of particle sizes. Small particles are needed for sensitivity to fine discontinuities. Coarser particles are needed to bridge large discontinuities and to diminish the powder's dusty nature. In addition, large particles can help reduce masking by dislodging the background often formed by fine particles.

Particle shape also has important effects on background, particle application and test results. Elongated particles (large length-to-diameter ratios) are easily attracted to leakage fields. When compared to particles of equal permeability but compact shape, long particles more readily form linear discontinuity indications, possibly because of their ability to easily achieve magnetic polarity. However, elongated particles cannot be used alone because of their tendency to mat and form clusters that cannot be easily applied.

Particles with a compact shape flow easily, have high mobility and can be simply dispersed into clouds for proper application. As a result, the most sensitive dry powders contain both shapes, in a ratio determined by the testing application and empirical data.

In AMS 3040, the upper size limit for sensitive dry particles is about 80 mesh or 180 μm (0.007 in.). Larger particles can plug powder applicators and do not add sensitivity.

Not all dry powder test procedures require high sensitivity. In some applications, high sensitivity is actually detrimental to the testing procedure. In these circumstances, size and shape are less critical and the most important particle characteristic is low residual magnetism.

Visibility and Contrast

Dry method magnetic testing powders are commercially available with three types of colors: (1) *visible colors* for viewing under white or visible light; (2) *fluorescent colors* for viewing under ultraviolet light; and (3) *daylight fluorescent colors*. The daylight fluorescent powders fluoresce brightly in visible light, greatly amplifying their visible color.

The visible light powders are normally available in gray, red, black yellow, blue and metallic pigments. This range of colors allows the user to choose the one that contrasts most strongly with the test object surface.

Fluorescent colors are seldom used in dry powder applications, partly because dry powder tests are typically performed on site or on large structures, making it difficult or impossible to enclose and darken the testing area. In addition, fluorescent dry powders often produce background that is bright enough to be objectionable.

Daylight fluorescent colors are occasionally used when a test indication's high visibility or contrast is more important than absolute sensitivity (fluorescent color augments the visible color and indications are extremely bright and visible). With these powders, there is no need for an enclosed, darkened test environment. In fact, the brighter the ambient light, the brighter the indications. Daylight, even in deep shadow, excites their fluorescence, as does blue mercury vapor lighting or the light from white fluorescent tubes. Ordinary incandescent lights work less effectively than white or blue light sources. However, the yellow light from sodium vapor lights does not excite fluorescence in daylight powders and cannot be used for this application.

In some applications, particle contrast may be enhanced by coating the test object surface with a thin white lacquer. The characteristics of the lacquer then become important considerations for the magnetic particle inspector. The white surface coating must dry immediately, so as not to slow the testing procedure and it must be easily removed after the test to avoid delays and additional costs.

Dry Particle Uses

Dry magnetic particles are often used to test welds or castings for surface discontinuities. Dry powder is not recommended for the detection of fine discontinuities such as fatigue cracks or grinding checks. Wet method testing is much more sensitive to small surface discontinuities.

Tests of Welds

In weld testing, the typical magnetic particle technique uses prods or yokes, with the inspector magnetizing and testing short overlapping lengths of the weld. The continuous magnetization method is used (the magnetic field is continuously activated while the inspector applies the powder and removes the excess).

Automatic processing has been used for testing linear welds on large diameter pipe. However, most welded structures are shaped in ways that make them difficult to handle automatically. In addition, much weld testing is done on site and only portable testing systems can be used.

Direct current magnetization is usually preferred for weld testing because it penetrates more deeply and allows the indication of slightly subsurface linear discontinuities. Half-wave direct current also has the advantage of providing increased particle mobility and increased potential for forming accurate discontinuity indications while reducing background.

Tests of Castings

Dry particles are particularly useful for magnetic particle testing of large castings. Cast objects are normally tested using prods or yokes, with the test covering small overlapping areas. Large portable power supplies may be used. In these applications, the magnetization equipment is set up in advance, with connectors for through current shots firmly clamped in place and coils or looped cables wound where needed. The current is applied throughout powder application making this a continuous method. Because the test procedure may take several minutes on a large casting, all test system cabling must be properly rated to avoid excessive heating.

The choice of magnetizing current depends on the type of discontinuities being sought. As a rule, direct current is recommended for weld testing because the direct current magnetic field penetrates deeper into the test object, providing some subsurface detection capability.

Application of Dry Magnetic Particles

Particle Applicators

Dry magnetic powders must be applied in a gentle stream or cloud. If applied too rapidly, the stream may dislodge indications already formed and will certainly build up too much background for easy removal or interpretation. If applied with too much velocity, typical particles gain too much momentum to be reliably trapped by discontinuity leakage fields. Manual and mechanized powder applicators can help provide proper density and speed of particle application.

The simplest and most common particle applicators are rubber bulbs or shaker bottles. For most magnetic particle applications, these simple devices provide the kind of application required for accurate testing. Mechanical powder blowers are another application option. They are designed to float a cloud of particles onto the test object surface and to then provide a gentle stream of air to remove the lightly held background particles. For best results, magnetizing current should be present throughout the application of particles and the removal of background.

Monitoring Particle Application

Regardless of the applicator that is used, the inspector must carefully monitor the test object while particles are being applied. It is critically important that powder application be done properly in order to ensure the reliability of the test.

This is especially true if subsurface discontinuities are being sought. Their particle indications are weakly held and not well delineated, so that they are very susceptible to damage from particles applied later.

Particle Reuse

It is recommended that dry magnetic particles be used only once. There are occasions when reuse is permitted but inspectors should understand the effects of frequent reuse.

Ferrous magnetic powders are dense (specific gravity of 7.68). When agitated in bulk, as in a powder blower or a bulb, a lot of shearing and abrasion occurs and this wears off some of the pigment. Each reuse, with its additional rehandling, wears off more pigment. As a result, color and contrast continually diminish to the point that discontinuity indications are not visible.

Reuse of magnetic powders also encourages fractionation, the separation of different sized particles from the composite. Particles sprayed over a test object are designed to have different sizes and to fall in different trajectories. Generally, finer particles float further away from the point of introduction. Unless great care is taken to collect *all* the particles, reused powders become gradually coarser and correspondingly less sensitive.

Particle Storage

The storage condition for dry method powders is critical to their subsequent use. The primary environmental consideration is moisture. If magnetic particles are exposed to high levels of moisture, they immediately begin to form oxides. Rusting alters the color, but the major problem is that the particles adhere to each other, forming lumps or large masses that are useless for magnetic particle testing.

Though not severe, there are also limitations on the temperatures at which dry powders can be stored and used. Visible light powders work on surfaces as hot as 370 °C (700 °F). Near this temperature some particle materials become sticky. Others lose much of their color, although their magnetic properties remain intact and they can still indicate discontinuities. Beyond 370 °C (700 °F), magnetic powders can ignite and burn.

Fluorescent and daylight fluorescent powders lose their visible contrast at 150 °C (300 °F) and sometimes at lower temperatures. This occurs because the pigments are organic compounds that decompose or lose their ability to fluoresce at particular temperatures.

Other Magnetic Particle Considerations

Dry method powders must not be used in wet method applications. Dry particles are designed and manufactured at densities that work well in air but cause them to settle quickly out of liquid suspensions. In water, typical dry powders settle at rates around 150 mm (6 in.) per second and accordingly cannot be kept suspended. In addition, dry powders are very susceptible to oxidation when exposed to water.

Note also that ferrous powders in general and particularly many of their pigments are classified as nuisance dusts by the Occupational Safety and Health Administration (OSHA) *and must be handled accordingly.*

Viewing and Interpreting Dry Particle Test Indications

Producing a discontinuity indication is the first stage of a magnetic particle test. Viewing the indication and interpreting its meaning is the second important step, and both procedures are critically dependent on the characteristics of the magnetic particles and light intensities.

Visible Particle Light Intensities

Military standard MIL-STD-1949A calls for *minimum* light intensities of 1,000 lux (100 footcandles) for magnetic particle testing with nonfluorescent powders. Other light level recommendations range from 800 to 2,000 lx (80 to 200 ftc).

The optimal light level is often a compromise between operator fatigue and visibility. On bright or reflective surfaces, high light intensities can cause glare that interferes with interpretation. On darker surfaces or those covered with thin scale, rust or other staining, the 1,000 lx (100 ftc) level may be barely adequate.

Fluorescent Particle Light Intensities

Because of their limited industrial application, there is little empirical data for light levels in dry fluorescent testing. In addition, there is presently no standard or specification for dry fluorescent intensity ranges. The few dry fluorescent powders that have had marginal applications were much brighter than typical wet method powders. Their viewing conditions were correspondingly less demanding than the conditions for wet fluorescent particle viewing (see below).

Daylight fluorescent dry powders also have no specifications for required light intensities. Sunlight, shaded or direct, as well as artificial blue or white light all excite daylight fluorescent powders to a high level of brightness and visibility. Incandescent light is somewhat less effective and yellow sodium vapor light is totally ineffective. Daylight fluorescent powders also fluoresce brightly under ultraviolet light but cannot be recommended for this method of viewing. They exhibit a high level of fluorescent background when viewed in the dark, high enough to nearly obliterate fine discontinuity indications. Testing under full visible light hides this background and keeps contrast high.

Dry Magnetic Particle Specifications

While the manufacturers of dry magnetic powders have their own quality control tests, additional testing is often needed to prove conformance to user specifications. One important specification is *Magnetic Particle Inspection Material, Dry Method* (AMS 3040) issued by the Society of Automotive and Aerospace Engineers. This specification is referenced in *Magnetic Particle Inspection* (MIL-STD-1949A) issued by the US Department of Defense. Specification AMS 3040 places an upper limit on particle size: 98 percent must be finer than an 80 mesh in the American Standard Sieve Series or 180 μm (0.007 in.) in diameter. The specification also defines the limiting amount of loose pigment (in a test called *magnetic properties*) and specifies a minimum sensitivity, six indications on the tool steel ring standard.

Other methods have been developed for dry magnetic particle testing of pipe, including requirements for the dry particles to be used.[1] Powder is required to have a range of particle sizes: at least 75 weight percent must be finer than 120 mesh ASTM sieve size (125 μm or 0.005 in.) and at least 15 weight percent must be finer than 325 mesh (44 μm or 0.0017 in.).

This specification also outlines a magnetic permeability test that uses a cylindrical powder sample as the core of a simple transformer. For an 11 $kA{\bullet}m^{-1}$ (140 Oe) input in the primary, at least 2.5 V shall show up across the secondary, with the prescribed circuitry. Such tests are sensitive to the amount of powder packed into the cylinder and effectively put a ceiling on the amount of magnetically inert pigment that the powder can contain.

PART 2
WET METHOD TESTING MATERIALS

Wet Method Particle Characteristics

In wet method magnetic particle testing, particles over 500 mesh (25 μm or 0.001 in.) in diameter, are considered coarse. These large particles exhibit diminished sensitivity to fine surface cracks and indicate no more than four indications on the tool steel ring standard. These coarse particles settle out of suspension in five to fifteen minutes and are difficult to keep in suspension.

Sensitive wet method particles range from 5 to 15 μm in diameter (0.0002 to 0.0006 in.) and unpigmented ferromagnetic oxide particles are an order of magnitude finer.

The small size and generally compact shape of wet method particles have a dominating effect on their behavior. Their size renders permeability measurements highly inexact and of limited utility. In addition, the size influences the brightness of fluorescent powders made from such particles.

Wet Particle Composition

Commercial wet method particles are made from finely divided iron, black iron oxide, brown iron oxide, and experimentally from ferrites, nickel and nickel alloys.

Black iron oxide or magnetite (Fe_3O_4) is available as ground ore or preferably as a fine synthetic powder. Brown iron oxide (gamma Fe_2O_3) is chemically identical to nonmagnetic red iron oxide (alpha Fe_2O_3) but has the same ferromagnetic cubic crystalline structure as magnetite.

Ferrites are hard ceramic materials that are difficult to make into fine powders. Some nickel alloy powders show good magnetic test sensitivity, if fine enough, but are slightly denser than iron and even harder to keep in suspension.

Fluorescent powders also contain fluorescent pigments as well as a binding resin to attach the fluorescent pigment to the ferromagnetic core.

Size and Shape

At sizes of 10 μm (0.0004 in.) and under, practically all low retentivity ferromagnetic powders have a compact shape, with length to diameter (L/D) ratios around one. This occurs because the methods of forming low retentive powders (grinding or precipitating from a highly agitated solution) preferentially break down long, narrow particles. Exceptions to this are the high retentivity, high coercive force oxides and ferrites used in magnetic tapes.

Fluorescent wet particles have a definite and measurable size, as do particles based on finely divided metallic iron. Synthetic iron oxides are more difficult to measure, with diameters around 0.1 μm. They are almost too fine to settle out of suspension.

Because of their slight residual magnetism, oxide particles collect to form loose clusters that settle out of suspension much faster than individual particles. The degree of clustering depends on the intensity of agitation. At high agitation rates, the clusters are small. At low agitation rates, they become larger. Clusters can often be seen on smooth shiny test surfaces after bath application. In this quiescent state, the clusters grow large enough to be seen with the unaided eye, often tens of micrometers in diameter.

Magnetic Properties

Because they can be shaped into ideal toroidal samples of one hundred percent density, metals and ferrites are subject to accurate measurements of their magnetic properties. Powders cannot be accurately measured because it is not possible to make samples with densities higher than about 50 percent. As an example, pure iron has an initial permeability of 1,000 at 8 $kA{\cdot}m^{-1}$ (100 Oe) field strength. Pure iron has a maximum permeability around 5,000. In laboratory tests, 10 μm (0.0004 in.) iron powder showed a permeability of about 10 (5 for iron oxides) at 8 $kA{\cdot}m^{-1}$ (100 Oe). With the lower field strengths associated with small leakage fields at discontinuities, permeabilities may well be lower still (the data above cannot be used to predict a ferromagnetic powder's behavior).

Because of their compact shape, the true material permeability of fine wet method particles may not be of practical importance. However high the core material's permeability might be, the apparent permeability of the individual particles does not exceed a value of about 2.5. This is because of the large demagnetization factor[2] associated with an L/D ratio of one.

$$\frac{1}{\mu} = \frac{1}{\mu'} - \frac{N}{4\pi} \qquad \text{(Eq. 1)}$$

or in SI units:

$$\frac{1}{\mu} = \frac{1}{\mu'} - N_d$$

Where:

μ = the true permeability of the parent ferromagnetic material;
μ' = the apparent permeability of the sample particle;
N = the demagnetizing factor;
N_d = the shape demagnetization factor.

At lower material permeabilities, the apparent permeability decreases, becoming 2.0 at a material permeability of 10. The apparent permeability decreases rapidly at still lower permeabilities. As a result, magnetic particles made from very high permeability material are little more effective than those of moderate permeability values (about 20 to 100). The most important consideration is avoiding the use of particles with very low permeabilities.

True material permeability becomes important when two or more particles touch and align in a leakage field. The *L/D* ratio of the joined particles begins to effectively exceed a value of one and the demagnetization factor of the string of particles shrinks. This allows the string to become more effectively magnetized and more firmly attached to the sites of discontinuity leakage fields.

Visibility and Contrast

Wet method particles are commercially available as fluorescent and nonfluorescent materials. Most nonfluorescent particles are simply ferromagnetic iron oxides, either black or brown. These are used in their natural color with no added pigment. As a result, these particles are very slightly more sensitive than the pigmented fluorescent particles. For this reason, the unpigmented iron oxides are preferred for some applications where sensitivity is more important than easy visibility. Bearing testing is an important application of these oxides — sensitivity is critical and the smooth reflective surface of the test objects give the best possible contrast to the dark oxide particles.

On darker surfaces, indications from brown and black particles are very difficult to see and locate, though a thin white lacquer painted on the test surface can improve contrast, much as it does with dry powders.

Fluorescent magnetic particles are composites, containing a ferromagnetic core, a fluorescent pigment and preferably a binder to hold the composite together. The size of the particle strongly influences its fluorescent brightness as the following data illustrate.

In 1 kg (2.2 lb) of 125 μm (120 mesh or 0.005 in.) iron particles, the pigmented surface area is about 6 m^2 (65 ft^2) and can be made brightly fluorescent with very little pigment. A finer iron powder, about 40 μm (325 mesh or 0.0017 in.) has a surface area around 18 m^2 (190 ft^2). In 1 kg (2.2 lb) of a 6 μm (0.00024 in.) oxide based powder, the pigmented surface area is about 420 m^2 (4,500 ft^2). Because the inspector's eyes register the fluorescent pigment on the particle's surface, ultrafine particles require 30 to 60 times as much pigment as the coarser particles in order to achieve the same relative brightness. Such ratios make manufacturing of bright ultrafine particles impossible (the particle would contain virtually all pigment with a trace of ferromagnetic core and no electromagnetic sensitivity).

An important consideration in fluorescent particle contrast is its durability. In an agitation system where the bath constantly passes through a centrifugal pump, the particles are subjected to constant high speed impact and shearing action from the pump's impeller. This slowly breaks the particle down to fragments. In the extreme case, two kinds of particles are formed: (1) nonfluorescent magnetic fragments which form indications that cannot be seen; and (2) nonmagnetic fluorescent fragments which do not indicate discontinuities but which do cause background. In practice, baths never reach this stage of total deterioration, but as breakdown progresses, indications become dimmer while background fluorescence increases (indication-to-background contrast diminishes).

The onset of particle breakdown can be detected in an already operating bath by an extension of the settling test. Fluorescent fragments are both less dense and finer than the intact particles and settle out of suspension much more slowly, requiring 10 to 15 hours. After a settling test is performed, allow the settling tube and sample to sit unagitated overnight. Loose fluorescent pigment will produce a thin, brightly fluorescent layer on top of the sediment (see *Settling Test* below).

No firm correlation has been made between the extent of particle breakdown, the relative amount of free pigment and the reliability of the bath. This settling test simply detects the occurrence of breakdown. The individual user can best relate the evident breakdown to the quality of the fluorescent magnetic particle bath.

Oil Vehicles for Wet Method Particles

There are two kinds of vehicles used for wet method testing: water and oil. *Oil vehicles* are preferred in certain applications: (1) where lack of corrosivity to ferrous alloys is vital (finished bearings and bearing races, for instance); (2) where water could pose an electrical hazard; (3) on some high strength alloys, where exposure to water may cause hydrogen embrittlement (hydrogen atoms from water can diffuse into the crystal structure of certain alloys thereby causing embrittlement).

Water vehicles are preferred for the following reasons: (1) lower cost, (2) little fire hazard, (3) no petrochemical fumes, (4) quicker indication formation and (5) little clean up required on site.

Specifications for Oil Vehicles

In the past, a variety of petroleum solvents and oils were written into magnetic particle testing specifications but most of these early oil vehicles were designed for other purposes. For example, federal specification P-D-680 (dry cleaning solvent) and federal specification VV-K-220 (kerosene, deodorized) were referenced in MIL-I-6868E (1976), *Magnetic Particle Inspection Process*.

The P-D-680 document was originally applied to nondestructive testing before high flash point fluids were required. This specification called for: (1) a minimum flash point of 59 °C (138 °F); (2) a low distillation range (no contemporary oil vehicle would meet this specification); and (3) two inappropriate purely chemical tests (the *doctor* test and sulfuric acid absorption).

The VV-K-220 document allowed a similarly low flash point and low distillation range and required a different sulfuric acid reactivity test.

Military specification MIL-STD-1949 (August 1985) called for magnetic particle oil vehicles that met the requirements of AMS 3161 and DOD-F-87935.

The American National Standard Institute's AMS 3161 (1972), *Odorless Heavy Solvent Inspection Oil*, addresses one of the specific needs of magnetic particle testing, a viscosity limit of 32 to 34 Saybolt Universal Seconds. Viscosity is measured in the SI system as *square meters per second* ($m^2 \cdot s^{-1}$). It may also be measured in $mm^2 \cdot s^{-1}$ or its equivalent in the cgs system, *centistokes* (cs). The 34 SUS level is a markedly low viscosity range equivalent to 2.0 $mm^2 \cdot s^{-1}$ (2.0 cs) to 2.3 $mm^2 \cdot s^{-1}$ (2.3 cs). Such viscosity is typical of light, volatile, low flash point petroleum solvents. The flash point minimum given in AMS 3161 is only 65 °C (150 °F).

Flash point is important for two reasons. Fire safety is the primary consideration: the Occupational Safety and Health Administration has placed costly restrictions on the use of lower flash point solvents in open tanks.[3] These restrictions may be avoided if the vehicle's flash point is over 93 °C (200 °F). Health considerations are less obvious but also important. Low flash point vehicles are more volatile than high flash solvents. A typical petroleum solvent having a flash point of 65 °C (150 °F) is much more volatile than one having a flash point of 93 °C (200 °F) or more, and burdens the inspector's breathing air with many times more solvent vapor.

The MIL-STD-1949A standard no longer provides requirements for magnetic particle oil vehicles, but instead references DOD-F-87935 and AMS 3126.

The requirements of DOD-F-87935 are listed below.

1. *Viscosity*: maximum of 5.0 $mm^2 \cdot s^{-1}$ (5.0 cs) at bath temperature (ASTM D445).
2. *Flash point*: 93 °C (200 °F) minimum (ASTM D93).
3. *Fluorescence of vehicle*: no more than reference standard.
4. *Odor*: none.
5. *Particulate matter*: 0.5 $mg \cdot L^{-1}$ maximum (ASTM D2276).
6. *Total acid number*: 0.0015 mg $KOH \cdot gm^{-1}$ maximum (ASTM D3242).
7. *Color*: 1.0 maximum (ASTM D1000).

The requirements of AMS 2641 (January 1988) are as follows.

1. *Flash point*: 93 °C (200 °F) minimum for Type I vehicles; 60 to 93 °C (140 to 200 °F) for Type II vehicle (ASTM D-93).
2. *Viscosity*: no more than 3.0 $mm^2 \cdot s^{-1}$ (3.0 cs) at 38 °C (100 °F); no more than 5.0 $mm^2 \cdot s^{-1}$ (5.0 cs) at bath temperature (ASTM D-445).
3. *Fluorescence*: same as specified in DOD-F-87935.

The AMS 2641 specification prescribes the same limits as DOD-F-87935 on the amount of particulate matter, acidity, odor (inoffensive) and visible color.

Water Vehicles for Wet Method Particles

Water Conditioning

Water cannot by itself be used as a magnetic particle testing vehicle. It rusts ferrous alloys (including the testing equipment), it wets and covers test surfaces poorly and does not reliably disperse fluorescent magnetic particles. Water conditioners or wetting agents must be added to remedy these shortcomings.

Water conditioners are not well covered in existing specifications. MIL-STD-1949A requires only that a conditioned water vehicle (1) wets a test surface without the film of water breaking; and (2) has an alkalinity not exceeding pH 10.0. Common sense indicates that a conditioned bath should not rust test objects and should not foam so as to interfere with the formation of indications. In magnetic particle tests, a water conditioner needs to perform the four following functions.

1. Reliably wet and cover all test surfaces.
2. Encourage wetting and dispersion of fluorescent particles, with their water repellent organic pigments and binders.
3. Minimize foaming caused by the necessary presence of wetting agents in the bath.
4. Retard rusting of test object surfaces.

Where the bath does not at first cover the test object surface, there can be no particles and no indication formation. Beyond this, the bath film must cover the test object surface (without breaking) throughout the magnetic particle test procedure. If the water film does break or peel from the surface to form separate drops, it also peels off most of the particles in affected indications. The result is poor and unreliable inspection.

Wetting Abilities

Different surfaces require different degrees of wetting. Steel billets, with porous, oxidized surfaces are easily wetted by untreated water. At the other extreme, very smooth surfaces covered with a trace of oil require very strong wetting ability. In such cases, surface tensions as low as 0.025 $N\cdot m^{-1}$ (25 $dynes\cdot cm^{-1}$) may be required.

Magnetic iron oxides used in nonfluorescent wet method baths are easily wetted by untreated water. However, fluorescent particles typically contain organic pigments and binding resins that tend to be water repellent. Fluorescent baths must therefore include treated water to achieve the wetting ability needed to cover common oily test surfaces and to adequately wet and disperse the fluorescent particles. When fine fluorescent magnetic particles are not wetted by the vehicle, they float on the bath surface like dust and no amount of agitation will disperse them.

Foaming Solutions

Because they contain powerful wetting agents, magnetic particle water baths easily generate stable foams when agitated at the surface. Masses of foam that reach the test surface during bath application slide to the lowest edge of the surface, erasing indications in their path. It is therefore important that water baths (1) do not foam excessively and (2) generate unstable foam that disappears quickly. While careful formulation of a water conditioner can minimize foaming, full foam control occasionally requires the use of antifoaming agents. Such agents cover the bath surface with a microscopically thin layer of an oily substance. Antifoaming agent concentrations are critical: if too much is present, it acts like an oily contaminant, coagulating the magnetic particles and destroying the bath's wetting ability.

Corrosion Inhibition

Corrosion was at one time controlled by including small amounts of sodium nitrite or traces of sodium chromate in the magnetic particle bath. These chemicals have high levels of toxicity and, when present, must be listed by suppliers on Materials Safety Data Sheets as ordered by the Occupational Safety and Health Administration (29 CFR 1910.1200). Sodium nitrite and sodium chromate are also among the waste water contaminants regulated by the Environmental Protection Agency. These safety restrictions limit the use of the chemicals and alternative corrosion inhibitors are being studied.

Water baths have never been expected to provide long term corrosion protection for the test object after testing is complete. Accomplishing this protection requires separate post testing treatment.

Bath Contamination

Both water and oil vehicles can be contaminated by solid materials (see *Settling Test* below). Introduced oil may also be a contaminant of water and oil baths. In addition, oil vehicles can be contaminated by introduced water.

The most common form of contamination is oil in a water bath. This occurs in recirculating systems where bath runoff returns to the bath reservoir and oil on the test surface is washed into the water. When enough oil is present, it causes magnetic particles to congeal and also destroys the bath's wetting ability. Oil contamination can be avoided by effectively precleaning test objects. If this is not possible, stringent control of the bath is required and should include regular visual inspections and monitoring of production levels. Contaminated bath is discarded and replaced.

Highly fluorescent oil or grease on test object surfaces can easily dissolve into oil-based magnetic particle baths. The accumulation of introduced oil produces a blue fluorescent background that can hinder discontinuity indication detection. Frequent inspection of the bath and monitoring of production levels are again the solutions, if precleaning is not possible.

Particle coagulation also occurs when water contaminates an oil bath. The condition is accompanied by a build-up of a sticky mass on the bath tank walls. Adding small amounts (0.1 percent or less) of a suitable oil-soluble emulsifier will restore the bath. The addition of emulsifiers must be done carefully — too much will markedly increase the bath's viscosity and fluorescence.

Bath Preparation

Wet magnetic particle baths may be mixed by the supplier or may be sold dry for mixing by the user. When the magnetic particle system contains a recirculating bath, mixing is relatively easy.

Recirculating System Bath Preparation

After the liquid vehicle is added to the bath tank, the manufacturer's required amount of powder is added directly above the sump. The bath is allowed to recirculate for five minutes while the pump disperses the powder.

When a conditioning agent is needed for a water vehicle, the agent is added to the bath and dissolved before the magnetic powder is added. Because the conditioning agent must be dissolved before it becomes active, it is faster to begin the process with warm water.

Nonrecirculating System Bath Preparation

If the magnetic particle system has an air agitated bath, or if the bath is applied from spray guns, then bath preparation is more difficult. Magnetic particles often stick together during manufacture, storage or shipment and simple stirring does not separate them — manually mixed baths are therefore susceptible to uneven distribution of particles and are unreliable for testing.

The best way to manually prepare a finely dispersed bath is to add premeasured powder to a small food blender along with enough oil or conditioned water to nearly fill the container. At low speed this takes about thirty seconds.

An alternative method is to add premeasured powder to a small container along with enough liquid to form an easily worked paste. Mixing by hand precedes adding the paste to the bath.

Bath Maintenance

The effectiveness and reproducibility of a magnetic particle bath depend on its concentration. If the concentration is too low, indications will be weak and difficult to locate. If the concentration is too high, the background will be intense enough to camouflage indications. Correct particle concentrations fall between these extremes.

Keeping the concentration at a constant level eliminates one variable in the test: the indication-to-background contrast. It is important to regularly monitor bath concentrations throughout the testing cycle, not only after bath preparation. Suppliers of magnetic powders specify bath concentration both in weight of powder per volume of bath and also in settling volume ranges that result from these concentrations. Most industry standards specify only the acceptable settling volume.

Visible Particle Concentrations

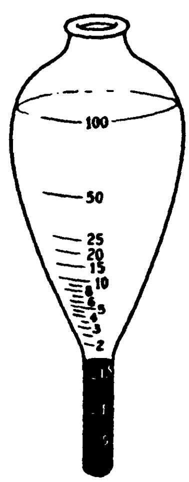
The Society of Automotive Engineers specifications AMS 3042 and AMS 3043 for visible wet method particles call for settling volumes from 10 to 24 mL/L or (using a 100 mL centrifuge tube) 1 to 2.4 mL (1 to 2.4 cm^3). The MIL-STD-1949A specification calls for a range of 1.2 to 2.4 mL after thirty minutes settling in a vibration free location.

All three standards specify the use of the particular pear-shaped tube illustrated in ASTM D-96, *Water and Sediments in Crude Oils* (Fig. 1 shows a similar settling tube). The D-96 tube has a 1.5 mL (1.5 cm^3) stem graduated in 0.1 mL (0.1 cm^3) increments. The next graduation is at 2.0 mL (2.0 cm^3) in the conical portion of the tube. If the expected settling volume is in an inadequately graduated portion of the settling tube, a permanent mark should be made at the correct location so that a constant bath strength can be accurately maintained without estimation.

Fluorescent Particle Concentrations

The AMS 3044, AMS 3045 and MIL-STD-1949A standards also specify concentrations for fluorescent particle

FIGURE 1. Diagram of a typical centrifuge tube used for magnetic particle settling tests



baths but again the requirements differ slightly. The AMS specifications call for a range of 0.2 to 0.5 mL (0.2 to 0.5 cm^3), while MIL-STD-1949A calls for 0.1 to 0.4 mL (0.1 to 0.4 cm^3) settling volumes. The ASTM D-96 tube is required for the test.

Fluorescent particle baths are much more dilute than visible baths, so that all likely settling volumes fall within the graduated stem of the tube. More reproducibility for small settling volumes can be achieved if the tube has a 1 mL stem graduated in 50 μL intervals.

Use of Settling Ranges

It is not productive to assume that all concentrations within broad specified ranges are equally effective or desirable. For example, it has been shown that fluorescent particle concentrations around 2 mL/L give the best results on a tool steel ring standard.[4] Higher concentrations produce backgrounds that obscure faint discontinuity indications. Lower concentrations produce indications too faint to be easily detected.

In another special case, it was found that increasing particle concentration from 1 to 4 mL/L gives increasingly brighter indications with very little increase in background. In this application, clusters of very fine cracks were being located under a chromium plate. The cracks were very close together (less than 0.5 mm apart) so that expanding indications totally depleted the narrow strips of background between the cracks, producing dense bright indications.

Some users *prefer* a substantial fluorescent background during testing because in their applications this lessens the need for frequent bath concentration measurements. Such modifications of recommended procedure are allowed only after firmly establishing and verifying the results of such tests for the individual application.

The broad concentration ranges outlined in most specifications cover the *limits* that are allowed and that may be required. Testing beyond either specified extreme may not produce the best results and higher or lower concentrations should be considered.

There is a strong tendency in some industries to test at the lowest possible concentration. This is valid for economic reasons and it additionally ensures that excessive background does not become a problem. There is one precaution necessary for this approach: if particles are applied from a recirculating system where the excess bath returns to the reservoir, particle depletion is a likely result. Most magnetic particles adhere to the test object while most of the vehicle returns to the reservoir. The particle concentration decreases steadily with usage over time and may not be noticed by inspectors. For reliable, reproducible magnetic particle tests with low bath concentrations, the frequency of concentration tests must be increased.

The Settling Test

Since the 1940s, a settling test has been used to measure magnetic particle bath concentrations.[5] It is a convenient method that requires little equipment, a simple procedure and only thirty to sixty minutes to perform. Its accuracy is sometimes less than 80 percent but the levels of precision are appropriate for most applications.

The military standard MIL-STD-1949A specifies that the filled settling tube be demagnetized before the settling test begins. Because the magnetic condition of a bath can affect the speed of settling and the final settling volume, the demagnetization procedure is an effort to standardize the magnetic level of the bath regardless of its use.

Settling Parameters

It is essential that the settling test take place in a location that is free from vibration. The settling tube must be positioned in an area that is proven to be free of strong magnetic fields.

Freshly magnetized bath settles very rapidly, often in fifteen minutes or less. Magnetization causes the particles to clump together quickly and form large, fast-sinking clusters (agglomerated settling). However, these clusters form a much larger settling volume than if the individual particles were unmagnetized (the structure of the clusters cannot be compacted by gravity).

Speed of settling and settling volume depend on the particle's magnetization level and this is the basis for requiring demagnetization of the settling tube sample. Vibration during settling does not affect the speed of settling but it can compact the sediment to give falsely low settling volumes.

The Settling Tube

Settling test equipment is simple: (1) a 100 mL pear-shaped graduated glass centrifuge tube (see Fig. 1); (2) a stand for supporting the tube vertically; and (3) a timer to signal the end of the specified settling period.

The tube referenced in most specifications has a 1.5 mL (1.5 cm^3) stem graduated in 0.1 mL intervals. According to ASTM D-96, the maximum reading error of this tube is 30 μL. Another common tube has a 1.0 mL stem graduated in 0.05 mL intervals. This configuration is easier to read for baths with small settling volumes, including most fluorescent particle baths.

For very dilute baths, even 0.05 mL intervals are too large and a tube with a 0.2 mL stem in 0.01 mL graduations gives the most reproducible results. This stem is very nearly the size of a capillary tube and is extremely difficult to clean after a settling test.

The typically specified tube is probably a compromise. It can be used to measure dilute fluorescent particle baths (under 0.2 mL with diminished accuracy) as well as more concentrated visible particle baths (also with diminished accuracy if the settling volume is over 1.5 mL). The three tubes do not show the same settling volumes for the same bath. Tubes with narrower stems show higher settling volumes. Hindered settling behavior mentioned below acts to retard settling in the more constricted stems.

Effect of Contaminants

Recirculating magnetic particle baths can pick up solid contaminants from three main sources. The first source includes solids washed into the bath from test object surfaces. Vapor phase degreasing, a common procedure for cleaning test objects before magnetic particle testing, does not remove non-oily contaminants such as sand, dust, lint or grit.

A second source is particulate matter in the testing atmosphere that settles into the bath. The quantity of these solids is determined by the geographic location and the nature of the manufacturing facility, but some airborne particulates can be in quantities sufficient for increasing the settling test volume.

A third source, unique to water baths, is a highly dilute but bulky and gelatinous precipitate. The contaminant is caused by increasing water hardness in the bath as water is added to replace evaporation loss. Water hardness is determined by the concentration of certain salts, including calcium and magnesium. The resulting precipitate does not affect settling tests of baths with high particle concentrations because too little of it is present and the weight of the settled ferrous particles compacts it. In dilute baths (settling volumes of 0.1 mL or less in the 100 mL centrifuge tube), the precipitate adds bulk to the sediment and can give falsely high settling volume readings.

Contaminating particles do not necessarily settle out first or last to form obvious layers in the sediment. The effects of contamination contribute strongly to the low absolute accuracy of the settling test. Contamination of oil baths by water and contamination of water baths by oil tend to produce bulk sediments and substantial amounts of the magnetic particles adhering to the sloping walls of the settling tube.

Stages of Settling

The sedimentation of magnetic particles during the settling test consists of four separate but overlapping stages.[6]

The first stage is simple *unhindered settling* of the individual particles. This changes to *agglomerated settling* where their slight residual magnetism causes the particles to collect into larger and faster settling clumps. When most of the particles have settled into the narrowing portion of the centrifuge tube, *hindered settling* begins. In this stage, the local particle concentration is high enough that the falling particles get in each others way and restrict further settling. In addition, the upward flow of the displaced liquid now becomes rapid enough to further retard settling. The final stage is *compact settling*, where all the particles are in contact and apparently settled but the sediment slowly shrinks in volume as more liquid is displaced.

Condition of the Vehicle after Settling

In its early versions, MIL-STD-1949 required that the supernatant liquid (the vehicle after settling) be essentially nonfluorescent. Naturally, fluorescence in the liquid vehicle can detract from the contrast of fluorescent indications. It can also signal the breakdown of fluorescent magnetic particles into their components. A fluorescent magnetic particle bath composed of unattached fluorescent pigment along with nonfluorescent particles, whose indications cannot be seen under ultraviolet light, is not a usable bath and should be discarded.

Three different conditions can lead to fluorescence in the supernatant liquid after settling is complete but not all of them indicate a substandard bath. Fluorescent oils or grease can be swept into the bath from test surfaces, making the whole liquid fluorescent. Particles can break apart, leaving tiny slow settling fragments of fluorescent but nonmagnetic pigment behind. Finally, some very small but complete particles can escape agglomeration and, settling at individually slow rates, may require another hour or more to finally settle out.

A fluorescent supernatant liquid is a warning to further monitor the condition of the bath. Is the blue fluorescence due to the presence of oils bright enough to interfere with indication contrast? If not, then it is not excessive. Does the sediment after overnight settling show a bright fluorescent layer on top? If not, the particles have not been broken apart. Does the green fluorescent supernatant liquid give feeble indications because of the extremely low concentration of particles? If so, then the bath contains fine, slow settling but useful particles. The converse to any of the above answers indicates that the bath should be replaced.

Various instruments are available for automatically monitoring bath concentrations. Low consumer acceptance of these instruments is based on two disadvantages: (1) the much lower cost of simple settling test equipment; and (2) the accuracy of continuous monitoring equipment can be compromised by certain kinds of bath contaminants.

Applications of Wet Magnetic Particles

Magnetization Methods

Wet method materials can be used in practically any kind of magnetic particle testing, although they are most useful for indicating the fine surface cracks that dry powders cannot reliably locate.

Wet particles can be used with the residual and the continuous magnetization methods. In the residual method, the test object must have high magnetic retentivity. It is first magnetized, then the magnetic field is removed and the object is dipped into an agitated magnetic particle bath. Agitation must be gentle or sometimes stopped during immersion to avoid dislodging indications. Longer immersion or exposure times yield larger indications, an advantage of the residual method.

The continuous magnetization method is more widely used, with slight variations in procedure that depend on the specific application. In the typical wet horizontal testing unit, the inspector flows agitated bath onto the test object from a hose. After the hose is shut off, the magnetic field is activated. At this point, the bath is draining off test surfaces slowly enough to avoid dislodging indications. If these actions are not properly sequenced and bath is still being applied after the magnetizing current ceases, the continuous method is no longer being used but rather the residual method. This degrades the inspection and can actually nullify it if the test objects are of low magnetic retentivity.

Sample test objects are available to teach, as well as test, application technique. They feature a very low retentivity iron test object containing a discontinuity. If the sequencing of bath application and magnetization is not correct, the discontinuity is not indicated.

Multidirectional magnetization allows the use of automatic bath application. Precise timing and sequencing are also important in this application, where the test object is exposed to various magnetic orientations in order to locate discontinuities positioned in various ways throughout the object.

Because an object can retain only one magnetic field at a time, the fields are rapidly switched. The discontinuities indicated by the final field orientation are effectively located by a short lived continuous method. Discontinuities magnetized by earlier fields in the rapid sequence are subject to erasure if the bath flow is too rapid. This also explains why test objects with some surface roughness (13 RMS or rougher) are better candidates for multidirectional testing than those with very smooth surfaces. Not only do rougher surfaces retard the rate of bath flow and drainage, but they also retain indications by increased friction.

Means of Applying Wet Magnetic Particles

In on-site testing using portable or movable power supplies, wet magnetic particles are typically applied in a spray, with no provision for collecting or recovering excess bath. This method avoids bath contamination from particulates present on the test object. Often, the continuous magnetization method is employed in this test, with the magnetizing current deliberately kept on throughout bath application.

Several means of spraying are available: aerosol cans, prepressurized spray guns and spray guns supplied from a separate container (a drum of bath or a pressurized spray pot).

Each of these devices has its own advantages and disadvantages. Aerosol cans free the testing process from the need for pressurized air, but the cans must be frequently shaken to keep the bath suspended. Prepressurized spray guns cost less than bath in aerosol cans, but they require pressurized air or a supply of carbon dioxide cartridges and must still be shaken and constantly agitated. Prepressurized guns are also much heavier than aerosol cans and handling can be strenuous. Spray guns supplied from separate containers often have recirculating systems immersed in the bath. These automatically keep the bath agitated and are quite effective where electrical power is available. Pressurized spray pots can be equipped to supply constant agitation and are handy to use where pressurized air is available.

Wet Magnetic Particles for Special Applications

Wet method fluorescent particles can be used for nondestructive testing of underwater structures such as drilling or production platforms. Test procedures parallel those used on dry land with a number of added complications.

First there are the personnel hazards: (1) exposing inspectors to deep underwater conditions for long periods; and (2) the electrically conductive environment demands perfect insulation to avoid the danger of electrocution. Beyond the safety aspects, the magnetic particle test procedure is itself complicated. Often the tests are performed in murky surroundings with poor visibility where currents can carry particles away from the test surface. Before testing can begin, the structure must be cleared of all sediment and other marine fouling.

The magnetic particle materials are usually special fluorescent powders that mix equally well with fresh water or sea water. The particle suspension is taken to the test site in a plastic bottle where it is applied near the magnetizing yoke commonly used for underwater tests. The particles are in a concentrated aqueous slurry that is immediately diluted to normal particle concentrations by the surrounding water.

In another special application, thick, concentrated slurries of paramagnetic flakes in a viscous liquid are occasionally used to locate surface cracks. These reflective particles do not migrate to leakage fields but rotate in place to line up with the fields.

The inspector brushes the slurry onto the surface, producing a shiny film that stays in place and does not run or drip off. Where a leakage field exits, the particles present their dull edges to the surface, delineating cracks with dark lines on the otherwise bright surface. Post testing clean-up is tedious for this technique.

Temperature Limits for Water Vehicles

Wet method testing is susceptible to temperature limits that do not affect dry particle testing. Water baths change little in viscosity between the freezing and boiling points of water but they do freeze on test surfaces colder than 0 °C (32 °F). At near subfreezing temperatures, water does not freeze instantly and magnetic particle indications have time to form before the water bath solidifies.

At lower temperatures, antifreeze must be added to keep the bath liquid. Antifreeze is useful only in those applications where high sensitivity is not desired, such as the testing of steel billets. Solutions of water and either ethylene glycol or methyl alcohol rapidly become far too viscous below freezing and drastically retard the formation of discontinuity indications.

The upper temperature limit of the test object has not been established for water baths. At 100 °C (212 °F), water evaporates too quickly for indications to form and this can happen at somewhat lower temperatures as well.

Temperature Limits for Oil Vehicles

Oil baths, though still liquid below −18 °C (0 °F), increase noticeably in viscosity as the test piece or bath temperature decreases. Type I baths (defined in AMS 2041) have a viscosity around 2.4 $mm^2 \cdot s^{-1}$ (2.4 cs) at 38 °C (100 °F) and reach the 5 $mm^2 \cdot s^{-1}$ (5 cs) limit at about 10 °C. (50 °F). Type II baths (AMS 2641) have a viscosity around 2.7 $mm^2 \cdot s^{-1}$ (2.7 cs) at 38 °C (100 °F) and reach the 5 $mm^2 \cdot s^{-1}$ (5 cs) limit at approximately 13 °C (55 °F). These figures may vary with the source or manufacturer of the oil vehicle.

The upper limit of practical temperature for oil baths is influenced more by health considerations than by fire hazards. When an oil bath is heated to its flash point (either in bulk or by contacting a test surface at this temperature), air in the immediate vicinity contains nearly 1 percent oil vapor (10,000 ppm). The vapor condenses to a fine oily mist as the vapor cloud cools. A vapor or mist concentration at the 1 percent level is 100 times more than OSHA's permissible exposure limit (PEL) of 100 ppm. This level can be considered hazardous. For health reasons, an oil bath should be used at maximum temperatures far below the flash point. Excellent ventilation is required for any use of an oil bath above 43 °C (110 °F).

Viewing Wet Method Indications

Visible Lighting Specifications

Visible wet method magnetic particle testing is subject to the same lighting requirements as dry particle testing in MIL-STD-1949A. This is a minimum of 1,000 lx (100 ftc) at the testing surface.

Because the nonfluorescent particles are often used on fairly bright, reflective surfaces (contrast on dark surfaces can be poor), glare can easily become a problem. Lowering the light intensity, when not prohibited by specifications, can decrease glare but this should not be done without careful evaluation of the test results. Where specular reflection of the light source is not a problem to inspectors, the specification requirements should be followed in all cases.

Fluorescent Lighting Specifications

For fluorescent wet method testing, MIL-STD-1949A requires a minimum ultraviolet light intensity of 1,000 $\mu W \cdot mm^{-2}$ at the test surface. Further, the maximum allowable visible light intensity at the surface is 20 lx (2 ftc). This is because the presence of visible light reflected from the test surface lowers the contrast of the fluorescent indications. Visible light intensity must be measured with the ultraviolet light source on since they themselves emit small amounts of visible light, primarily in the violet portions of the visible light spectrum. This small amount of visible light, added to the ambient visible light already in the testing booth, can help lower a fluorescent indication's contrast.

The reliability of testing increases dramatically as the ultraviolet light intensity increases.[4] The probability of detection of 97 discontinuities on 37 test pieces has been shown to rise from 34 percent at 1,000 $\mu W \cdot mm^{-2}$ to 100 percent at 4,000 $\mu W \cdot mm^{-2}$.

PART 3
STUDIES OF MAGNETIC PARTICLE SENSITIVITY

The data below were compiled from application studies of magnetic particle process sensitivities. Discontinuity sizes were usually not known by the investigators. In five instances, the test objects were closely examined, sometimes with destructive techniques, to determine exactly what the magnetic particle method was detecting.

Studies to Determine Wet Method Particle Sensitivity

Discontinuity Size Limits for Carburized Steel

Case hardened (carburized) steel pins of unspecified size were tested with wet method magnetic particles, both visible and fluorescent.[7] A direct current coil was used and crack depths were not measured. Some indications of fine transverse cracks were found.

Microscopic examination of the smooth test object surface showed crack widths ranging from 0.25 to 2.3 μm (10 to 90 μin.). Such crack widths are typical of a surface under high compressive stress.

This range of widths could be considered the narrowest detectable discontinuity for a direct current test, which produces a magnetic field largely contained within the higher permeability core of this test object. An alternating current technique concentrates the magnetic field at the surface, possibly altering the detectable discontinuity size limit.

Discontinuity Size Limits for Nitrided Steel

Nitrided steel bushings of unspecified size were magnetic particle tested at 1 kA for grinding cracks.[7] The bushings had been nitrided to an average depth of 0.15 mm (0.006 in.).

The magnetic particle discontinuity sites were metallurgically examined and showed grinding cracks from 13 to 65 μm (0.5 to 2.5 milli-in.) in depth. Some quench cracks with depths from 0.05 to 0.13 mm (0.002 to 0.005 in.) were also detected with magnetic particle techniques. All cracking was normal to the surface.

Correlation of Discontinuity Size with Other Parameters

Several 20 mm (0.8 in.) high explosive projectiles were tested with fluorescent magnetic particles. The tests used direct current, a central conductor and a head shot, with current passing lengthwise through the projectiles.[8]

Though not a common application, the two test reports present documented correlations of discontinuity size, location, magnetizing current and indication quality. The reports' original drawings are reproduced in Fig. 2 through Fig. 11.

FIGURE 2. Tracings of photomicrographs showing fluorescent magnetic particle indications on shell casings

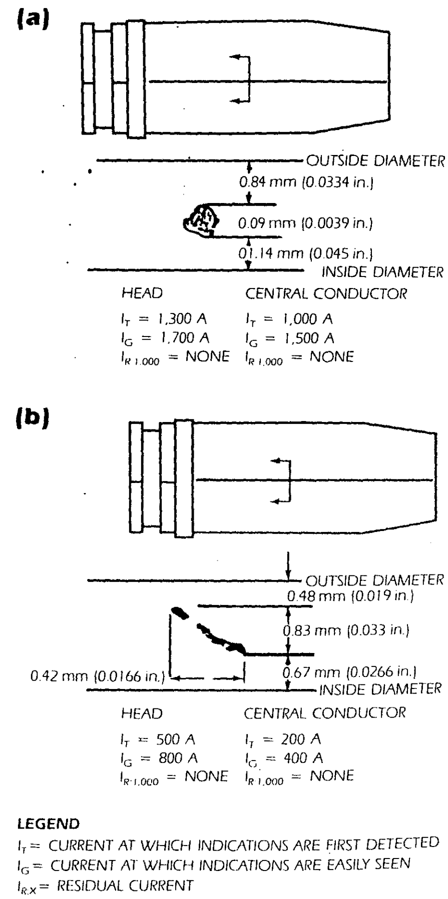


FIGURE 3. Tracings of photomicrographs showing fluorescent magnetic particle indications on shell casings

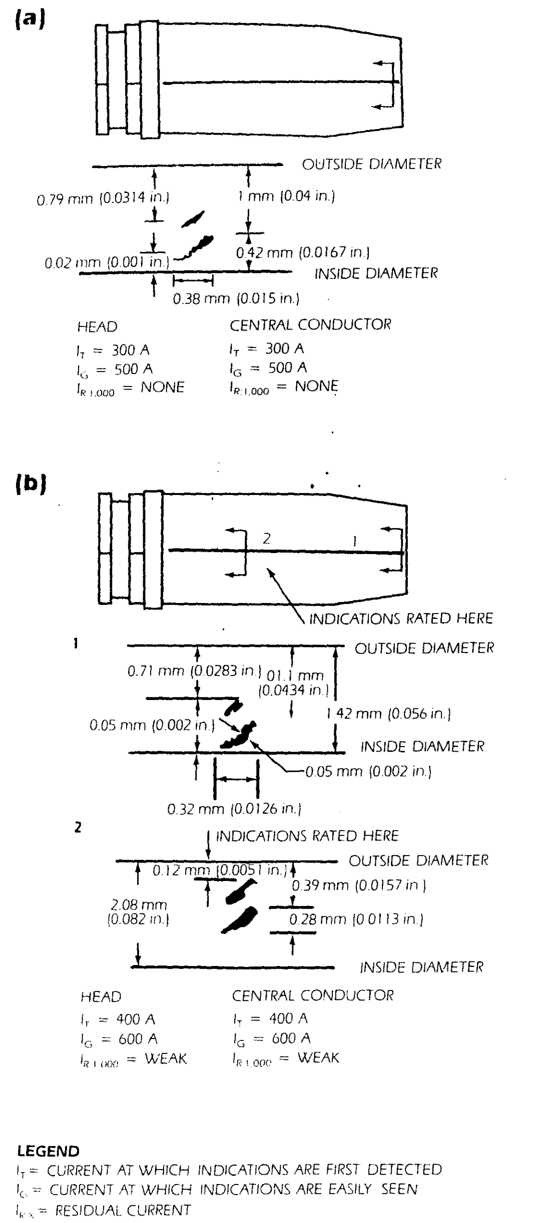


FIGURE 4. Tracings of photomicrographs showing fluorescent magnetic particle indications on shell casings

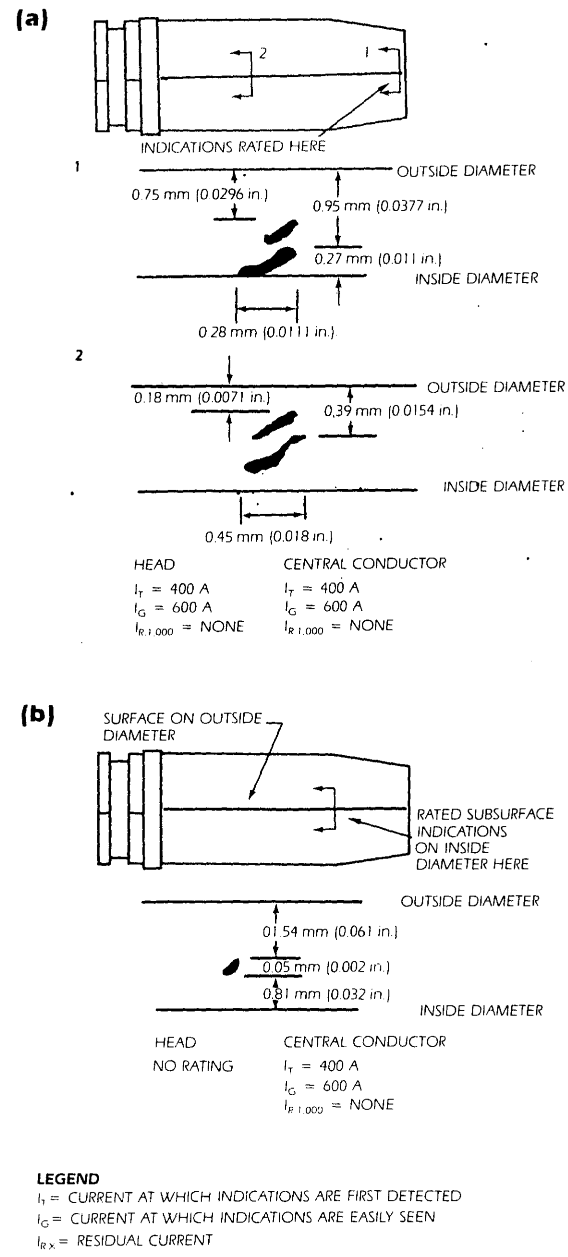
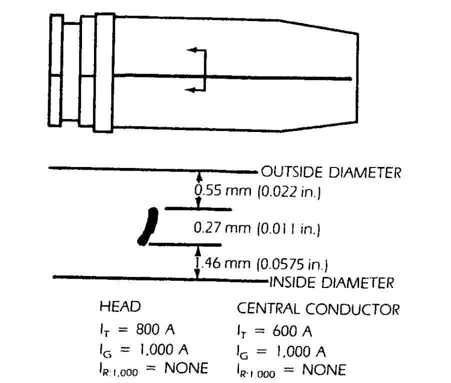


FIGURE 5. Tracings of photomicrographs showing fluorescent magnetic particle indications on shell casings



LEGEND
I_T = CURRENT AT WHICH INDICATIONS ARE FIRST DETECTED
I_G = CURRENT AT WHICH INDICATIONS ARE EASILY SEEN
I_{RX} = RESIDUAL CURRENT

Correlation of Discontinuity Indication Brightness

A study of indication brightness versus seam depth was made on two 60 mm (2.4 in.) square steel billets. Ultraviolet photographs were taken at the ends of six billets at two continuous current settings and one residual current level.

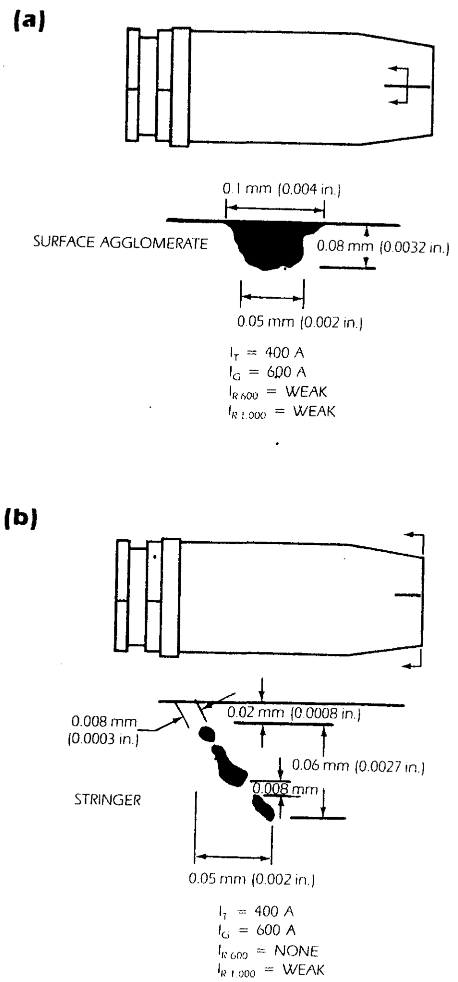
Figures 12 through 18 show the brightness of magnetic particle indications for the various discontinuity depths. Although some clarity is lost in the reproduction process, the original photographs indicate a direct relationship between increased crack depth and increased indication brightness.[9]

Discontinuity Size Limits in Steel Billets

During processing, certain steel billets are heated to a temperature where the outer 0.4 mm (0.015 in.) oxidizes to form scale. Magnetic particle tests of such billets are concerned only with cracks likely to remain after scale removal. The goal of the study below was to lower the sensitivity of the testing technique to avoid detection of fine temporary cracks.

Test indications were established using a special low sensitivity fluorescent wet method particle. These coarse particles had diameters from 25 to 50 μm (0.001 to 0.002 in.). Test indications were compared to those for

FIGURE 6. Tracings of photomicrographs showing fluorescent magnetic particle indications on shell casings



LEGEND
I_T = CURRENT AT WHICH INDICATIONS ARE FIRST DETECTED
I_G = CURRENT AT WHICH INDICATIONS ARE EASILY SEEN
I_{RX} = RESIDUAL CURRENT

FIGURE 7. Tracings of photomicrographs showing fluorescent magnetic particle indications on shell casings

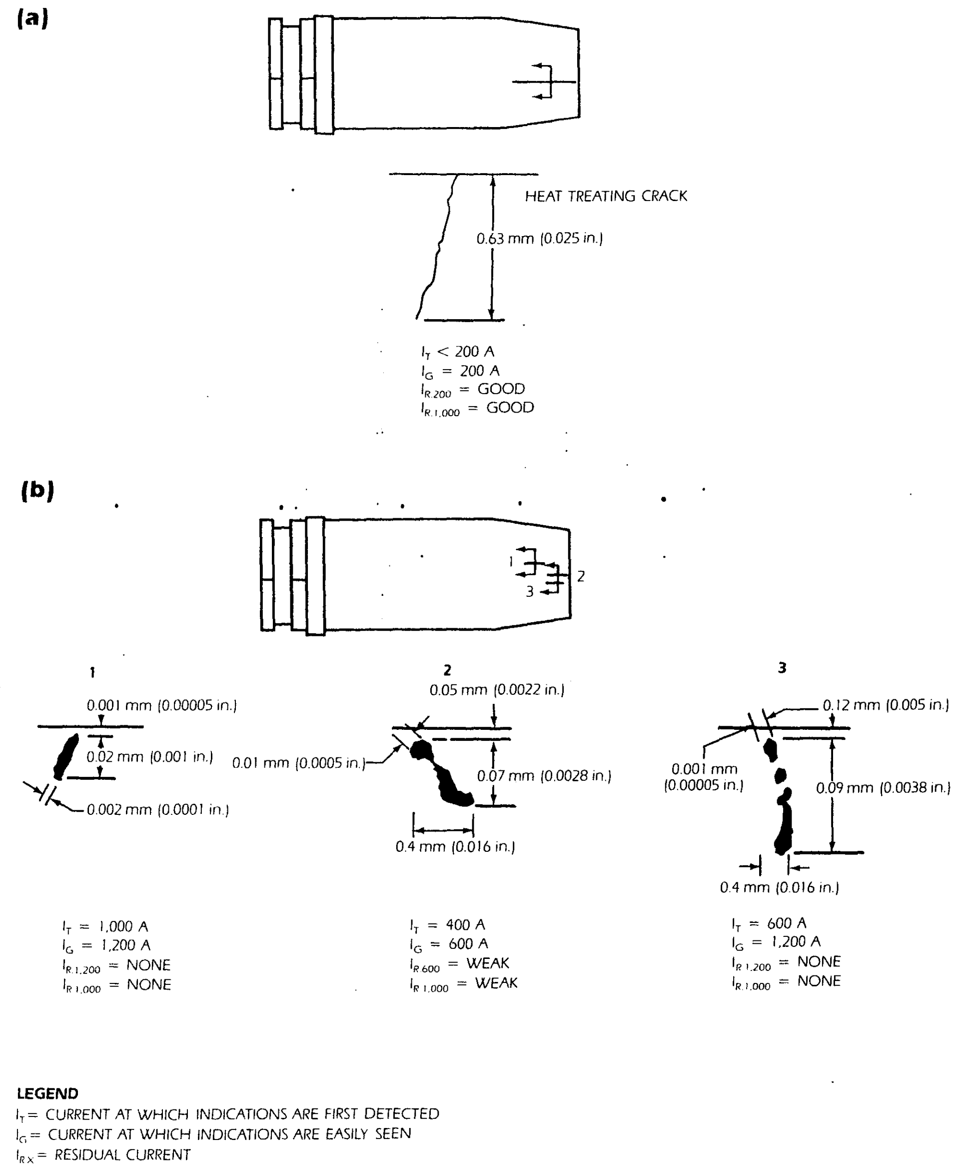
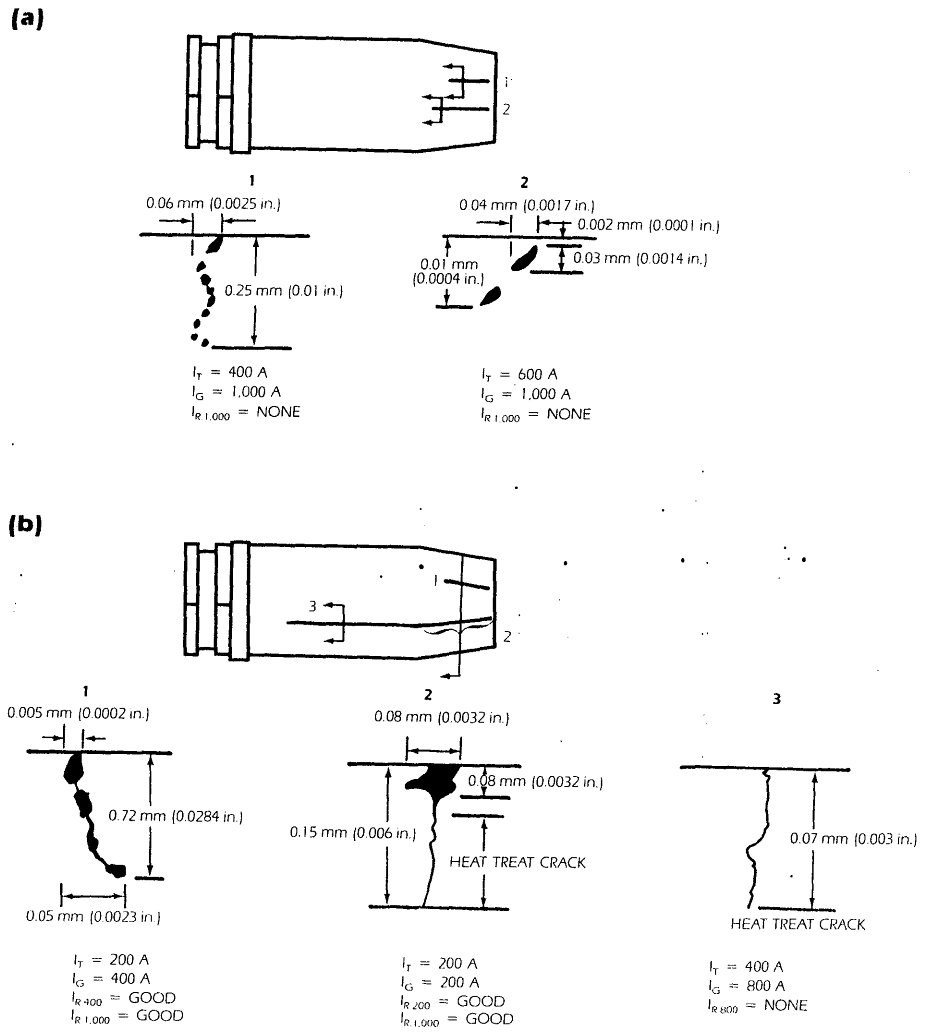


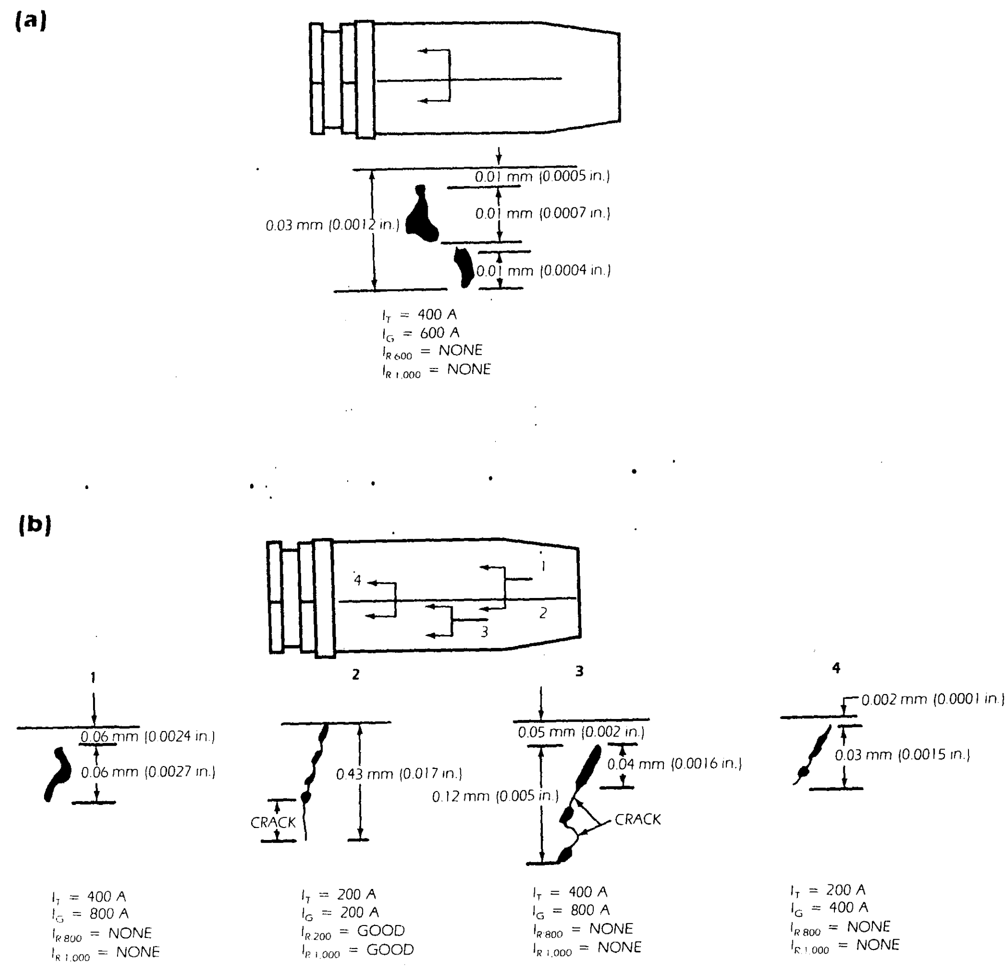
FIGURE 8. Tracings of photomicrographs showing fluorescent magnetic particle indications on shell casings



LEGEND

I_T = CURRENT AT WHICH INDICATIONS ARE FIRST DETECTED
I_G = CURRENT AT WHICH INDICATIONS ARE EASILY SEEN
I_{RX} = RESIDUAL CURRENT

FIGURE 9. Tracings of photomicrographs showing fluorescent magnetic particle indications on shell casings



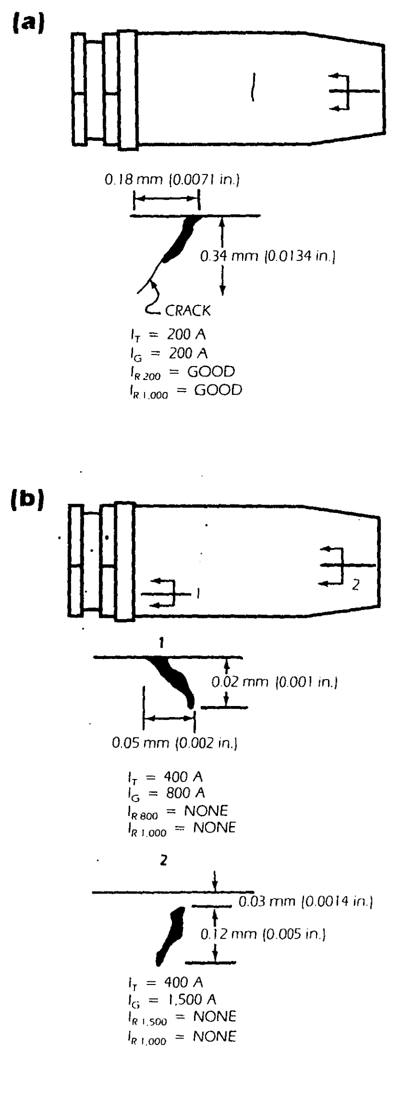
LEGEND

I_T = CURRENT AT WHICH INDICATIONS ARE FIRST DETECTED

I_G = CURRENT AT WHICH INDICATIONS ARE EASILY SEEN

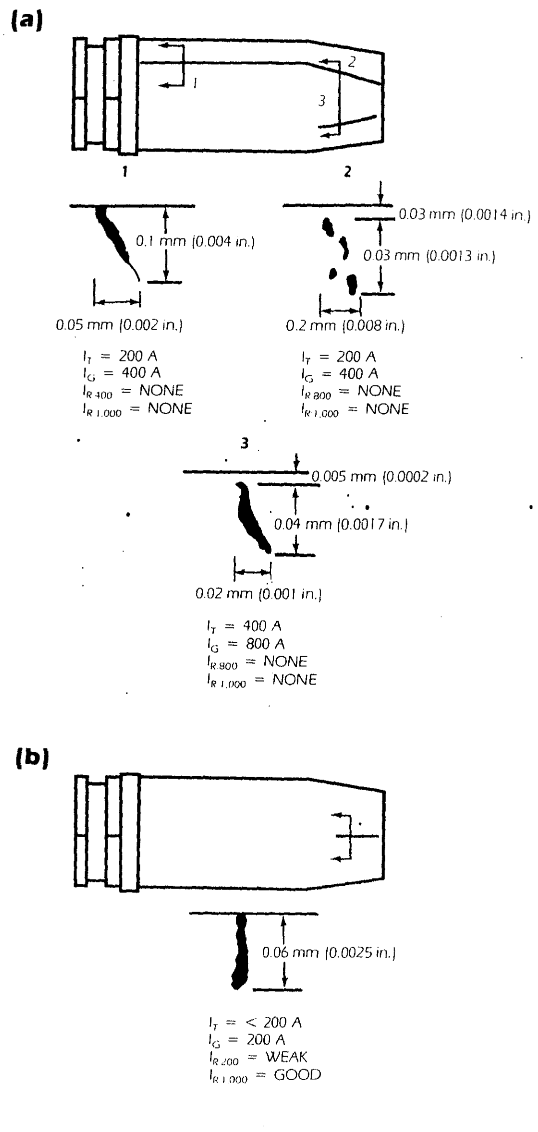
I_{RX} = RESIDUAL CURRENT

FIGURE 10. Tracings of photomicrographs showing fluorescent magnetic particle indications on shell casings



LEGEND
I_T = CURRENT AT WHICH INDICATIONS ARE FIRST DETECTED
I_G = CURRENT AT WHICH INDICATIONS ARE EASILY SEEN
I_{RX} = RESIDUAL CURRENT

FIGURE 11. Tracings of photomicrographs showing fluorescent magnetic particle indications on shell casings



LEGEND
I_T = CURRENT AT WHICH INDICATIONS ARE FIRST DETECTED
I_G = CURRENT AT WHICH INDICATIONS ARE EASILY SEEN
I_{RX} = RESIDUAL CURRENT

FIGURE 12. Ultraviolet photographs taken at the ends of square steel billets for comparison of magnetic particle indication brightness versus crack depth: (a) continuous direct current at 200 A; (b) continuous direct current at 800 A; and (c) residual direct current at 200 A

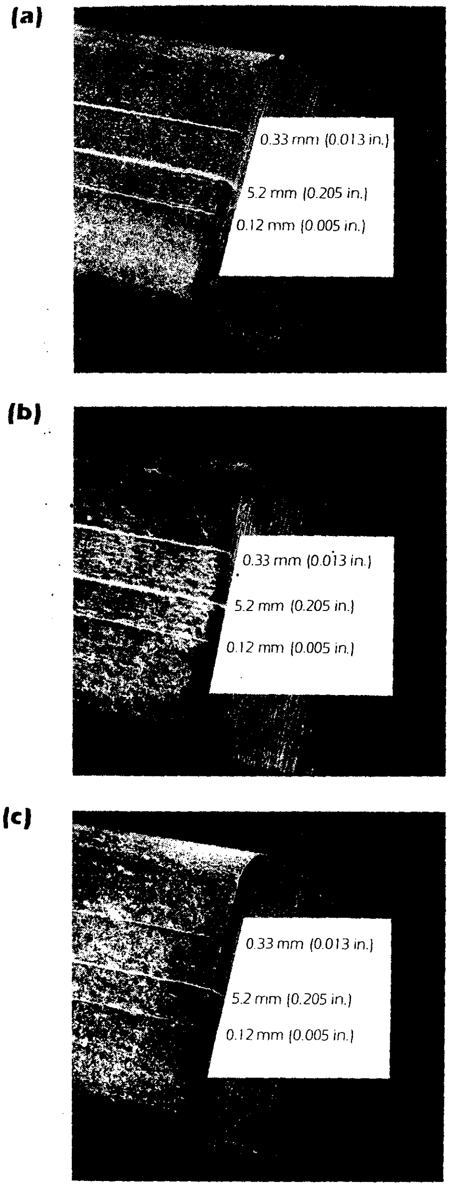


FIGURE 13. Ultraviolet photographs taken at the ends of square steel billets for comparison of magnetic particle indication brightness versus crack depth: (a) continuous direct current at 200 A; (b) continuous direct current at 800 A; and (c) residual direct current at 200 A

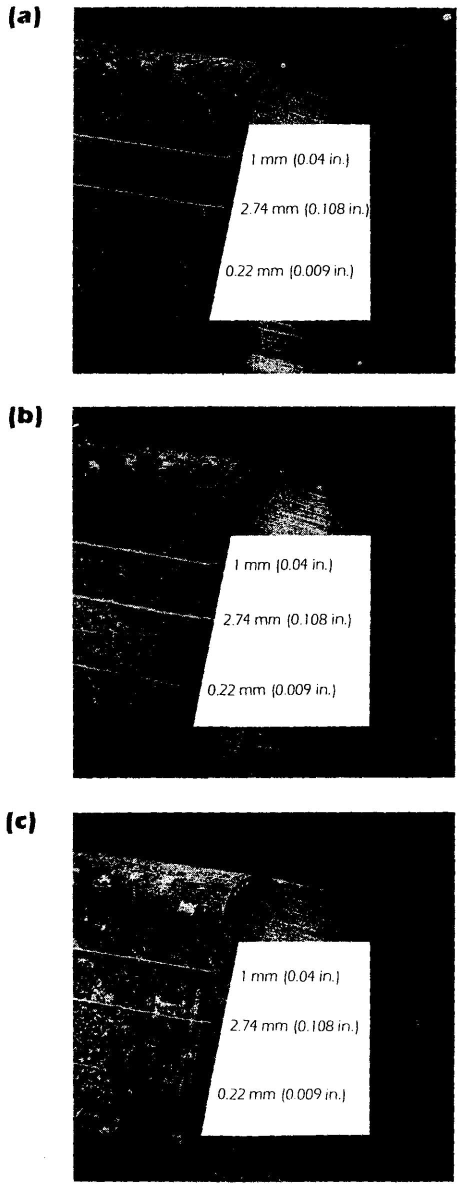


FIGURE 14. Ultraviolet photographs taken at the ends of square steel billets for comparison of magnetic particle indication brightness versus crack depth: (a) continuous direct current at 200 A; (b) continuous direct current at 800 A; and (c) residual direct current at 200 A

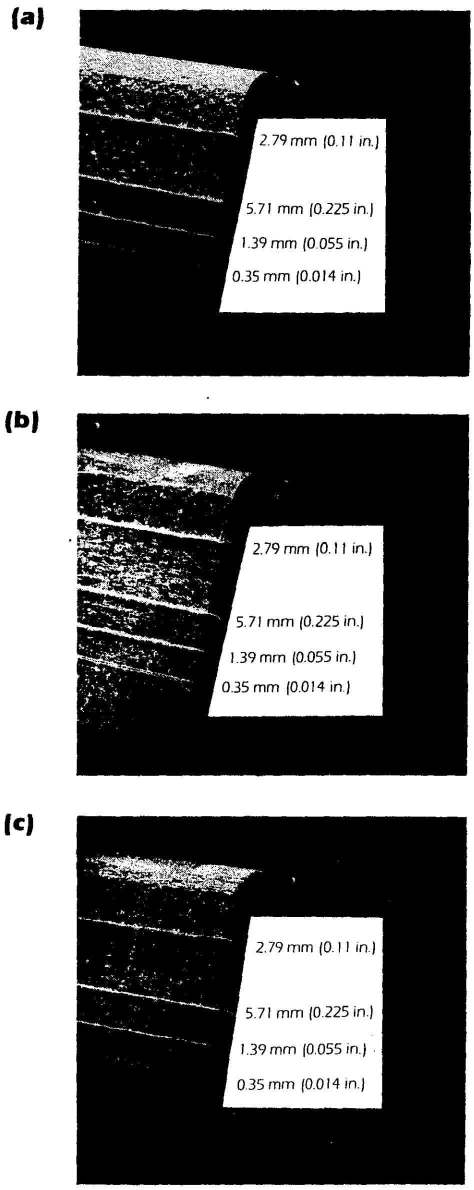


FIGURE 15. Ultraviolet photographs taken at the ends of square steel billets for comparison of magnetic particle indication brightness versus crack depth: (a) continuous direct current at 200 A; (b) continuous direct current at 800 A; and (c) residual direct current at 200 A

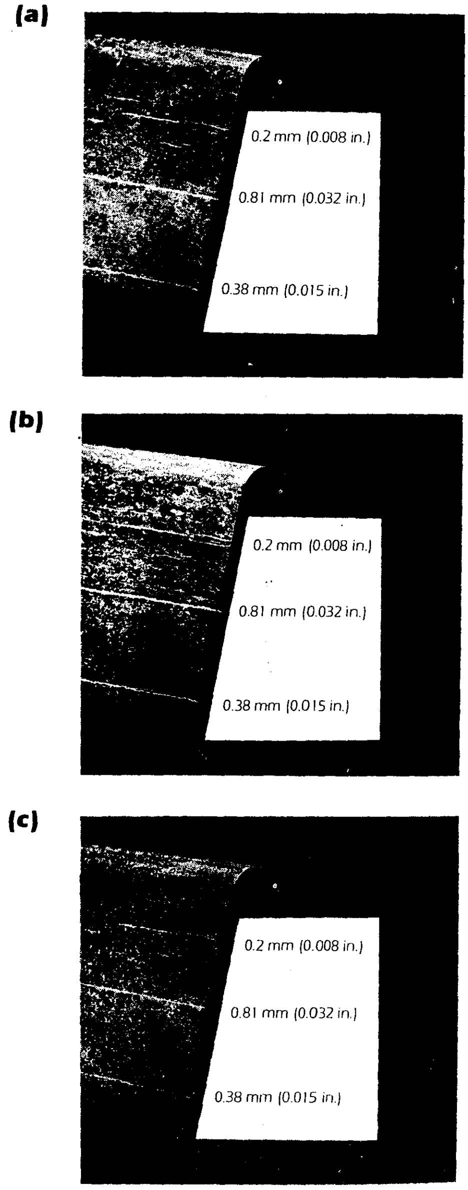
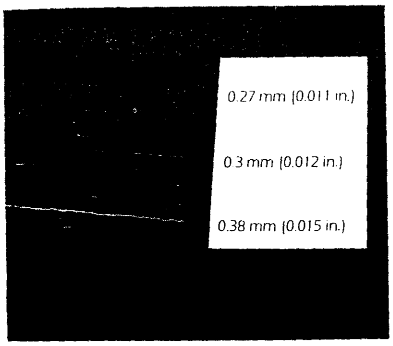
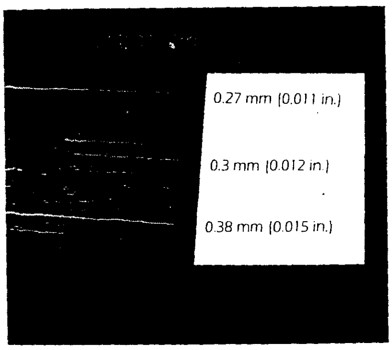


FIGURE 16. Ultraviolet photographs taken at the ends of square steel billets for comparison of magnetic particle indication brightness versus crack depth: (a) continuous direct current at 200 A; (b) continuous direct current at 800 A; and (c) residual direct current at 200 A

(a)



(b)



(c)

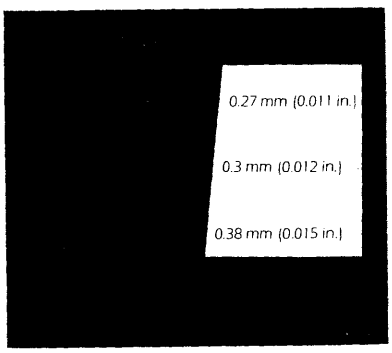
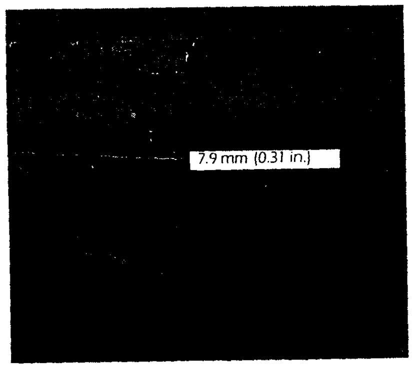
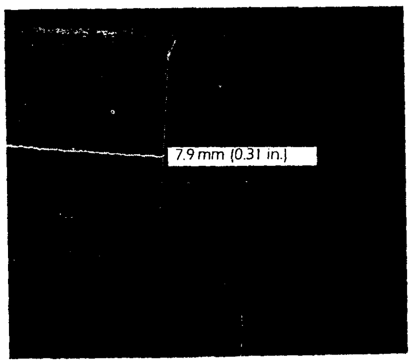


FIGURE 17. Ultraviolet photographs taken at the ends square steel billets for comparison of magnetic particle indication brightness versus crack depth: (a) continuous direct current at 200 A; (b) continuous direct current at 800 A; and (c) residual direct current at 200 A

(a)



(b)



(c)

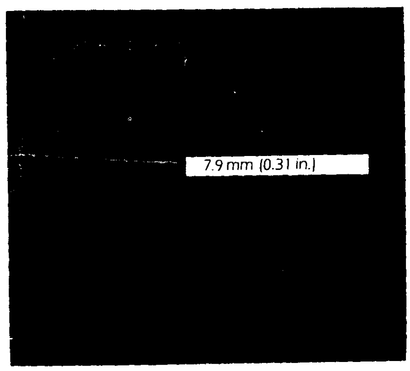


FIGURE 18. Ultraviolet photographs taken at the ends of square steel billets for comparison of magnetic particle indication brightness versus crack depth: (a) continuous direct current at 200 A; (b) continuous direct current at 800 A; and (c) residual direct current at 200 A

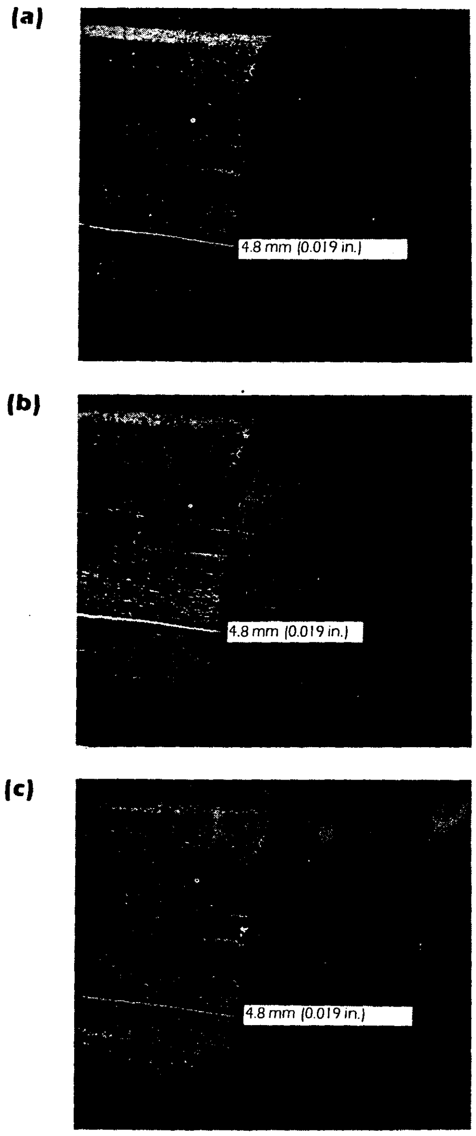


FIGURE 19. Standard sized fluorescent magnetic particles with bath concentrations at 1.25 $g{\cdot}L^{-1}$ used to test a 64 mm (2.5 in.) square steel billet at: (a) 300 A full-wave direct current; (b) 600 A full-wave direct current; and (c) 1,050 A full-wave direct current

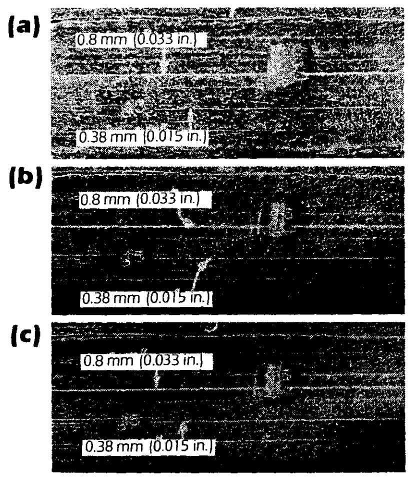
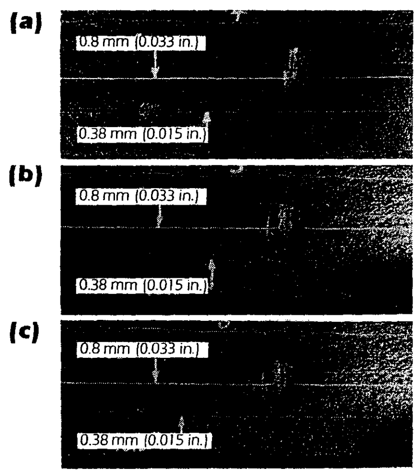


FIGURE 20. Coarse, large sized fluorescent magnetic particles with bath concentrations at 1.25 $g{\cdot}L^{-1}$ used to test a 64 mm (2.5 in.) square steel billet at: (a) 300 A full-wave direct current; (b) 600 A full-wave direct current; and (c) 1,050 A full-wave direct current



commercial powders with 3 to 5 μm (0.1 to 0.2 milli-in.) diameters. Figure 19 shows the test indications from standard sized particles. Figure 20 shows the results of tests with the coarse particles. The larger particles did exhibit depth discrimination, scarcely indicating fine cracks. Crack depth was verified by grinding.

The low sensitivity particles indicated discontinuities with depths of 0.37 to 0.8 mm (0.015 to 0.033 in.), but did not consistently detect shallower cracks. By this criterion, surface discontinuities less than 0.37 mm (0.015 in.) in depth may be called *fine cracks*. Those deeper than 0.8 mm (0.033 in.) may be considered *coarse cracks*.

Dry Powder Sensitivity

Little information exists on the surface discontinuity sensitivity limits for dry magnetic particles. However, a typically sensitive dry powder contains by weight about 35 percent coarse particles, in the 25 to 50 μm (0.001 to 0.002 in.) diameter range. It is likely that this portion of the dry powder conglomerate has roughly the same sensitivity as the similarly sized coarse wet particles cited above.

Effect of Discontinuity Depth on the Tangential Field Component

In a particle sensitivity study, measurements were recorded for the leakage fields emanating from a series of five milled slots. The slots were milled lengthwise down the center of one face of a 82 mm (3.25 in.) square steel billet.

Three of the slots were a constant 0.12 mm (0.07 in.) width, with depths of 0.38, 0.75 and 1.25 mm (0.015, 0.03 and 0.05 in.). The two other slots were a constant 0.75 mm (0.03 in.) depth with widths of 0.4 and 0.5 mm (0.016 and 0.021 in.). All measurements were made at a magnetizing current of 500 A using full-wave rectified direct current.

The tangential component of the leakage field H_t was measured with a meter operating in the differential mode. Errors in probe position were no greater than 0.5 mm (0.02 in.). Field strength readings were estimated to be accurate to 40 $A \cdot m^{-1}$ (0.5 Oe). The results of this study are summarized in Table 1.

Note that H_t increases with the slot depth. The tangential component also increases with slot width, though possibly not in direct proportion. These slots are not particularly fine cracks but they do indicate a downward trend of H_t for decreasing slot size. At distances beyond 0.5 mm (0.02 in.) from the slot centerline, there is no reading for the tangential component.

TABLE 1. Tangential magnetic field component at centerline of milled reference slots

Depth millimeters (inches)	Width millimeters (inches)	Lift-Off millimeters (inches)	Magnetic Field Strength (H_t) amperes per meter (oersteds)
0.38 (0.015)	0.18 (0.007)	0	190 (2.4)
0.38 (0.015)	0.18 (0.007)	0.5 (0.02)	111 (1.4)
0.38 (0.015)	0.18 (0.007)	1.0 (0.04)	80 (1.0)
0.38 (0.015)	0.18 (0.007)	1.5 (0.06)	48 (0.6)
0.75 (0.03)	0.18 (0.007)	0	549 (6.9)
0.75 (0.03)	0.18 (0.007)	0.5 (0.02)	334 (4.2)
0.75 (0.03)	0.18 (0.007)	1.0 (0.04)	223 (2.8)
0.75 (0.03)	0.4 (0.016)	0	573 (7.2)
0.75 (0.03)	0.4 (0.016)	0.5 (0.02)	374 (4.7)
0.75 (0.03)	0.4 (0.016)	1.0 (0.04)	255 (3.2)
0.75 (0.03)	0.5 (0.021)	0	653 (8.2)
0.75 (0.03)	0.5 (0.021)	0.5 (0.02)	390 (4.9)
0.75 (0.03)	0.5 (0.021)	1.0 (0.04)	255 (3.2)
1.40 (0.057)	0.18 (0.007)	0	1,274 (16.0)
1.40 (0.057)	0.18 (0.007)	0.5 (0.02)	892 (11.2)
1.40 (0.057)	0.18 (0.007)	1.0 (0.04)	573 (7.2)

Conclusion

The magnetic particle testing technique is extensively used in virtually all of the world's major industries — its successful application on any ferromagnetic material has ensured its position among the most valuable nondestructive testing methods. Because it is so widely used, so simple to apply and so familiar, the complexity of magnetic particle testing is often underestimated.

The technique is, in fact, founded on the complicated interactions of several electromagnetic fields and at least two separate materials for every test. The particles serve as magnetic field sensors and, as with any critical testing component, need to be fully understood for efficient and accurate use.

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SECTION 9

DETECTION AND EVALUATION OF MAGNETIC PARTICLE TEST INDICATIONS

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INTRODUCTION

This section of *Magnetic Particle Testing* covers the two procedures that occur *after* the formation of discontinuity indications: (1) detection of the test indications and (2) interpretation of their meaning.

With information on contrast ratios, Part 1 discusses the detectability of visible and fluorescent test indications. Part 2 covers detection devices, primarily the human eye. Part 3 outlines the categories used for evaluating test indications. Part 4 covers the process controls used to verify that the magnetic particle test has been properly performed, providing discontinuity indications for accurate detection and interpretation.

PART 1
CONTRAST AND CONTRAST RATIO

Magnetic particle discontinuity indications on the surface of a test object serve no purpose until they are detected and interpreted. Until the early 1950s, all indication detection was accomplished by the eye of the human inspector. In some cases, detected indications were then recorded by photography, but no other mechanical or electronic detection systems existed.

Today, electro-optical devices can be used to detect discontinuity indications and computers are then used to interpret the detected signals. Because these devices are costly and inflexible, their use is limited to high volume applications where speed and reproducibility are cost justified. Nearly all magnetic particle tests still base their procedures on the human eye as a detector. To obtain the highly sensitive results within the capability of the method, it is therefore necessary to understand the operation and limitations of the eye.

Since all test results do *not* automatically indicate a rejectable discontinuity, it is also necessary to understand test indication interpretation. Some magnetic particle indications are relevant, others are not relevant and still others are false indications of discontinuities.

Test indications are visually detectable because they contrast with the background they are formed on. All detection devices, including the eye, work by detecting this contrast. In electronics, contrast is called *signal-to-noise ratio*. Provided there is enough energy present to operate a detector, then the greater the contrast, the more reliable is its detection. Two types of contrast are important to magnetic particle tests: *brightness contrast* and *color contrast*.

Brightness Contrast

Brightness contrast is the amount of light reflected by one surface compared to that reflected by another adjacent surface. High brightness materials transmit or reflect most of the light striking them, a characteristic related to the surface texture of the material. Magnetic particle test indications can be high or low brightness, so long as the background is the opposite brightness.

In the visible test systems, indications are typically low brightness and the backgrounds are high brightness. The background may reflect 15 to 75 percent of incident light. Test indications may reflect 3 to 8 percent of incident light. Dividing an average background reflection of 45 percent by an average indication reflection of 5 percent produces a contrast ratio of 9:1.

If this indication is large enough to be resolved, a 9:1 contrast ratio is easily seen by the human eye and most other detectors. Contrast ratios as low as 1.25:1 can be detected, although the ratio should be at least 2:1 to achieve reasonable probability of detection.

In visible test systems, there is sometimes a correlation between brightness and color of the particles: low brightness particles are often dark colored and high brightness particles are light colored.

In fluorescent systems, the indication is bright, both because it emits large amounts of visible light and because ultraviolet light is not visible to the eye. This makes a nonfluorescent background appear low in brightness and the contrast ratio is accordingly high. In a fully darkened viewing area, the effective contrast ratio can be 200:1 or higher.

Color Contrast

The visible portion of the electromagnetic spectrum includes wavelengths between 400 and 700 nanometers (nm). If all wavelengths are present in equal amounts, the light is white. If no wavelengths are present, the eye sees black. Light from 450 to 480 nm is pure or saturated blue. Light from 550 to 600 nm is pure or saturated red. If both wavelengths are present, the color is perceived as purple.

Few visible light sources produce pure light of any color. Generally, the light is predominantly of one color but also contains some of all the other visible wavelengths. As the proportion of white light (all wavelengths) to colored light (a specific range of wavelengths) increases, the color becomes less saturated or more impure.

Color contrast can be defined as the difference between two colors of equal brightness and it therefore includes both color (wavelength) and saturation (percentage of a certain wavelength). At the same brightness, two impure colors have very little contrast, while one pure color and one impure color may contrast strongly.

Color contrast contributes a small percentage to total visibility or total detectability, with brightness contrast making up the primary contribution. A pure red indication is not highly visible against a pure blue background of equal purity and brightness. In fact, such a situation can decrease detectability because of eye strain (red and blue wavelengths focus at different points in the eye).

In nondestructive testing, the magnetic particle material usually has a relatively pure color, while the background is typically as nearly white or nearly black as possible. The main importance of color to detectability is its difference from the background.

PART 2

DETECTION DEVICES

There are three types of detection devices for magnetic particle testing: the human eye, imaging detectors (cameras) and nonimaging detectors (scanners).

The Human Eye as a Detector

For magnetic particle tests, there are two important characteristics of visible light. Illumination is measured in lux (lx) or footcandles (ftc). Luminance or photometric brightness is measured in candela per square meter ($cd \cdot m^{-2}$) or footlamberts (ftL). For the practical purposes of visible magnetic particle tests, these two characteristics may be considered equivalent.

The eye is the first and still the most common detector used in the magnetic particle testing industry. When considered simply as a component of the test system, the eye is widely available, highly sensitive, very flexible and interfaced to a sophisticated computing device that can produce instantaneous interpretations of test results.

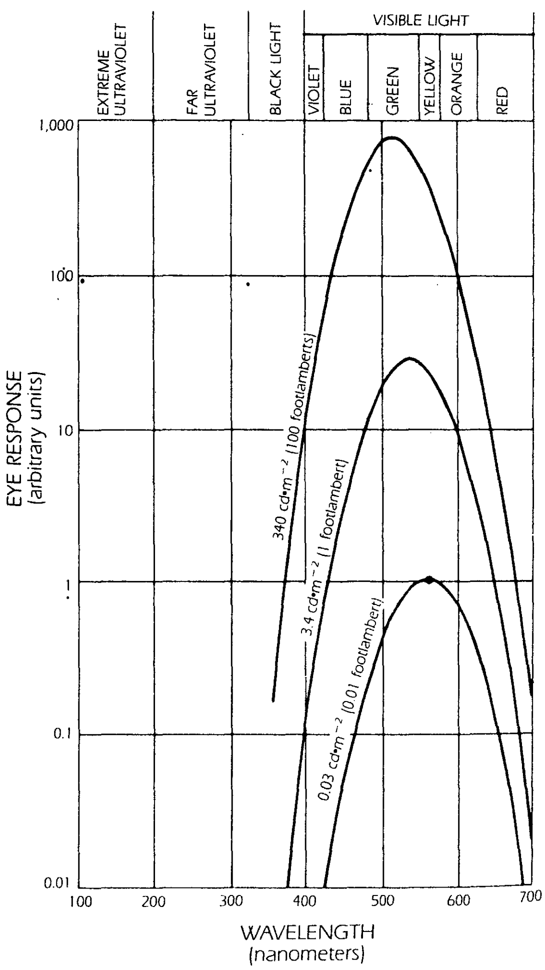
The eye is sensitive to both color and brightness. However, it is not equally sensitive to brightness at all intensity levels and it is not equally sensitive to all colors. The human eye responds to all wavelengths between 400 and 700 nm but it responds most strongly to the yellow green wavelengths in the center of the spectrum. The response curve is bell shaped, falling off to no response at about 400 and 700 nm (see Fig. 1).

The eye changes its absolute and color sensitivity at different ambient light levels. Figure 1 shows this effect for three typical light levels: 340, 3.4 and 0.03 $cd \cdot m^{-2}$ (100, 1.0 and 0.01 ftL).

Bright Light Conditions

The 340 $cd \cdot m^{-2}$ (100 ftL) level is the amount of light found in a brightly lighted indoor room or outdoors on a bright day in deep shade. It is a light level often used for visible magnetic particle tests. It is also the level where the eye is considered fully adapted to bright light and where increased brightness does not cause further sensitivity

FIGURE 1. Average human eye response to various wavelengths at different light levels



change. Under these conditions, the peak sensitivity is at 555 nm and the eye is only 10 percent as sensitive to blue (470 nm) and red (650 nm) light. This means that blue and red appear only one tenth as bright as yellow green or that ten times as much blue and red light is needed to appear as bright as yellow green.

Figure 1 also indicates why fluorescent particles are often green, yellow or orange. Since the peak response of the eye is to yellow, less light of this color is required for minimum visibility. Less exciting ultraviolet radiation (or less fluorescent dye surface area) is necessary for the indication to be visible. Green (520 nm) or orange (590 nm) produce 75 percent as much eye response as yellow. If a testing application requires one of these for color differentiation, the drop in brightness is often acceptable in exchange for the increased color contrast.

Low Light Conditions

At low light levels, the operating mode of the eye changes. The retina or detecting portion of the eye is coated with two types of receptors known as *rods* and *cones*. Cones are used in high brightness conditions and respond to color as well as brightness. Rods have much more sensitivity to light and are used in low brightness conditions, but they are do not detect color.

Cone vision (340 cd•m^{-2} or 100 ftL) is called *photoptc vision*. Rod vision (0.03 cd•m^{-2} or 0.01 ftL) is called *scotopic vision*. The region in between, where both rods and cones are partially operative, is called *mesopic vision*. Full rod vision is about 800 times as sensitive to brightness as full cone vision but it is totally insensitive to color. The eye cannot see color in low light.

Although the dark adapted eye cannot distinguish or differentiate colors, it can detect certain wavelengths and is more sensitive to some colors than others. As the 0.03 cd•m^{-2} or 0.01 ftL curve shows, the maximum response wavelength shifts to 512 nm (blue green) and most sensitivity to red light is lost. However, sensitivity to blue and ultraviolet increases. It is possible to see wavelengths as low as 350 nm in the absence of all other light.

Lighting in Typical Testing Conditions

In a magnetic particle testing booth, it is not possible to attain full darkness. Ultraviolet lamps emit some blue visible light and stray fluorescence or light leaks are almost unavoidable. The light level in most testing booths ranges between 1.7 and 14 cd•m^{-2} (0.5 and 4 ftL).

A good booth has about 3 cd•m^{-2} (1 ftL) of visible light on the test object surface. Figure 1 shows that peak eye response at this level is at 530 nm (green) and that light of 380 nm and above is visible. The figure also indicates that the eye is about 30 times as sensitive as in full bright conditions. Color is barely discernible and most test indications are perceived as blue white.

The eye does not adapt instantly to changes in light level. Moving from full bright adaptation to full dark adaptation can take as long as twenty minutes. Going from full bright adaptation to the 3.4 cd•m^{-2} (1 ftL) level can take two minutes. If critical tests are being performed, the inspector should wait at least two minutes after entering the booth before beginning the test. Less critical tests in lighter booths can often be done after 30 seconds of adaptation time.

With visible magnetic particles, testing should not be attempted with less than 100 lx (10 ftc). Between 300 and 1,000 lx (30 and 100 ftc) are best for most visible testing applications. Critical tests of small discontinuities may require 2,000 to 5,000 lx (200 to 500 ftc). Extended testing at levels over 2,000 lx (200 ftc) may produce eyestrain.

Fluorescent tests should be carried out in the darkest conditions possible. Specifications typically call for less than 20 lx (2 ftc) of visible light in the booth and in some cases the measurement must be made at the test site on the test object surface.

Rough magnetic particle tests can be made with up to 100 lx (10 ftc) but contrast levels and detectability are low. A light level of 500 lx (50 ftc) may be acceptable if (1) large amounts of ultraviolet are available; (2) bright fluorescent particles are being used; and (3) high sensitivity is not required. In no case should fluorescent tests be attempted when the visible light level is higher than 1,000 lx (100 ftc). Fluorescent tests should be done outdoors in daylight only if the test site can be partially darkened.

Personnel Vision Requirements

In order to properly perform magnetic particle tests, it is necessary for the inspector to possess a certain level of visual acuity. Vision tests are typically done with near vision and all inspectors should be tested to ensure proper visual acuity. The American Society for Nondestructive Testing's *Recommended Practice SNT-TC-1A* recommends minimum type size reading ability at specified distances. The document also recommends that the inspector demonstrate the ability to differentiate between colors used in the magnetic particle test method.

Good close vision is required to properly perform magnetic particle tests. Good color vision may be helpful in visible light tests, but it is not as critically important for fluorescent tests because everyone loses some color vision in the low light levels of a testing booth.

Scanning Detectors

Scanners are nonimaging detection systems. In their simplest form, they consist of a light source, a means of moving the test object, a detector and signal processing equipment. In use, the light source illuminates the test object surface and the detector measures the light reflected or emitted from it. The test object is moved past the detector in a uniform manner. If the measured amount of light changes significantly, a discontinuity indication is detected.

Usually, the light source is focused or collimated into a narrow beam that moves over the test surface. Since only a small area is illuminated, it is possible to exactly locate any indication that may be detected. It is also possible to focus the detector on a small area, but the mechanical alignment becomes much harder.

Scanners may be built for use with either the visible or fluorescent method. With the visible method, the light source can emit any wavelength the detector can see. Lasers are often used as light sources because they produce very narrow, intense beams. With visible systems, the reflection from the background is typically high and reflection from the indication is low. A sudden *decrease* in signal results from the presence of a particle an indication.

With the fluorescent systems, the detector is covered by a filter that absorbs the wavelength of the light source but transmits the wavelengths produced by fluorescence in the particles. It is not necessary that either light be in the visible range, as long as the detector is sensitive to the emitted light.

The photoelectric detectors used in scanners seldom have the same color or brightness sensitivity as the human eye. It is necessary that the detector be sensitive to some of the emitted or reflected wavelengths. Filters are used to remove unwanted light and undesirable background can often be eliminated.

Scanner systems are relatively simple, compared to television systems. Scanners are optically and electronically less complicated and are potentially less costly. They are often designed with very sensitive detectors. A major advantage is the scanners' great depth of field. They usually have no lenses in the detector system and do not need to be focused.

Television Detectors

Television is often used as a test indication detector in automatic magnetic particle systems. Television cameras produce images that may include the test object as well as the test indications. This property allows more sophisticated interpretation, a task usually accomplished through a dedicated computer.

Television camera detector systems use broad field illumination sources that cover a large portion of the test object. Television is essentially sensitive to visible light so standard visible or ultraviolet light sources may be used. These sources may in turn be specially filtered or filters may also be placed over the camera lens. As with scanners, television does not have the same color sensitivity as the human eye, so care must be taken to guarantee the compatibility of light sources, camera and test materials.

Because of the higher contrast ratios, most television camera detector systems use fluorescent testing techniques. In such tests, the light source and camera are filtered to transmit and receive the necessary wavelengths.

PART 3
INTERPRETATION OF DISCONTINUITY INDICATIONS

Interpretation is the culmination of the magnetic particle test procedure but certain interpretation decisions must be made early in the testing process. Two of the most critical involve the appropriateness of the magnetic particle method: (1) is it the correct testing technique for the anticipated discontinuities; and (2) is it appropriate for the type of test object and its characteristics. Once these decisions are made, magnetic particle indications can be formed. These are then detected and interpreted to determine if they represent discontinuities and, if so, to determine severity and the effect on test object service.

Testing for Subsurface Discontinuities

Magnetic particle tests can be used to locate specific types of subsurface discontinuities in ferromagnetic materials, depending on: (1) the type of magnetic particle equipment and the kind of magnetizing current; (2) the nature and characteristics of the discontinuity (its orientation and depth under the surface); and (3) the dimensions and shape of the test object. This ability to detect subsurface discontinuities should not be overemphasized. Other nondestructive test methods have better capabilities for subsurface discontinuity detection.

For the dry particle method, only the detection of major linear discontinuities (shrinkage cracks or incomplete penetration) is possible and then only if the discontinuity's depth below the object surface is less than 6 mm (0.25 in.). When the wet method is used, the maximum depth below the surface is 0.2 mm (0.008 in.). These depth limits are based on empirical data and vary with type and size of the discontinuity, the dimensions and shape of the test object, and with the magnetic properties of the test object material.

Effect of Test Object Shape

The shape of a test object can cause magnetic flux lines to bypass some areas of the object surface. No flux leakage occurs in those areas and no particle indications are formed, despite the presence of possible discontinuities.

Sensors can and should be used to indicate the presence and direction of magnetic flux leakage, particularly with test objects having changes in cross section or unusual configurations. Sensors can also provide a relative value for the number of flux lines needed to obtain specified test reliability.

Choosing the Magnetic Particle Technique

The fact that an object is ferromagnetic does not mean that magnetic particle testing is the best surface inspection method. The exceptions depend mainly on the size, shape and finish of the test object. For example, under some specifications, over-magnetization of finish machined objects can create high background, making the magnetic particle test ineffective. In forgings, flow lines and particle buildup at corners or grooves produce nonrelevant indications that mask possible discontinuities and reduce the effectiveness of the magnetic particle method.

In addition, if magnetizing current is applied to the test object by direct contact, there is a high probability of arcing and the resultant damage to fine surfaces. In aerospace components, for example, arcing inevitably causes minute cracks into which copper from contact pads can penetrate. Copper penetration is cause for rejection in virtually all aerospace components.

Determining the Nature of an Indication

The first step in interpretation is to decide the character of a magnetic particle indication: is it relevant, nonrelevant or a false indication?

If it is relevant (representative of an actual material discontinuity), the indication is then evaluated, based on the data given in the acceptance criteria for that type of test object. If the test object is within the acceptance criteria, it can be accepted, even though there is a discontinuity present. However, such acceptable discontinuities do not affect the quality, future use or service life of the test object. If the acceptance criteria are not met, the test object is rejected and a full report goes for further evaluation to a materials review board. Members of that board typically include quality assurance managers, engineers and in most cases a customer representative.

The review board decides future action for the test object: scrap, use as is, rework or repair. After rework or repair the object is retested. Scrapped components are destroyed to prevent accidental use.

Nonrelevant indications are caused by magnetic leakage fields resulting from the shape of the test object: sharp corners, splines, thread roots or magnetic writing, for instance. Nonrelevant indications are not cause for rejection but they can mask actual discontinuities critical to the object's service life. Proper testing techniques reduce the occurrence of nonrelevant indications.

False indications are *not* caused by magnetic flux fields but by material obstructions and improper processing: dirt, fingerprints, gravity, scale or drain lines are examples. Proper housekeeping can prevent false indications. They are not cause for rejection but often require retesting before acceptance.

Nonrelevant Test Indications

Nonrelevant indications are caused by magnetic leakage fields but they do not represent accidental discontinuities. Flux leakage may be caused by sharp corners, holes drilled close to the surface, threads, changes in the structure of the material, shrink fits or dissimilar metals.

The main problems with nonrelevant indications are: (1) they can mask actual discontinuities or (2) actual discontinuities can be interpreted as nonrelevant.

Metallurgical Properties

Alloy and hardness directly influence the magnetic properties of metals such as steel. Variations in hardness from cold working create localized variations in magnetic properties. Depending on the alloy, such variation can cause magnetic particles to form sharp, distinct patterns.

Heat affected zones near welds can give similar indications. Some of the tool steels with high retentivity and high coercive force are well known to produce sharp, well defined nonrelevant patterns. If such a condition occurs, magnetic particle test results should be verified by a test method such as a liquid penetrant or ultrasonic testing.

When a coupon is taken from such an area and metallurgically examined, a minor change in the grain structure is often visible. This change does not typically influence the strength of the test object but it can cause nonrelevant particle indications. In some cases, high internal and external stresses cause variations in magnetic properties and this can also cause nonrelevant indications.

Contact Indications and Stamping Marks

Objects that touch each other during magnetization may set up local polarities at their surfaces and can cause leakage fields. This happens most often when a number of objects on a central conductor are magnetized at the same time. Contact indications are sometimes called *magnetic writing*. Confusing particle patterns can be caused and, as with all nonrelevant indications, these patterns can mask relevant discontinuity indications.

Numbers or letters stamped onto a component are sometimes ground out before magnetic particle testing. The changes to the structure caused by stamping are sometimes sufficient to cause changes in the metal's magnetic properties. Magnetic particles occasionally can indicate these magnetic changes and outline or indicate the previously stamped characters. This is considered a nonrelevant indication but it may also be used to benefit by verifying the test object's identification.

Structural Indications

At abrupt changes in section of a magnetized object, there is an increase in internal flux density which in turn creates local external polarity and can produce magnetic particle indications. Sharp corners, keyways, internal splines or holes close and parallel to the object surface are the kinds of component design features that produce nonrelevant indications. Such indications are characterized by their width and lack of clarity. Their relationship to the object's design is usually apparent.

Again, the primary concern over structural indications is their ability to mask relevant discontinuity indications. When structural indications occur, the magnetic lines of force exit the material normal to the surface, an unfavorable orientation for the detection of discontinuities. Quick break magnetization can partially eliminate structural discontinuities.

A shrink fit may also be considered a structural indication. The interface between two objects gives a distinct magnetic particle indication that is apparently not related to the pressure used for the shrink fit operation.

Particle indications seen in the roots of threads are often caused by gravity rather than by a magnetic leakage field. Very careful examination of the threaded area is required to distinguish relevant from nonrelevant indications. In this case, relevant indications turn in a slightly transverse direction with a hook at the end of a crack.

Dissimilar Metals and Welded Joints

When two metals with different magnetic properties are fused together, the interface produces a very sharp indication during magnetic particle testing. An automotive valve is typical of such a component: the valve body is fusion welded to a stem fabricated from a different metal. Under test, the fusion line shows up very clearly, making it impossible to inspect the weld for lack of bond. A supplementary ultrasonic test is required for complete inspection of an object such as a valve body, containing dissimilar metals.

In addition to the indications that can occur in the heat affected zone of welds, nonrelevant particle indications can also appear in the weld reinforcement. Indications caused by abrupt changes in the crack's cross section can also occur at that location. A very thorough visual test with magnification or grinding of the weld cap is often necessary to supplement magnetic particle procedures.

False Test Indications

Dirt and Scale

If a test object is improperly cleaned and foreign material remains on the surface, magnetic particles may become trapped. Improper cleaning contributes to contamination of a wet particle suspension and it causes drainage lines, forming patterns that resemble discontinuity indications. These indications do not reappear after the object is cleaned and retested, thereby establishing their false character.

Scale on the test object surface often produces false test indications but the source of scale indications is simply determined and accounted for. If scale is forced into the surface of the test object during forging operations, a significant discontinuity is formed and, depending on the stage of manufacture, such a discontinuity can be very relevant to future service life.

Scratches and Burrs

Surface scratches and burrs trap magnetic particles and form patterns that may have the characteristics of a discontinuity indication. For example, these false indications can mimic a crack with an orientation transverse to the magnetic particle flow. Often, such indications can be distinguished from relevant indications by the lack of particle buildup. Verification at 10× magnification in visible light may sometimes prove necessary.

Scratches and burrs are classified as false indications, unless the scratches occur in notch sensitive and highly stressed materials, on polished surfaces or if burrs are found in threads and splines.

A good visual examination before the magnetic particle test generally locates these conditions. Since the indications are linear, they must be reported.

PART 4
PROCESS CONTROL OF MAGNETIC PARTICLE TESTS

Technique Sheets

One of the basic ways for controlling the outcome of a magnetic particle test is to properly use *technique sheets* (see Figs. 2 and 3). These forms comprise a valuable record of the test procedure, including all pertinent magnetizing data: (1) the direction of the magnetic field; (2) how the field is generated (coil, central conductor, yoke); and (3) the magnetizing current values. Certain positional data can also be found on technique sheets (the test object's location within the coil, the yoke contact points or the placement of shim standards, for example).

Under military standards, such records are mandatory and must be signed and approved by a certified Level III magnetic particle inspector. In most cases, technique sheets are retained for future use. Filing systems are often based on part number and technique information can be transferred to computerized data banks.

As a source of empirical data, technique sheets perform a vital system analysis function. Their information can help determine the cause of problems that occur throughout magnetic particle test procedures. If properly completed and retained, technique sheets can also provide valuable information on successful inspection setups used for similar test objects.

Control of Wet Method Particle Concentration

Cost of Suspension Control

The majority of wet magnetic particle installations depend on the settling test for control of particle concentrations in suspension. The settling test has been in use since the 1940s and it is now possible to use this simple technique to detect other attributes in a particle bath.

Note that the particles in suspension are an insignificant part of a testing operation's total cost. Frequently changing the magnetic particle suspension does not materially inflate the cost of the testing operation. Even if the bath is changed each week, it is still a very small fraction of the total cost, when compared to equipment depreciation and labor.

Uses of the Settling Test

Low signal-to-noise ratio is the principal reason for failure to detect fluorescent discontinuity indications — it is nearly impossible to detect fluorescent indications in high fluorescent backgrounds, for either automated tests or the human eye. The principal causes of low signal-to-noise ratio are: (1) excessive current density, (2) excessive magnetic particles in suspension, (3) excessive fluorescent background in the vehicle or (4) excessive particle contamination. The settling test can detect the last three causes.

In a typical setting test done with fresh particles, a concentration of 0.15 to 0.25 mL particles should be found in a 100 mL centrifuge tube. A lower concentration, on the order of 0.1 mL is usually satisfactory. Anything above 0.3 mL is excessive and should be avoided, even though many specifications allow up to 0.5 mL.

The settling test may also be used to determine two of the primary kinds of bath contamination: (1) the loose fluorescent material from the particles themselves; and (2) extraneous oils (such as cutting oils) that remain on the test object after cleaning. The degree of such contamination can be monitored with a centrifuge tube that retains an initial sample of the vehicle for reference purposes. This is then compared to a concentration test after at least one hour settling.

Another source of contamination is sand from prior sand blasting operations, residue from grinding or shot dirt. These contamination sources are the result of inadequate precleaning and can be determined by a settling test comparison.

FIGURE 2. Technique sheet for wet method magnetic particle testing

TECHNIQUE SHEET
Magnetic Particle Testing
Wet Method

IDENTIFICATION

Part number: ______________________ Name: ______________________

Drawing number: ______________________ Alloy: ______________________

MAGNETIZATION	Shots	Amperage	Diameter	Turns
CIRCULAR				
Contact	______	______	______	
Internal conductor	______	______		
LONGITUDINAL				
Coil	______	______		______

APPLICABLE SPECIFICATIONS: ______________________

ACCEPTANCE CRITERIA: ______________________

DRAWING (indicate all dimensions critical to the test)

SYMBOLS

Contact points	+ + + +
Internal conductor	= = = =
Field direction	>— — >
Coil	[ ]

The inspector shall ensure compliance with all requirements of the quality assurance procedures for magnetic particle testing

INSPECTOR: ______________________ **FOR APPROVAL:** ______________________

Signature: ______________________ Signature: ______________________

SNT-TC-1A Level II MT SNT-TC-1A Level III MT

Date: ______________________ Date: ______________________

FIGURE 3. Technique sheet for dry method magnetic particle tests of welds and castings

TECHNIQUE SHEET
Magnetic Particle Testing
Dry Method
Welds and Castings

IDENTIFICATION
Job Site ____________________
Construction ____________________
Stations ____________________

SPECIAL INSTRUCTIONS: ____________________

MAGNETIZATION	Model	Amperage	Spacing	Turns
Prods	______	______	______	
Coil	______	______		______
Yoke	______	______		

□ AC □ DC □ Half-wave □ Multidirectional

MATERIALS
□ Dry powder — color ____________________
□ Black oxide suspension — spray can ____________________
□ Fluorescent suspension — spray can ____________________

APPLICABLE SPECIFICATIONS: ____________________
ACCEPTANCE CRITERIA: ____________________

WELDS
□ Single V groove □ Single J groove
□ Double V groove □ Double J groove
□ Corner, edge flange □ Single U groove
□ Square groove □ Double U groove
□ Single bevel groove □ Flare bevel groove
□ Double bevel groove □ Flare V groove
□ Full penetration □ Partial penetration

JOINTS
□ Butt joint □ Lap joint
□ Corner joint □ Edge joint
□ Tee joint

CASTINGS
Surface condition ____________________
Contact points*: ____________________
Reference standard*: ____________________
*indicate type and position on drawing

DRAWING (indicate position of reference standard and contact points)

SYMBOLS
Contact points + + + +
Internal conductor = = = =
Field direction >— — ->
Coil ( )

The inspector shall ensure compliance with all requirements of the quality assurance procedures for magnetic particle testing

INSPECTOR: ____________________ **FOR APPROVAL:** ____________________
Signature ____________________ Signature ____________________
SNT-TC-1A Level II MT SNT-TC-1A Level III MT
Date ____________________ Date ____________________

Particle Control at the Indication Site

Control of particles in suspension at the point of the discontinuity is of vital importance. Fluorescent magnetic particles are used in the overwhelming number of applications (about 10 percent of the magnetic particle suspensions are nonfluorescent), so that fluorescent particle control is more often needed than control of visible particles. Ideally, a discontinuity should have a high contrast ratio under ultraviolet light. The indication should be sharp with virtually no background either from the particles themselves or from the vehicle.

The relative number of particles in suspension per unit volume should be controlled within close limits. This is important because the basis for evaluation of an apparent discontinuity is typically the visual detection of particle accumulation. Mass fluorescence in the background of an indication can greatly diminish detectability by significantly lowering the contrast between background and indication.

Application of a Wet Method Concentration Test

After a maximum of eight hours, the concentration of a magnetic particle suspension should be measured (concentration must be at the proper level before testing can continue). If there are insufficient particles in the suspension no indications can form. Too many particles give a high background that can mask small indications.

The concentration is usually measured with a technique called a *settling test* that is performed as follows.

1. Run the circulating pump for a minimum of thirty minutes.
2. Flow enough suspension through an applicator nozzle to ensure uniformity of the suspension.
3. Fill a thoroughly cleaned, 100 mL centrifuge tube to the 100 mL line with the suspension sample.
4. Allow the tube to stand *away from magnetic fields and vibration* for sixty minutes when oil is the vehicle, thirty minutes when water is the vehicle.
5. Verify the volume of settled particles on the tube's graduated scale. The precipitate volume should be 0.15 to 0.3 mL per 100 mL for fluorescent particles and 1.0 to 2.4 mL per 100 mL for black oxide particles.
6. Adjust the suspension concentration by adding particles or vehicle and repeat the settling test.
7. Repeat step 6 until the correct concentration is obtained.
8. Record each concentration reading in the log book.

Brilliance and Contamination Tests

Each week that magnetic particle equipment is used, the brilliance of fluorescent suspension should be checked by comparing it to a fresh, unused sample. Whenever suspension is mixed, a minimum of 200 mL should be retained in a dark glass bottle for reference purposes.

Used suspension is compared with the unused sample under ultraviolet light. If the brilliance is noticeably different, the test system's tank should be drained, cleaned and refilled with fresh suspension. The results of these procedures are recorded in the log book.

Contamination of the suspension by foreign matter should also be checked at least once a week. If the suspension is contaminated, the tank should be drained, cleaned and refilled with fresh suspension. The following procedure is used to verify contamination.

1. Run the circulating pump for thirty minutes.
2. Fill a graduated 100 mL centrifuge tube with suspension and allow it to stand for sixty minutes.
3. Examine the liquid above the precipitate with an ultraviolet light. If the oil or water fluoresces green or yellow green, the tank should be drained, cleaned and refilled with fresh suspension.
4. Examine the precipitate. If two distinct layers are visible and the top layer of contaminate exceeds 50 percent of the bottom layer's magnetic particles, then the tank is drained, cleaned and refilled with fresh suspension.
5. Record the results in the log book.

Specifications may vary in the allowable ratio between particles and contaminant in the precipitate. Results of these tests are always logged in writing.

Since both of these tests take at least sixty minutes, it is normal to begin magnetic particle testing before the brilliance and contamination procedures are completed. If the suspension does not meet specification, all objects tested during the thirty minutes must be retested with new suspension.

Viscosity Test

Viscosity is a measure of a fluid's resistance to flow. It is an important property of the oil used as a vehicle for magnetic particle testing. Viscosity is measured in square millimeters per second (these units are sometimes called *centistokes*, after George Stokes, the British physicist who developed the theory of motion through viscous fluids).

For many years, petroleum distillates or kerosene was used as a vehicle for magnetic particle tests. The flash point of these vehicles was typically around 60 °C (140 °F). The Occupational Safety and Health Act of 1972 raised the requirement for open tank usage of such vehicles to 93 °C (200 °F) for a tank with surface exposure of 0.93 m^2 (10 ft^2) or more. The viscosity of kerosene was about 40 percent lower than those vehicles meeting OSHA minimum requirements. For equivalence, the settling time for particles had to be increased from 30 to 60 minutes.

In general, the measurement of viscosity is done in specialized commercial laboratories. Common viscosity values for the vehicle used in magnetic particle suspensions are: (1) must not exceed 3 $mm^2 \cdot s^{-1}$ at 38 °C (100 °F); and (2) must not exceed 5 $mm^2 \cdot s^{-1}$ at the temperature of use.

Contaminants from the surface of test objects tend to build up in the particle suspension and this increases the viscosity. Precleaning test objects to remove oil and grease helps resolve but does not eliminate this problem. Depending on the specifications in force, viscosity measurements are usually performed monthly. A 90 mL (3 oz) specimen from the tank is sufficient for accurate appraisal.

If the viscosity exceeds specified values, the suspension is discarded and the tank is drained, cleaned and refilled with fresh suspension. The results of viscosity tests are reported in the log book (third party reports are also kept on file).

Suspensions, solvents and similar materials must be discarded in compliance with federal, state and local laws.

Steel Ring Test

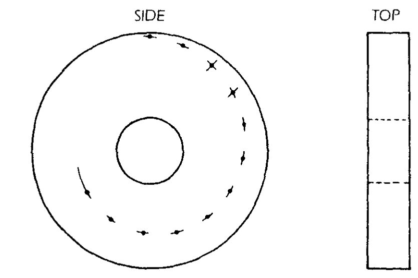
In the early 1940s, a steel ring was first used to demonstrate that magnetic particle techniques would detect subsurface discontinuities (see Fig. 4). It was difficult then to delineate linear discontinuities that were very tight and slightly angular, including those cracks found with radiography in nominally full penetration welds (ultrasonics was not yet being used).

The first application of the ring was by Robert Roehrs at McDonnell Aircraft for a measure of system effectiveness. At that time, there was no other reference standard for magnetic particle testing.

The ring was made of AISI-01 oil hardening, cold work tool steel and was generally machined from annealed bar stock. The hardness of the ring was specified between 90 and 95 on the Rockwell-B scale.

In 1985, the ring standard's accuracy was seriously refuted.[1] With all parameters remaining equivalent, the number of holes detected in a series of sample tests ranged from 3 to 11. In addition, it was determined that the hardness of the ring did not vary from the annealed or unannealed condition. The only property that was measurable and indicative was initial permeability. It was shown that a ring standard that could be repeatedly depended on to show 5 or 6 indications should show 9 indications when annealed or reannealed with the following procedure: (1) heat to 790 °C (1,450 °F); (2) furnace cool in 10 °C (50 °F) increments to 480 °C (900 °F); and (3) air cool.

FIGURE 4. Schematic diagram of tool steel ring used as a reference standard



With the following test parameters, 8 or 9 indications are detected: (1) a fresh suspension of suitable particles having a concentration of 0.2 mL or 1.6 mL visible particles; (2) current at 1,400 A induced with central conductor; (3) light levels at a minimum 3,000 $\mu W \cdot cm^{-2}$ fluorescent light. Increasing the amperage does not increase detectability. Former indications of holes were set as listed in Table X.

If used with threshold values, the ring standard becomes a measure of the efficacy of particles themselves. It is thus used as an acceptance test in many specifications. It cannot indicate overall system effectiveness.

Verifying Illumination

Ultraviolet Light Requirements

Ultraviolet light measurements are made daily. The common minimum intensity of ultraviolet light for magnetic particle testing is 1,000 $\mu W \cdot cm^{-2}$ at a distance of 380 mm (15 in.) from the face of the source (filter or bulb).

Intensity may be measured with a commercial ultraviolet light meter. Such instruments often measure infrared radiation with the ultraviolet, but filter out visible light. With this kind of meter, measurements of ultraviolet intensity are done in three steps: (1) determine the combined intensity of ultraviolet light and infrared; (2) by means of a filter, measure only the infrared radiation; and (3) mathematically determine the ultraviolet intensity by taking the difference between the two measurements.

The following procedure is used. First, switch the meter to the least sensitive scale and place the sensor 380 mm (15 in.) from the center of the light source. Move the sensor until a maximum reading is obtained and record the measured intensity value. Switch the meter to the high sensitivity scale and position the infrared filter without moving the sensor. Deduct the first reading from the second to determine the ultraviolet light intensity.

If the minimum intensity is not met, the following actions must be taken.

1. Clean the lamp filter, bulb or reflector. *It is mandatory to clean the ultraviolet source on a daily basis.*
2. Replace the ultraviolet light bulb if cleaning does not correct the situation. *Dispose of used ultraviolet bulbs as hazardous waste.*

As a final test for the ultraviolet light source, inspect the filter for cracks or visible light leaks and replace cracked or broken filters. *Do not touch ultraviolet bulbs with the bare hands: the acidity of the fingers can cause the glass to fail.*

Visible Light Requirements

The magnetic particle testing area must be darkened. Usually, a hood is mounted over the test equipment to keep out ambient light. Ambient light may not exceed 20 lx (2 ftc) for fluorescent magnetic particle tests.

Ambient light may be measured with a commercial light meter. Such meters should be filtered to exclude ultraviolet radiation. When visible particle suspension is used, the intensity of the visible light should be 1,000 lx (100 ftc) at the testing surface. This may also be measured with a commercial light meter and a reduction filter. Visible light intensity measurements are performed every week and the results reported in the log book.

Light meters must be calibrated every six months. This procedure is recorded in the log book and a calibration sticker is placed on the meter, covering the calibration control.

Calibration for Current Output

Under military specifications, the current output of all magnetic particle equipment must be calibrated. This is usually performed by an independent service organization with instruments calibrated to National Institute of Standards and Technology (NIST) standards. The NIST standards should be documented in the calibration report.

Since the magnetizing field strength depends on the current output of the system and on the accuracy of the ampere meter, it is essential that the inspector obtain the exact current value that the instrument indicates. For that reason the equipment must be calibrated at three month intervals. This procedure is entered into the log book and a calibration sticker is placed on the calibration adjustment of the meter.

Yoke Calibration

Calibration requirements for magnetic yokes are relatively simple: the yoke must be able to lift a specific dead weight. For alternating current yokes, a 4.5 kg (10 lb) weight is lifted with the pole pieces spaced at the testing distance.

For direct current yokes: (1) a 13.5 kg (30 lb) weight is lifted with the pole pieces 50 to 100 mm (2 to 4 in.) apart; and (2) an 18 kg (40 lb) weight is lifted with the pole pieces 100 to 150 mm (4 to 6 in.) apart.

The plates for these tests must be certified for the correct weight and are then considered and identified as standards. Two months is the interval between weight lifting tests for yokes.

Verifying the Magnetic Field

Pie Gages

The magnetic field indicator or pie gage was developed in Germany as an aid to determine the direction of magnetic fields for the detection of discontinuities. It is not a quantitative device and cannot determine the adequacy of the magnetic field.

The indicator is a disk made of ferrous material with very low retentivity. It is cut into four or eight slices, similar to the slices of a pie. The slices are bonded together with nonmagnetic material and, depending on the design, are covered with a thin copper shim or 0.25 mm (0.01 in.) copper chrome plating.

The disk is mounted in a holder so that the inspector can place it on the test object during the application of magnetizing current. Depending on the direction of the magnetic field, the position of the indicator and the adequacy of the magnetic field, one or more of the bond lines between the sections have a sufficient leakage field to attract magnetic particles. This in turn shows the direction and to some extent the adequacy of the field. It is recommended that indicators be demagnetized before each use.

The magnetic particle indicator has limitations and should be used accordingly. When placed on a nonmagnetic material through which a current is passed, the pie gage shows indications that could be misleading to an inexperienced inspector. With circular magnetization, magnetic flux lines exit the test object to pass through the device (only a strong magnetizing current causes indications). This is good, since it gives a margin of safety, but with longitudinal magnetization, the case is different. The magnetic field generated by the coil passes by preference through the object but it also passes through the magnetic particle indicator. For longitudinal magnetization, such indications do not represent an accurate estimate for the adequacy of the magnetizing current.

In the absence of a suitable reference standard, an actual part representative of the test object has been used. This so-called *flaw standard* has the following limitations.

1. The discontinuity is usually preferentially in a single direction.
2. The discontinuity is rarely at threshold but is typically gross.
3. The material is usually retentive and can be used in either a residual or continuous application.
4. Most discontinuities used in this way are so gross that excessive background becomes a factor.
5. It is frequently possible to use more than one direction of magnetization to produce a satisfactory indication.

Consider this illustration of component used as a flaw standard: a small forging with 25 mm (1 in.) sections throughout. A continuous magnetization cycle of 60 A in either of two directions (circular magnetization) produces a satisfactory test indication. The usual requirements of present process standards or specifications would be 300 to 1,000 A instead of 60. How then could this specimen be indicative of a malfunction in the system?

Shim Gages

Thin metal shims with artificial subsurface discontinuities have been designed and widely used in Japan. Such low retentivity shims have circles or lines etched close to one surface. When placed face down on the magnetized object, the circles or lines are made visible by magnetic particles, indicating the direction of the field and some quantitative value for the adequacy of the magnetization.

By accurately controlling the depth of etching, different sensitivities can be obtained. When the circular etching is used, the direction of the field can be determined by noting the sections of the circle that are indicated.

Similar devices in the United States have artificial discontinuities such as circles, lines and crosses precision etched to an exact depth below the testing surface. Since these shims are flexible, they can be placed in critical areas such as fillets, near protrusions and other complex areas.

Measuring the Hall Effect

A meter using Hall effect probes is particularly useful in setting up testing procedures. Readings can be related directly to artificial discontinuity standards. It must be recognized that field strength (H) not flux density (B) is being measured. Where the field is essentially contained within the test object, such as in circular magnetization of a regularly shaped object, the readings obtained have long been disputed as inconsequential.

However, it has been shown that a suitable instrument can be both quantitative and repetitive, when properly used. The limitations beyond that point are that a meter shows direction and approximate magnitude but does not show a gradient such as can be provided with a reference standard. The Hall effect instrument can be used to establish bases for quantifying other reference standards.

The Hall effect gaussmeter is relatively useless for guaranteeing that magnetic fields are existent and balanced in all directions in a multidirectional magnetizing operation. The only practical and inexpensive means of ensuring that this balance exists is with the shim standard.

Magnetoinductive Instruments

It is possible to electronically obtain a relative value for the adequacy of a magnetic field. This method is accurate and simple to apply, but it is costly and may only be used with continuous direct current magnetization.

The instrument has two sensor coils to which alternating current is applied at a frequency of 100 kHz. The sensor coils are mounted at right angles to each other and connected in series opposing. When the probe with the two sensors is placed on the material, eddy currents are generated in the test object, inducing a secondary current in the two sensor coils.

Since the coils are on the material at the same time and since the induced current is the same for both coils, the output for this *series opposing* circuit is zero. During the application of magnetizing current, magnetic lines of flux increase the current induced in the sensor coil, at right angles to the direction of the magnetic field, thereby unbalancing the circuit.

The unbalance is registered on a digital or analog meter built into the instrument. The higher the applied current, the more the circuit is unbalanced and the greater the indication on the meter. Because magnetic properties vary with alloy and hardness, the instrument only indicates the level of magnetization. The meter is generally divided into ranges corresponding to insufficient, questionable and sufficient magnetization.

Quick Break Test

The effect of a quick break was first observed in the 1940s. The only major design change since then involves the introduction of a break in the secondary magnetizing circuit.

Utilizing only the primary break results in some self-demagnetization and failure to observe circumferential discontinuities.

An early result of this self-demagnetization was repetitive failure of an automotive plant in 1946. At that time, all automotive manufacturers could sell every vehicle that was manufactured and a failed conveyor line at any time directly reduced income. In the case in question, conveyor pins were shearing at frequent intervals. These had been tested in the manufacturer's plant with magnetic particle techniques and older equipment. By testing returned conveyor pins with updated, quick break systems, it was discovered that grinding cracks underneath a flash chrome was the cause of the problem. These were not detected with the equipment having only the primary breaker.

It was thought at the time that no failures of this sort could occur in properly designed magnetic particle systems. However, with the advent of electronic controls and triggering, it was discovered that a malfunction in the firing circuit could result in a loss of the quick break. It is essential that a periodic measurement with a quick break tester be required.

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SECTION 10

PROCESS AUTOMATION OF MAGNETIC PARTICLE TESTING

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PART 1

TEST OBJECT HANDLING FOR MAGNETIC PARTICLE TESTS

Manual Handling with Automated Testing

The simplest automation of the magnetic particle test procedure occurs when test objects are *manually* positioned in the testing system and the magnetizing process then proceeds without operator intervention.

Consistency and reproducibility are achieved with this level of automation by: (1) providing accurate levels of magnetizing current or field; (2) producing accurate timing of magnetizing field or current flow; and (3) applying consistent volumes of magnetic bath in the same manner and the same direction for each test object. This consistency of processing considerably improves both the quality and efficiency of the testing. To include this kind of automation in a standard magnetic particle testing system is relatively simple and inexpensive, and can be achieved with electronic current leveling devices and electronic timers.

Fully Automated Handling

Fully automated magnetic particle testing systems can be cost justified only when large volumes of similarly sized and similarly shaped test objects are inspected. To move from simple to complete automation requires the installation of mechanical handling systems that feed test objects into and out of the testing machine. Automatic scanning after magnetization, classification and distribution after the testing process are very complex and costly procedures.

The cost of handling in a manufacturing operation forms a large part of the typical production cost: in the United States, the cost of handling varies from 15 to 85 percent.[1] More than any other single factor, materials handling offers a greater opportunity for cutting production costs and increasing productivity.

When considering a fully automated testing system, the reduction of labor costs is not necessarily the most important factor. Other considerations are detailed below.

1. *Safety*: statistics indicate that a very large portion of industrial accidents happen during the movement of materials. Many of these accidents can be prevented by the use of mechanical handling systems.
2. *Space utilization*: it is often possible to increase output from the same amount of space by a mechanical handling system. Such automation ensures the flow of objects from process to process and eliminates the need for temporary storage spaces before and after each manufacturing process.
3. *Quality control*: accurate control of handling system speed ensures that each test object receives the same treatment. Counters can be installed to monitor system speeds and this information may be stored on-site or delivered to a remote controlling center.

Designing Fully Automated Magnetic Particle Testing Systems

Fully automated magnetic particle testing systems must be specifically made for a particular product (or a limited range of products) and are usually designed for a specific manufacturing site. This is done so that the testing system is compatible with existing manufacturing facilities. For example, the system for moving objects through manufacturing operations may be an overhead monorail conveyor or a powered roller track. The testing system must be designed as an integral part of the site's existing handling facility. It is equally important for the testing system to accommodate particular production rates, depending on whether the plant uses a batch system or continuous flow line production.

Another important design consideration is the size of the test object. If large, they may be attached to or loaded onto the conveyor singly and are presented in that way to the testing system. Small objects are often loaded into baskets or fixtures and conveyed through the plant in these containers. On arrival at the magnetic particle testing system (which may have its own system for presenting test objects into magnetizing positions), the fixtures must be unloaded singly and this requires a simple form of robot arm. Very small test objects (fasteners, for instance) may be singly presented into the testing system by means of a vibrating bowl feeder.

The most important considerations for successful design of a fully automated magnetic particle testing system are:

1. reducing test object movement to a minimum;
2. mechanizing handling in a manner compatible with the rest of the manufacturing process; and
3. controlling test object movement and the testing process with a single program installed in a programmable logic controller.

It is also important for the programmable logic controller to have sufficient capacity for future expansion and the capability for linking with other on-site computers. This permits communication of test data to other systems and enables the magnetic particle testing system to be controlled by the plant's manufacturing mainframe.

PART 2
MONITORING AUTOMATED TESTING EQUIPMENT

Magnetic particle testing systems are designed to meet specific testing requirements for detectability of discontinuity location, direction and size. Also included in design considerations for automated systems are such parameters as test object symmetry, size, weight, configuration, magnetic properties and throughput requirements.

All of these factors influence the final design criteria for the load station, conveyor system, test object positioning fixtures, magnetizing method, magnetizing apparatus, bath application, test object manipulation, visual or automatic scanning testing stations, demagnetization apparatus, offloading and tested part segregation.

Automated Magnetizing Techniques

Establishing the proper magnetizing technique for a specific test object is a fundamental requirement. Selection of the type and level of magnetizing current may be dictated by the controlling process specifications. Alternating current, half-wave direct current and full-wave direct current, single-phase and three-phase, and single-shot all have their place in automated test systems.

In most manufacturing applications of magnetic particle testing, test objects are sequentially processed with circular and longitudinal magnetization using coil and contact techniques. This has long been standard practice for manually operated equipment and semiautomated systems as well as for automated tests.

This is a reliable but slow magnetization method when considering the requirements of automated testing line throughput. For example, test objects magnetized in both the circular and longitudinal methods require: (1) magnetizing in a circular direction, (2) testing and interpretation, (3) demagnetizing, (4) magnetizing in a longitudinal direction and (5) a second testing and interpretation.

Multidirectional Magnetization

When automatically processing large numbers of similar test objects (automotive forgings or castings, for example), there is a critical need for performing magnetic particle tests at the highest reliable speed. This is done by using a system that indicates discontinuities in all directions with one magnetizing operation.

Several systems for this kind of testing are commercially available, including alternating current swinging field systems. In a typical alternating current swinging field system, current is applied to the headstock and tailstock simultaneously, with a second alternating current 120 degrees out of phase with the first, applied to the coil. These currents are two phases of a three-phase electrical supply.

A multidirectional, contact and noncontact magnetization technique provides a significant increase in the speed with which magnetization can be established in a given test object. The implementation of electronic firing circuitry enables phase switching rise times on the order of 4 ms in a 0.5 s shot. Controlling the current level in each firing circuit is another valuable characteristic. With proper multidirectional magnetization, time savings up to 70 percent have been reported in the literature.

A test system design incorporating multidirectional magnetization techniques must account for the following considerations: (1) the strength and direction of the magnetizing fields; (2) the sequencing of the magnetizing shots; (3) the duration of the overall shot; and (4) the application of the magnetic bath and, in turn, the availability of magnetic particles on the test object and their freedom to move and form indications.

It takes considerable time and experimentation to ensure that all these parameters are correct. If the magnetic field strengths in different directions are not correctly adjusted relative to each other, test indications may not be distinct and significant discontinuities can be missed. Field strength adjustments may not necessarily be accurate if a pie gage or other artificial discontinuity devices are used. A multidirectional magnetic particle system should be set up using a gaussmeter and a reference standard (a typical test object containing known discontinuities).

Computer Components of Automated Testing Systems

An automated magnetic particle testing system may be managed by a programmable logic controller consisting of the following components: (1) central processing unit (CPU), (2) programmable memory, (3) input cards, (4) output cards and (5) power supplies for the internal electronics and the outputs to be controlled.

The CPU processes instructions stored in the computer's memory. Among other functions, the central processing unit uses the system software for the following purposes: (1) to interrogate the status of the inputs; (2) to set or reset the outputs; (3) to perform counting and timing functions; and (4) to continuously monitor the system for malfunction.

This kind of controller provides much flexibility for many of the magnetic particle testing or manufacturing procedures. Magnetizing current levels, shot duration and magnetic bath application parameters can be easily changed and monitored. Test object identity and programming requirements can be fed in from an external computer and data on inspected parts may be filed as the test objects progress through the system.

Monitoring Automated Test Systems for Malfunction

With a totally automated magnetic particle testing system, it is critical to verify correct performance of the system. For instance, if the magnetizing current has not reached its full value because of bad contact, or if the magnetic bath concentration is low or high, test objects move through the system but discontinuities are not reliably indicated. Subsequent interpretation, manual or automatic, will consider this lack of indications to mean freedom from discontinuities.

It is essential therefore to monitor all the parameters of the magnetizing process *and* to monitor with equivalent care the transducers and other devices introduced into the testing system to detect malfunction.

Test System Malfunction Alarms

Malfunction systems are normally connected to alarms and two levels of alarm should be provided. A soft alarm sounds an audible tone, warning of a malfunction requiring operator intervention. The operator interrogates the programmable controller to determine the nature of the malfunction. In a typical soft alarm malfunction, the concentration of the magnetic bath may have moved beyond preset limits or the magnetizing current may have dropped within ten percent of a preset value. Based on established procedure, the operator then decides: (1) to accept the test objects in question; (2) to reprocess the test objects; or (3) to stop the system.

A hard alarm sounds a different audible tone and immediately shuts down the system. A hard alarm is sounded if a test object is jammed in the clamping mechanism, if the bath pump fails, or if any part of the hardware or software fails.

Current Leveling Monitor

It is necessary to monitor a test system's current leveling device to ensure that it is operating correctly. The magnetizing power unit in an automated testing system includes current leveling capability to ensure that, when the current output control has been set, the precise amount of current is supplied at each shot.

Without such a device, the variations in output from one shot to another can be enough to set off a soft alarm. In addition, when the output current is kept consistent, a drop in current may be attributed to conditions external to the power unit (bad contact with the test object or loose cable connections, for example).

Magnetizing Current Monitors

Current passing through the test object or the coil must be monitored. Current levels at 90 to 100 percent of a preselected value should be acceptable in most testing situations. Current values at 80 to 90 percent should cause a soft alarm. Below 80 percent, a hard alarm should sound and the system is shut down. These threshold points may be adjusted to suit particular applications.

Monitoring current levels for multidirectional magnetization is more complex because the current is only flowing in any one direction for very short periods of time. It is probably more efficient to integrate the current levels in each direction and average them over the duration of the current shot. Monitoring of the duration of the shot itself is also necessary but this can be a straightforward function of the programmable controller.

Magnetic Particle Bath Monitoring

The concentration of magnetic particles in the bath is a very important system characteristic yet few devices have been designed for this monitoring function. One commercially available model continuously monitors the opacity of a magnetic bath. As the bath flows through the monitor, a light source and photocell translate the concentration of suspended particles into a signal which in turn activates alarms when the concentration is outside preset tolerances. The system also sounds an alarm if the bath becomes contaminated. These are all soft alarms and in each case the operator takes a sample of the bath and performs a settling test.

The programmable controller should also monitor the magnetic bath application time, the magnetic bath pump pressure and the flow rate. This ensures consistency in the application of the bath and helps provide consistent, reproducible test results.

All of these monitoring steps — current level of the system, current level in the test object, bath concentration and dwell time — are important steps for verifying the operation of an automated testing system and, in turn, for ensuring the reliability of the system's test results.

PART 3

AUTOMATING THE MAGNETIC PARTICLE TESTING PROCEDURE

In today's industrial environment, interest in automation for production operations, from basic fabrication to final assembly, is commonplace. The interest has generated extensive research efforts and as a result of these efforts there are many claims, promises and hopes for lower costs and better quality through automation.

The claims for lower cost are based largely on the reduction of direct labor due to anticipated yield improvements and better quality. Better quality comes about because of the uniformity of products being produced. This uniformity is based on the consistency that is possible when fully automatic machines are used in manufacturing and because of the removal of human judgment from the testing function. While there is ample proof that lower cost and better quality do occur when automation is used in production, some questions persist about the benefits of automating the testing function.

One important comparison is the cost of equipment needed to perform automatic tests versus the anticipated savings from reduced labor, reduced scrap and reduced testing expenses. Perhaps the greatest savings occur by automating only a portion of the testing process. A feasibility study should compare savings with expenses *for each stage of the testing process*. Such a break-down can help determine which individual activities could best be automated.

Considered below are some of the factors that apply to the full automation of the magnetic particle nondestructive test method. Details are given for the history of automatic scanning; various factors that enter into automation of magnetic particle systems; specific methods of process verification; methods of scanning; image processing; and some examples of systems using various forms of automation.

Automation can be used in magnetic particle testing by certain combinations of the following processes:

1. automatic handling and positioning of the test object;
2. automatic test object magnetization;
3. automatic timing of the bath application relative to the timing of the magnetization cycle;
4. automatic detection and location of magnetic particle indications on the test object; and
5. automatic interpretation (deciding if indications are caused by discontinuities).

If all of these processes are used, then the process is said to exhibit *full automation*. The term *automatic system* often is used to describe a system with some combination of item 1, 2 and 3, but which still requires human intervention (such a system is not fully automatic). The term *automatic scanning* refers to the processes in items 4 and 5 above.

History of Automatic Scanning

Visible Light Scanning

One of the first recorded attempts at the full automation of magnetic particle testing was in 1956.[2] The product being tested was a welded steel tube commonly called electric resistance welded (ERW) pipe. Prior to this time, a number of partially automated magnetic particle testing systems were operational, and these performed as described below.

The pipe was formed from a continuous sheet of steel bent into a tubular shape. The seam was continuously welded. The product passed through a large yoke electromagnet with the weld facing upward and dry black magnetic particles were dusted onto the weld zone (Fig. 1). As the dusted area moved into the magnetic region between the poles of the yoke, the magnetic particle material was attracted to leakage fields developed around weld zone discontinuities. A weak air flow removed excess particles, leaving only the magnetic particles over leakage fields in the weld zone. At this point in the test, an operator visually inspected the test object and determined if discontinuities were present.

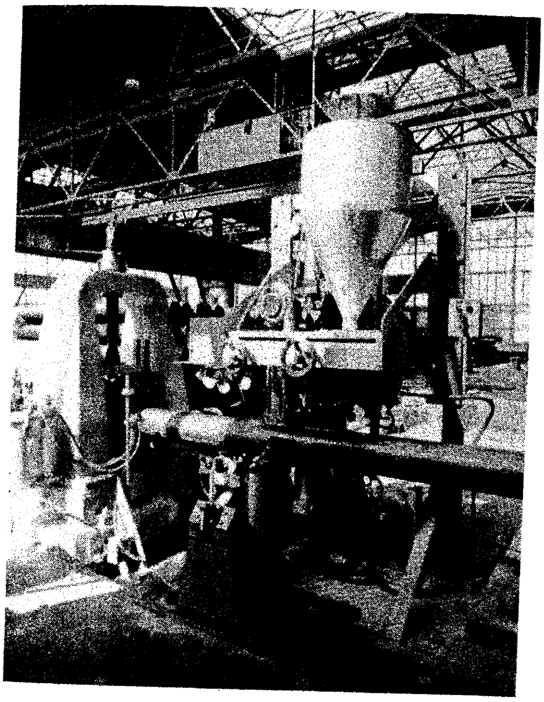
To automate the system, an optical scanner was developed to detect the presence of black magnetic powder. Detection of an indication by the phototube triggered an automatic marking device to identify the discontinuous area (Fig. 2).

For reliable discontinuity detection by the phototube, it proved necessary to paint the top surface of the pipe white to increase the contrast of the black powder indications. This additional operation made the cost of automation prohibitive.

Ultraviolet Light Scanner

Before 1960, an improvement was made to the visible light scanner, eliminating the need for painting the top surface of the pipe.[2] A wet fluorescent method was used for the test instead of the dry method. The surface was

FIGURE 1. Magnetic particle system for tests of electric resistance weld pipe



illuminated with ultraviolet light and the resulting fluorescent indications were scanned by a phototube. As in the earlier application, an automatic marking device painted the area of interest when triggered by a discontinuity.

A new problem occurred with this system: it was necessary to use direct current in the ultraviolet lights. This kept the power line frequency noise to a minimum and allowed reliable detection of indications. The use of direct current shortened the life of the high intensity ultraviolet lamps to a point that again made the system impractical and expensive.

Dye and Paint System

In 1959, another approach was developed to aid the detection of magnetic particle indications on steel billets and other products that required surface conditioning to generate a high quality product.[2]

In this approach, a special chemical was added to the pigment covering the magnetic particles. Normally the pigment is fluorescent and is the medium that absorbs ultraviolet energy and emits visible light. In the new form, the pigment also contained a bright visible red dye that was released by applying a suitable solvent. The solvent was in turn mixed with a white paint. When the test object surface containing retained magnetic particle material was sprayed with this mixture, the solvent released the dye from the pigment and the dye bled into the white paint, highlighting discontinuities (Fig. 3).

The intention of this approach was to aid the inspectors and also to have a permanent indication on the billet surface, allowing further testing at a convenient location and time.

FIGURE 2. Automatic scanner for magnetic particle tests of electric resistance weld pipe

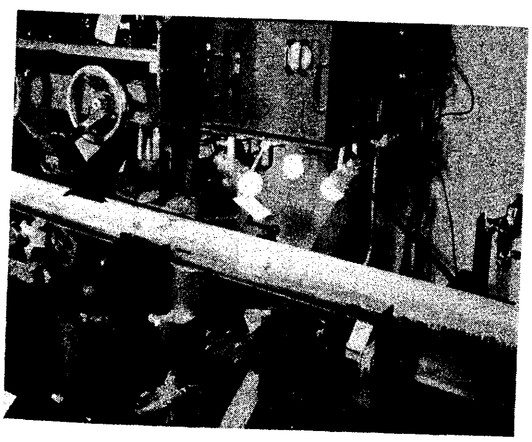


FIGURE 3. Results of paint/dye magnetic particle testing

The cost of the operation was high, mainly because of the large amount of paint used. A few years later, this system was improved by coupling to a television scanner that located and detected fluorescent indications.[3] Detection of the fluorescence activated a system to spray the white paint and solvent mixture *only* over suspect areas. If the discontinuity was present, the red dye bled into the white paint verifying its presence and location so that the grinder operators could remove it. This operation could be economically justified.

Laser Scanning

The first laser scanning system for magnetic particle testing[4] was installed in 1972 (see Figs. 4 and 5). This application was for testing torsion bars in automobiles. The discontinuities were seam inclusions and the system separated those bars that contained no seams from those that contained seams. Beam shaping was used for pattern recognition (described later).

Production Automation of the Magnetic Particle Method

Improved quality and lower cost have occurred by automating the production sequence and it seems likely that the same results would occur by automating testing and quality control functions.

Machines can usually be calibrated more accurately than human senses and simple go/no-go interpretations can be uniformly made by automated systems. Machines are usually more consistent, obtaining reliable and reproducible test results. In addition to these advantages, automated testing systems can offer testing speeds for certain applications that no human inspector can match.

Beyond this point of comparison, care is needed! As automation is applied and human involvement is removed from any operation, the requirements for consistency *at all levels* of processing become significant.

This can be illustrated by examining in more detail those routine procedures (cleaning, magnetization, particle bathing, observation and interpretation of the indications) used in the manual magnetic particle testing method.[5] In the manual method an inspector performs these functions each time a test object is handled. For study, the functions may be divided into three general groups.

Processing Stage

In a typical manual system, the testing process usually proceeds after the test object is rinsed or cleaned in some way, so that the surface is clear and free of debris, oil or foreign matter.

FIGURE 4. Laser scanning in a magnetic particle testing system

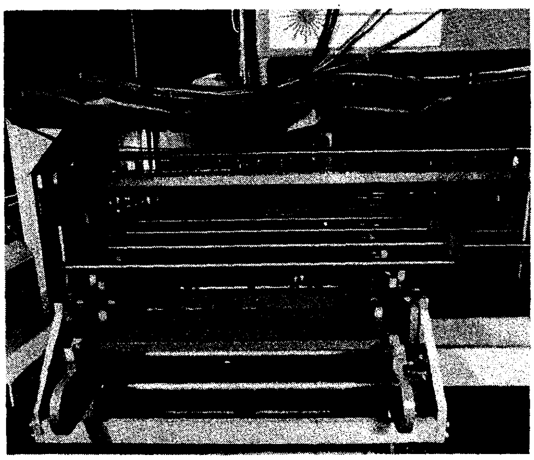
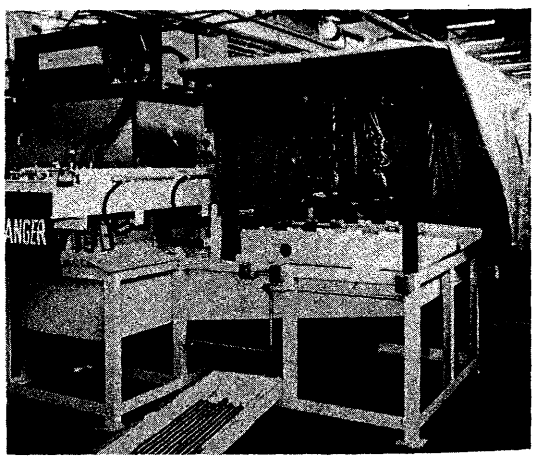


FIGURE 5. Laser scanning test system loading bars



The test object is then magnetized. The operator can use a number of methods to determine if the magnetizing level is correct. These include: the monitoring of the magnetization current level with an ammeter;[5] the use of Hall effect devices to monitor surface field levels;[6] flux shunting devices;[7] use of a reference standard containing known discontinuities; visual observation of the background level; or the use of specialized eddy current equipment to measure internal magnetization levels.[8]

Magnetic particle bath is applied after the operator determines that the magnetizing level is appropriate. While applying the bath, the operator carefully observes the procedure, verifying that all of the surfaces of interest are covered with magnetic material. The required skill level for this process varies with the shape of the test object, its magnetic characteristics and the material it is made of.

If the wet testing method is used, the application effort is less critical than with the dry method, providing that the bath is applied during the correct magnetization time window. The time window is determined by the magnetic retentivity of the test object. Higher retentivity materials require less magnetization time. They also have a less critical bath start time because of fewer problems with bath washing of developed discontinuity indications.

Observation Stage

The operator rotates, twists or otherwise manipulates the test object through three dimensions in order to observe all the critical surface areas. Magnetic particle indications formed during the processing stages are located at this stage.

Interpretation Stage

The operator studies the indications and determines if discontinuities are present. This is done with the benefit of training and experience, making judgments based on the shape and brightness of the retained magnetic particle indications.

Each of these three fundamental stages may be automated. Details of those procedures are covered in the text that follows.

PART 4
MONITORING THE PROCESSING STAGE OF MAGNETIC PARTICLE TESTS

Full automation comprises more than automatic scanning. The term *automatic scanning* usually refers only to the automation of those actions performed in the observation and interpretation stages discussed earlier. When the magnetic particle testing process is fully automated, all three stages are performed automatically; there is no operator or inspector. Processing, observation and interpretation are performed and monitored by automatic apparatus.

Partial automation is achieved when certain operations are automated. For example, it is common to use automatic cleaning and bath application methods tied to an automatic magnetization cycle (processing stage) and still use inspectors to observe and interpret the magnetic particle indications.[9]

It is most important to remember that a good inspector *verifies* that each stage of the testing procedure is properly performed. If full automation is used, *automatic verification* is required and maintenance of such components becomes a critical procedure. At production speeds, inoperative verification equipment can invalidate large numbers of magnetic particle tests.

There is a variety of ways to verify proper performance of processing stages. The text below is a summary of these important procedures.[10]

The first decision in this and all verification processes is determining the need for verification. For example, if cleaning is critical to the accurate testing of a particular product, then the cleaning procedure must be verified.

The next decision is determining the characteristics of interest (in this case, those that affect magnetic particle test results) and how they can be quantified.

Verification of Cleaning Operations

If a spray cleaning system is used, a flowmeter may be used to monitor the cleaning bath as it moves through the pipes leading to the spray head. The flowmeter should be placed as close to the spray head as possible and the signal generated by the flowmeter should be compared to the control signal used to activate the flow valve. Some timing differences occur but this is a good way to verify that valves are working and that the flow is at proper magnitude. The cleaning solution should be also monitored to determine if the bath is viable or contaminated and at proper concentration.

The cleaning of magnetic particle test specimens is usually not a very critical matter. Unlike penetrant testing, magnetic particle tests are generally very forgiving of nonmagnetic dirt. For example, it is possible to have nonferritic foreign material contained in surface cracks and still do an excellent job of detecting these discontinuities with magnetic particle techniques. Good judgment and cost considerations determine the degree of cleaning process monitoring that is justified.

Verification of Magnetization

A number of approaches can be used for this procedure. Current flowing during the correct magnetization window is a good indication that the test object is being magnetized properly.[5] Further assurance occurs when the monitored current value falls within predetermined threshold levels. Monitoring of the current time and value is straightforward. Flux shunting devices are commercially available for determining proper magnetization levels[7] and such devices can be used in a manner similar to reference standards containing minimum rejectable discontinuities.

It is also possible to measure the normal and tangential components of the surface magnetic flux density with a Hall effect device.[5] This measurement is then used as a relative indicator of internal flux density for test objects with simple shapes. It is best to measure this value during the magnetization time window and use it to activate predetermined threshold limits.

Another approach is to use an eddy current device to measure the change in relative permeability of the material being magnetized (Fig. 6). The optimum value of permeability is that value at the knee of the initial magnetization curve.[8] It is possible to monitor this point with eddy current techniques. As with the other methods, predetermined values should be used, proper threshold levels should be set and subsequent measurements should be taken during the magnetization time window.

FIGURE 6. Eddy current response versus magnetization curves for two sample test bars 13 × 25 × 150 mm (0.5 × 1 × 6 in.) with electrodischarge machined notches at 0.6 μm (0.015 in.) depth

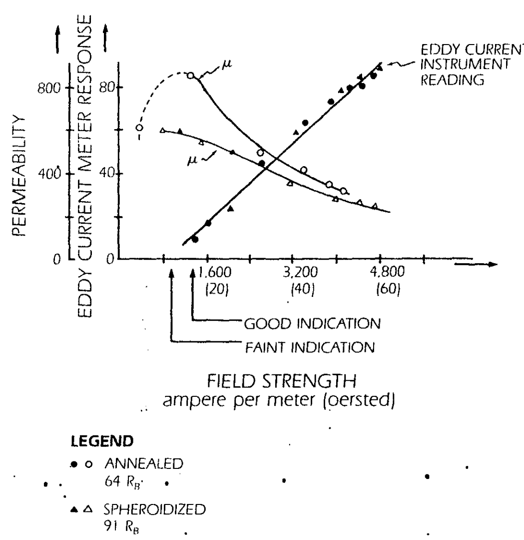
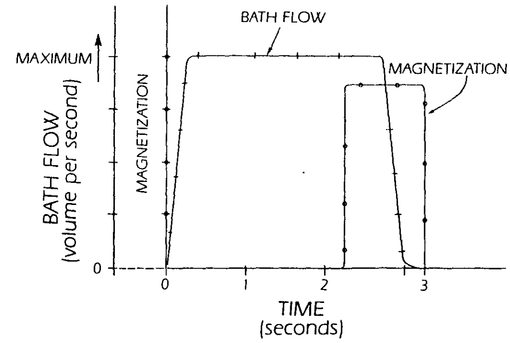


FIGURE 7. Typical magnetic particle bath flow versus magnetization time



Monitoring the Magnetic Particle Bath

Bath Application for Low Retentivity Parts

Bath application is a very crucial parameter for test objects with low magnetic retentivity. If such a test object has a smooth surface and bath continues to flow over developed indications after the end of the magnetization cycle, it is probable that the developed magnetic particle indications will be washed off.

In this situation, it is crucial that the timing of the magnetization cycle be carefully considered when determining the bath procedure.[5] Flow conditions should be checked and cycles should be carefully adjusted to ensure that all bath flow has stopped in critical areas of the test object before the magnetization cycle ends. Once these parameters have been determined, then both the magnetization and bath cycles must be monitored in time and compared with the predetermined values. Appropriate threshold levels are set to detect deviations.

Flow can be monitored with a flowmeter (Fig. 7) located as closely as possible to the spray heads. Photocells and acoustic path devices have also been used to measure flow rates.

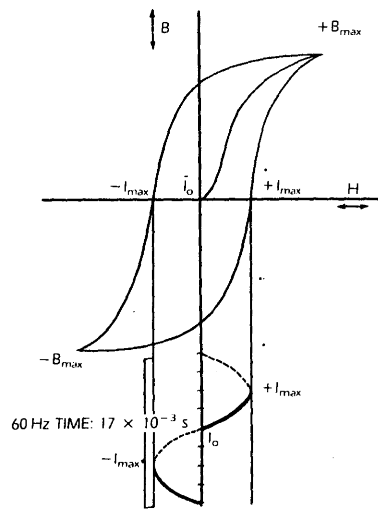
Bath Application for High Retentivity Test Objects

If the test object has high magnetic retentivity or if the surface is rough, bath application is not as critical. If proper magnetization is used in a high retentivity test object, the magnetic leakage field around the discontinuity continues to exist and attract particles after the magnetizing current is shut off. In this case, discontinuity indications develop even if bath flow continues after the end of the magnetization cycle.

Multidirectional applied fields are not retained in test objects[5] (only one of the directions remains after the current is stopped). The usual compromise is to end magnetization with a field orientation in the direction covering the most critical discontinuity orientation.

If alternating current magnetization is used, the current should be cut off at the same point in the cycle for every test object to ensure consistency of magnetization. For maximum retained field, the current should be cut off at zero or when it is decreasing from a maximum value (see Fig. 8). With modern electronic components, it is most convenient to cut the current at zero. If coils or yokes are used for alternating current magnetization, it is very easy to demagnetize the test object as it moves through the tapering field at the exit end of the coil or yoke.[5] As in the case of low retentivity materials, little or no retained field then exists around the discontinuity and washing of the indications must be considered. However, if the test object's surface is rough, embedded particles may resist the washing effect, even if the test object is demagnetized. A sufficient number of particles might remain in place to indicate the presence of discontinuities.

FIGURE 8. Flux density versus magnetizing current; to ensure maximum retained field, current should be shut off during the two parts of the waveform illustrated as solid lines; shutoff must be at the same point for all test objects to ensure consistency



Bath Coverage and Concentration

It is vital for critical areas to be covered with magnetic particle bath. Positioning of the test object relative to the bath applicator is therefore a very important parameter. When an automatic loading system is used, it is possible for the test object to shift and critical areas are not then exposed to the bath. For this reason, test object positioning should be monitored by means of limit switches, photocells or acoustic path monitors.

Another critical bath parameter is the magnetic particle concentration. In manual systems, this is monitored using a centrifuge tube as part of a settling test.[6] It is possible to monitor particle levels automatically with electromagnetic methods, optical methods and particle counters.

A number of bath parameters may be checked at the same time by using a standard test object containing a known discontinuity. The reference standard is passed through the entire test system in front of each part being tested or in some frequent, repetitive manner. The standard is cleaned, magnetized, bathed and tested automatically. When the system is working correctly, the standard's discontinuities are accurately detected and this verifies that following test objects are also being processed and inspected properly.

PART 5

AUTOMATING THE OBSERVATION STAGE OF MAGNETIC PARTICLE TESTS

Methods of Scanning

Scanning of fluorescent magnetic particle indications is done in order to automate the viewing of test results. Automatic scanners usually comprise the following components:

1. a source of ultraviolet radiation (may be a commercial ultraviolet floodlight or a laser with a movable beam);
2. a photodetector sensitive to visible light but not sensitive not to ultraviolet radiation (may be a phototube, a photomultiplier or a vidicon camera);
3. an imaging apparatus (may be a television photodetector or a flying spot system);
4. amplification and discrimination equipment (electronic processing networks with the ability to determine whether intensity and patterns of detected indications are caused by discontinuities); and
5. material handling accessories.

Material handling accessories are needed to move test object to and from the scanner; to index or move the test objects under the scanner so that all desired areas are inspected uniformly; and to mark or separate rejected test objects.

These components are integral to the two basic types of scanning systems: the television scanner and the flying spot scanner.[11]

Television Scanning Systems

A television scanner first illuminates the test object with filtered ultraviolet light. The camera is used as a detector of visible indications (Fig. 9). It is equipped with an image intensifier and a filter to remove superfluous ultraviolet light. The output video signal is processed through a computer or other electronic equipment designed to distinguish noise from discontinuities.

After receiving a discontinuity signal, the computer is often programmed to initiate some rejection procedure such as marking the area with paint for later disposal, or sorting appropriate test objects into a reject bin. Some pattern recognition and classification of discontinuities are possible with a television scanning system.

Flying Spot Scanning Systems

System Operation and Arrangement

The flying spot scanner uses a deep blue, violet or an ultraviolet beam to illuminate the test object (Fig. 10). The source of the beam is usually a laser. For example, a helium-cadmium laser operates in the visible mode at a deep blue wavelength of 441.6 nm (4,416 Å). This wavelength will excite the pigments used in fluorescent magnetic particle materials. Such a light source produces a very narrow and intense beam.

The scanning occurs as the beam passes over the test object and illuminates a very small area at one time. The position of the beam is controlled by mirrors; by moving the light source, or by moving the test object in front of a stationary beam. The level of fluorescence generated in the area covered by the beam is low unless the laser strikes a retained indication. When this occurs, a larger amount of fluorescent (visible) radiation is emitted (reflected). The fluorescence is detected by a single phototube equipped to filter out blue or ultraviolet light from the illumination source.

The detection signal takes the form of pulses that are then processed through a computer or other electronic equipment. Signal processing is used to discriminate rejectable

FIGURE 9. Television camera with an image intensifier for automatic scanning of magnetic particle test indications

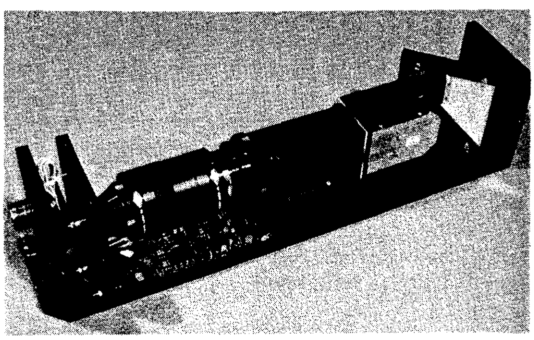
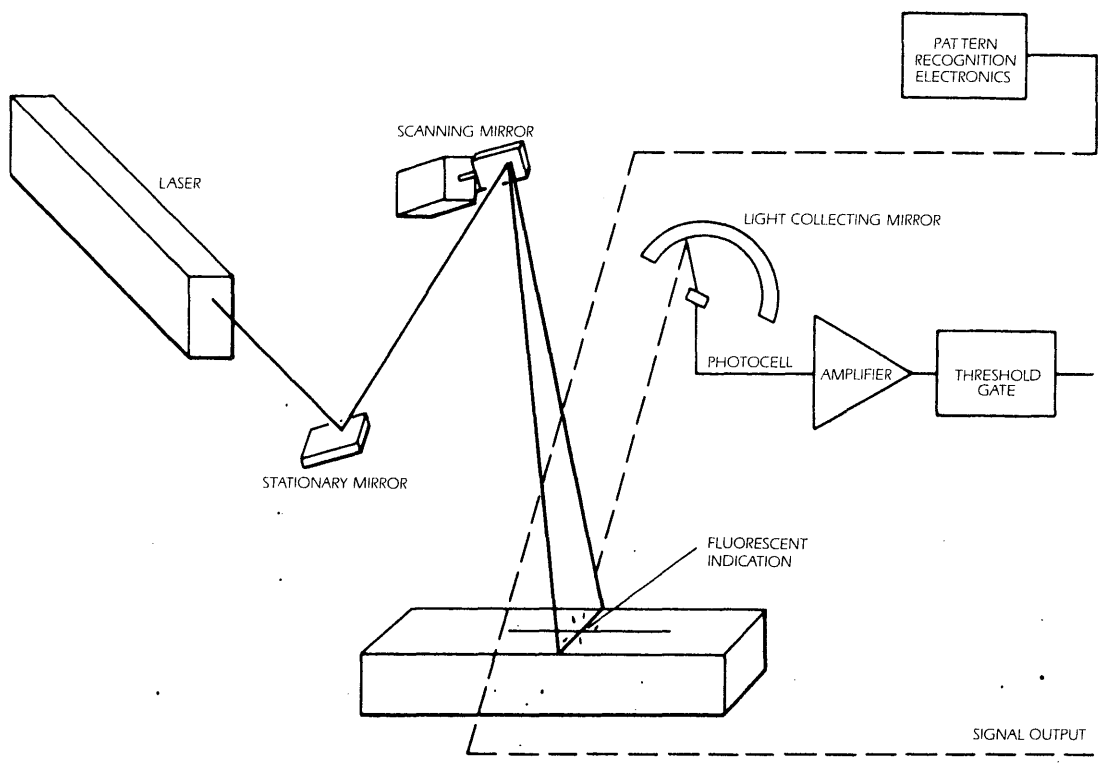


FIGURE 10. Flying spot scanner for automated magnetic particle tests



discontinuities from background noise and to initiate rejection action.

Comparison of Flying Spot to Television Systems

The flying spot scanner has several advantages over television systems. The laser provides much more intense illumination than an ordinary ultraviolet light. The resulting fluorescence is correspondingly intense and easily detected.

The detail discrimination is much better in a flying spot system. A phototube can handle a larger contrast ratio than a normal vidicon or the conventional television camera.

Problems with depth of field are minimal in flying spot methods because the system is not limited by optical imaging criteria. The depth of field is determined by the beam divergence not the f-number of the imaging lens. In addition, flying spot systems require electronic circuits that are much simpler than a television system.

The principal advantage of television systems is their wide distribution and the resulting economies of volume. Many useful accessories for television scanning systems are inexpensive, easily available and versatile.

Application of the Flying Spot System

A technique using a flying spot laser for the detection of fluorescent indications has been reported in the literature.[12] As shown in Fig. 10, the system consists of several functional components, including a scanning laser, a photodetector and electronic pattern recognition circuits.

The scanning laser causes a beam of intense light to move across the test object. When this beam strikes fluorescent material held over discontinuities on the test object's surface, a pulse of light is generated. The emitted light does not have the same wavelength as the incident light. The photodetector converts this fluorescent pulse into an electrical signal that is processed to determine if it represents discontinuities.

Pattern recognition techniques and signal intensity measurements are used in the signal processing. The optical pattern recognition system recognizes shape and size for discontinuity determination and generally ignores background fluorescence effects.

The system has extensive depth of field. System resolution is determined from the scanning beam cross section and not by the effective aperture of an imaging lens. High densities of excitation energy are possible with a laser and extremely sensitive photodetectors allow detection of weak fluorescent indications.

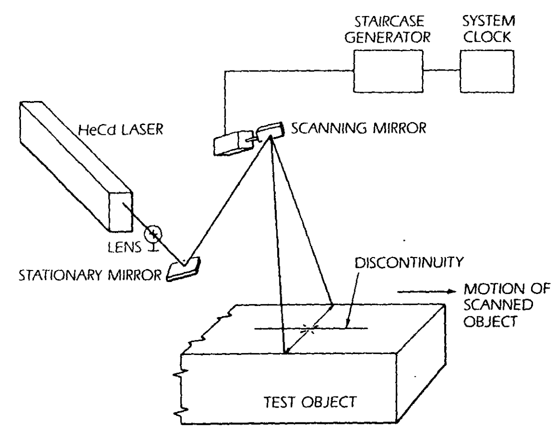
System Characteristics[13]

The scanner portion of the system contains a helium-cadmium (HeCd) laser operating at a deep blue wavelength of 441.6 nm (4,416 Å). The pigments used in magnetic particle testing materials absorb blue and ultraviolet excitation and emit visible yellow light. A blue excitation source may therefore be used instead of the familiar ultraviolet light. The blue is filtered out of the viewed image for visual interpretation and the ultraviolet light is invisible.

Photosensitive devices detect both wavelengths, so filters are required when either wavelength is used for automatic testing. The laser beam diameter is about 1 mm (0.04 in.) and the output power is nominally 15 mW. The laser beam divergence is very small so that no optical components are required. It is possible to use a lens or a combination of lenses to reduce the beam diameter to a very small value and thereby increase system resolution.

Figure 11 shows the arrangement of the system's components. The laser beam is directed to a scanning mirror that causes the light to move back and forth across the test object. This procedure effectively produces a line scan. The waveform used to drive the scanning mirror motor is a staircase function derived from the system clock. Thus each position of the scanning mirror can be directly related to a specific clock pulse. The scan motion is at right angles to the motion of the test object so that the entire surface is covered by the scanning beam.

FIGURE 11. Line scanning procedure for magnetic particle tests



Signal Detection and Processing

As the beam strikes retained fluorescent material, it emits a pulse of yellow light. Some of this light strikes the face of the photocell and is converted into an electrical pulse signal. The amplitude of this pulse is directly related to the intensity of the pulse of yellow light. The phototube pulses are amplified, filtered and, if they are to be used in a digital circuit, converted to a binary value representing amplitude.

These pulses may be used to generate a raster similar to a television image. The beam position information and the phototube analog output are required to produce such an image.

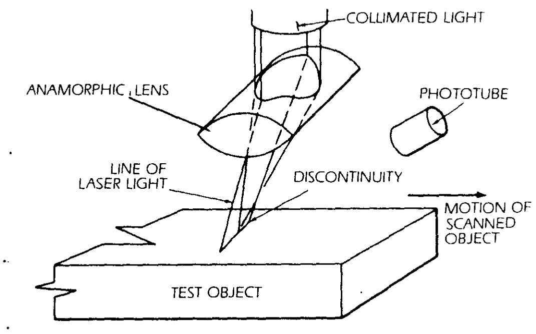
PART 6

AUTOMATING THE INTERPRETATION STAGE OF MAGNETIC PARTICLE TESTS

Recognition of significant test indications and distinguishing them from background indications are generally the two most complex problems for an automated testing system. Background often appears as a foggy glow containing a number of isolated bright spots. Frequently, there are also some false indications that share the characteristics of discontinuities. These include tool marks, scratches, thread crests, valleys, hole edges and other anomalies.

A trained operator ignores nonrelevant indications and so should an automated system. This discrimination capability dramatically increases system complexity, yet most automated testing applications do require some sort of pattern recognition. This may range from a simple coincident light technique to a digital computer programmed with pattern recognition algorithms. The most prevalent pattern recognition procedures include: (1) optical techniques, (2) dedicated digital processors, (3) microprocessor algorithms, (4) SRI algorithms and (5) neighborhood processing algorithms.

FIGURE 12. Optical pattern recognition of straight, linear fluorescent test indications



Optical Pattern Recognition

In optical pattern recognition, a linear laser beam is positioned in the direction of a discontinuity.[13] Figure 12 illustrates the formation of this line of light using an anamorphic lens. An anamorphic lens is curved so that it focuses the collimated laser light into a line parallel to the lens axis. The beams' cross sectional width in the orthogonal direction is maintained because there is no focusing in that axis.

A phototube detects and integrates the fluorescent flash that occurs when the exciting beam is coincident with the indicated discontinuity. Good parallel alignment of the beam and the discontinuity are necessary and this requirement in some ways limits system flexibility.

A similar result can be obtained using a scanning laser system and integrating the output of the photodetector across the scan. This has the advantage of a larger depth of field (no optics are used for focusing) but requires more complex scanning and electronics.

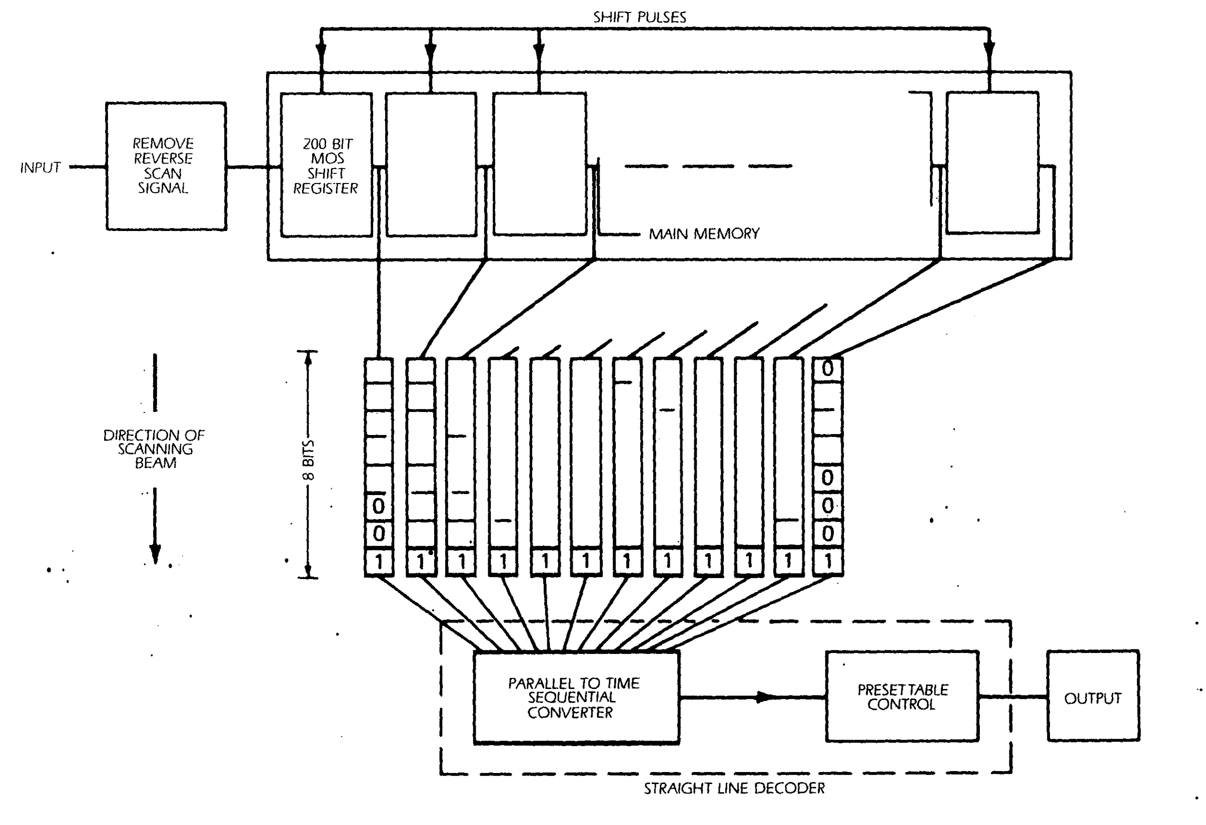
Far less sensitivity results if the beam and the discontinuity are not parallel. Using a parallel line of exciting radiation is considered a form of pattern recognition because optical integration of the fluorescent light occurs from the entire length of the indication. Slits of excitation illumination could conceivably permit optical pattern recognition for straight line indications in other orientations.

Pattern Recognition with Dedicated Digital Processors

The system described below is a parallel processor designed for use at high speeds.[14] It consists of multiple circuit boards, each containing a number of logic functions (Fig. 13). The basic component of each board is a large memory array with multiple bit elements. Each scan of the testing system is adjusted for zone width and the discontinuity input signal is gated and fed into the array. System clock pulses used to determine the scanning waveform are also used as shift pulses. Discontinuity signals shift in synchronism with the scanning beam. Auxiliary registers arranged at the output of each array are grouped together to form a two-dimensional array.

If a discontinuity indication is straight, long and bright enough to activate the input threshold, the input pulse will be exiting the last register in a 2,400 bit line after twelve scans. Simultaneously, signals will be exiting all the other registers in 200 bit increments, beginning with the 200 register. These signals are coupled into the matrix array and appear as a row of ones on the top. After eight clock pulses,

FIGURE 13. Block diagram of digital processor used for optical enhancement of magnetic particle test indications



this row appears at the bottom and exits the system (Fig. 13). Background fluorescence shows up as a random distribution of ones in the array. When a row is filled, the probability is high that a seam or some other linear discontinuity has caused it.

Linear discontinuity conditions are detected with a number of decoders wired to specific registers in the matrix array. It is shown in Fig. 13 for straight line decoding (the decoding is wired to detect straight lines only). These parallel channel pulses are converted into a time sequence and then registered on a counter. Any number of pulses may be preset on the system so that an intermittent linear discontinuity with four to eleven counts in a twelve count window can activate the output gate. A decoder can be wired to detect an angled linear discontinuity indication in a similar manner (Fig. 14).

FIGURE 14. Scanner memory matrix signal storage for a straight discontinuity (at bottom)

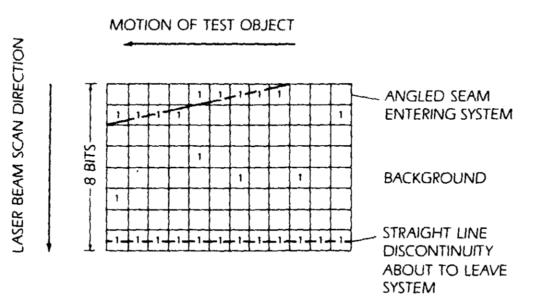


FIGURE 15. Scanner memory matrix signal storage for a discontinuity at an angle to the line of test object motion

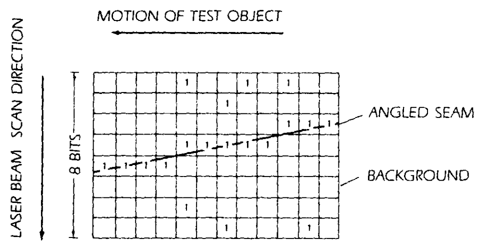
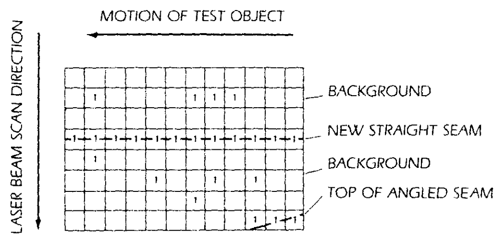


FIGURE 16. Scanner memory matrix after an angled discontinuity has moved out of the array (at bottom) and a new discontinuity parallel to test object motion is in storage (near center)

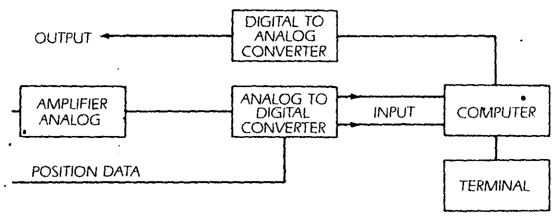


Figures 14, 15 and 16 show memory matrix signal states during scanning of sequential linear discontinuity indications. In Fig. 14, the matrix signal pattern shows: (1) a horizontal indication about to exit at the bottom, (2) an angled linear discontinuity entering above and (3) background. The direction of laser beam scanning across the discontinuity is shown vertically. The direction of the test object motion is shown horizontally.

Figure 15 shows the matrix signal state after the horizontal discontinuity has left and the angled discontinuity is in storage. Because all discontinuities eventually pass down through the matrix, a given decoder wired to detect this angled seam could be connected to the registers shown (or one above or below) so long as the pattern is the same.

In Fig. 16, the angled discontinuity has nearly exited the array and a new horizontal discontinuity is present in the middle of the display system. Random background signals are indicated by ones scattered throughout the matrix.

FIGURE 17. Conversion of analog test signals to digital input data



Simple Microprocessor Algorithm

A variety of ways are available for using a digital computer to detect certain patterns common to discontinuities. The important idea is to differentiate discontinuities from background. This is usually done based on the fact that most discontinuities are linear indications.

The ability of humans to visually distinguish linear indications in high noise clutter is well known. A large variety of algorithms are available for simulating this human characteristic. The following example shows a simple linking algorithm used to detect linear discontinuities in high background levels.

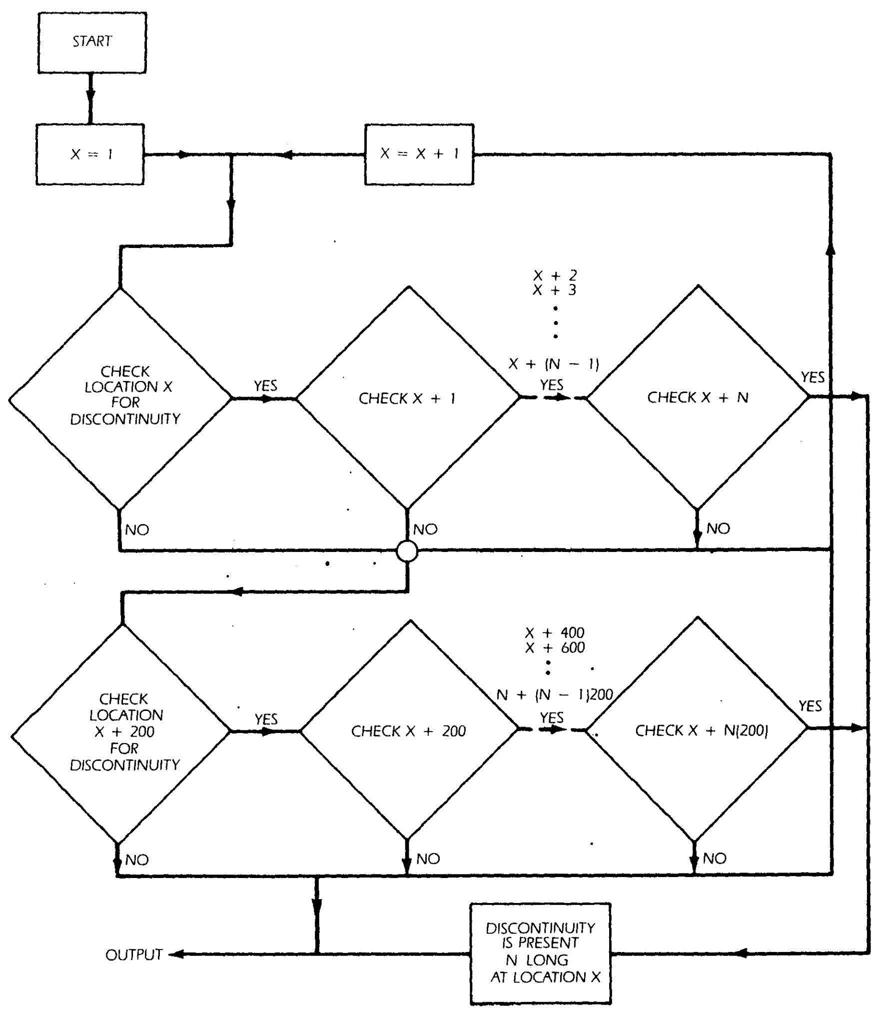
Certain computer based optical processing techniques may be used to enhance television images and it is possible to use these approaches with the image data from a flying spot scanner as well. It is required that the scanning format be similar to the television format and that the video signal be delivered in binary or digital format. These are powerful approaches and are used in machine vision applications to aid in pattern recognition by reducing noise and clutter on the images.

Figure 17 shows how analog signals move from the optical scanner and are processed in analog-to-digital converters and then coupled to a digital computer for analysis.

Adjacent Cell Linking

Figure 18 shows the simplified logic diagram of a pattern recognition program that will find horizontal and vertical lines.[13] The computer program uses a procedure called

FIGURE 18. Logic diagram of a computer program for finding horizontal and vertical test indications



adjacent cell linking. In this instance, if test indications (stored numbers in memory locations that are an analog of their locations on the test object) can be linked to adjacent indications, then the probability is high that these are caused by discontinuities. The greater the number of links, the greater the discontinuity probability.

Initially, the scanner data are stored in memory with addressing referenced to the position of discontinuity indications on the test object. To keep matters simple, the data are reduced to a single value. Thus, a certain threshold must be reached to store a binary value in memory. All values below this level are recorded as zero.

The scanning format is 12 × 200. Assuming a starting location of 1, the program first looks for the presence of data in location 1. If data are there, the program next looks in location 1 + 1. If data are there, the program checks location 1 + 1 + 1 (or 3) and so forth until a preset number *N* is reached. Reaching *N* indicates a vertical linear discontinuity indication with length proportional to *N* and a starting point at location 1.

To detect horizontal linear discontinuity indications, the number 200 is added to X and, if proper discontinuity data are present in this location, the counter moves to $X+400$ and so forth. After N progressions with discontinuity data recognized in each matrix cell, the computer recognizes a horizontal linear indication N units long starting at location 1. After this, X is changed to 2 and the process repeats. Analogous programs to recognize angled linear discontinuity indications can be incorporated with additional statements.

The SRI Algorithms

A popular set of algorithms used in pattern recognition systems are those developed at the Standard Research Institute (SRI).[15] These algorithms consist of a series of procedures that control about fifty different features extracted from a binary image. Some of the extracted features are: (1) the size of a blank area, (2) the size of solid objects, (3) the centroids of holes, (4) the centroids of blank areas, (5) the centroids of solid objects and (6) the number of these details registered.

FIGURE 19. Typical arrangement and labeling of neighboring pixels

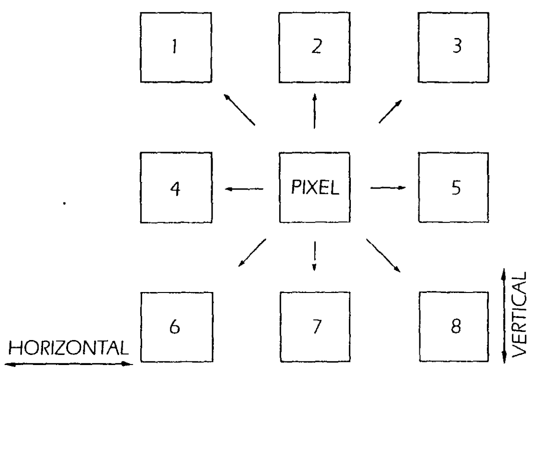


FIGURE 20. Use of neighborhood processing to enhance the image of a cylinder: (a) top view showing mirror held by gray block placed in the cylinder to image the inner wall; (b) video image of inner wall and crack indication; (c) image before removing background; and (d) image after processing

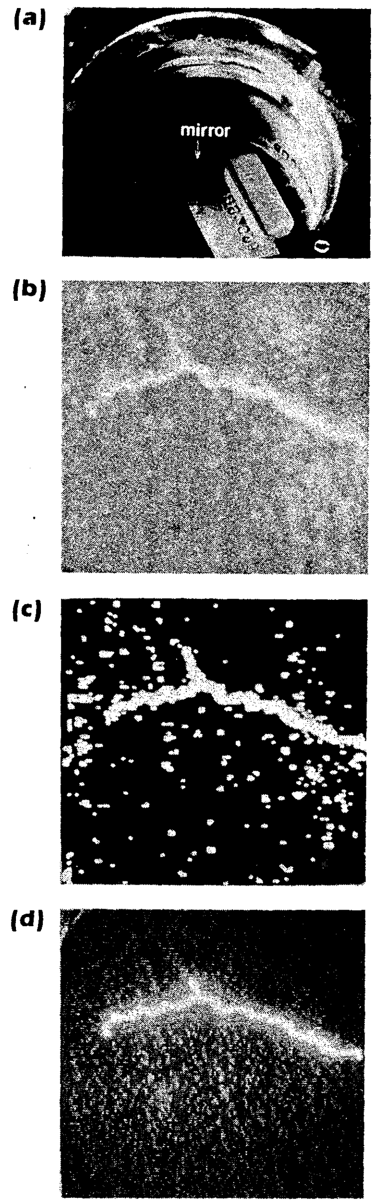
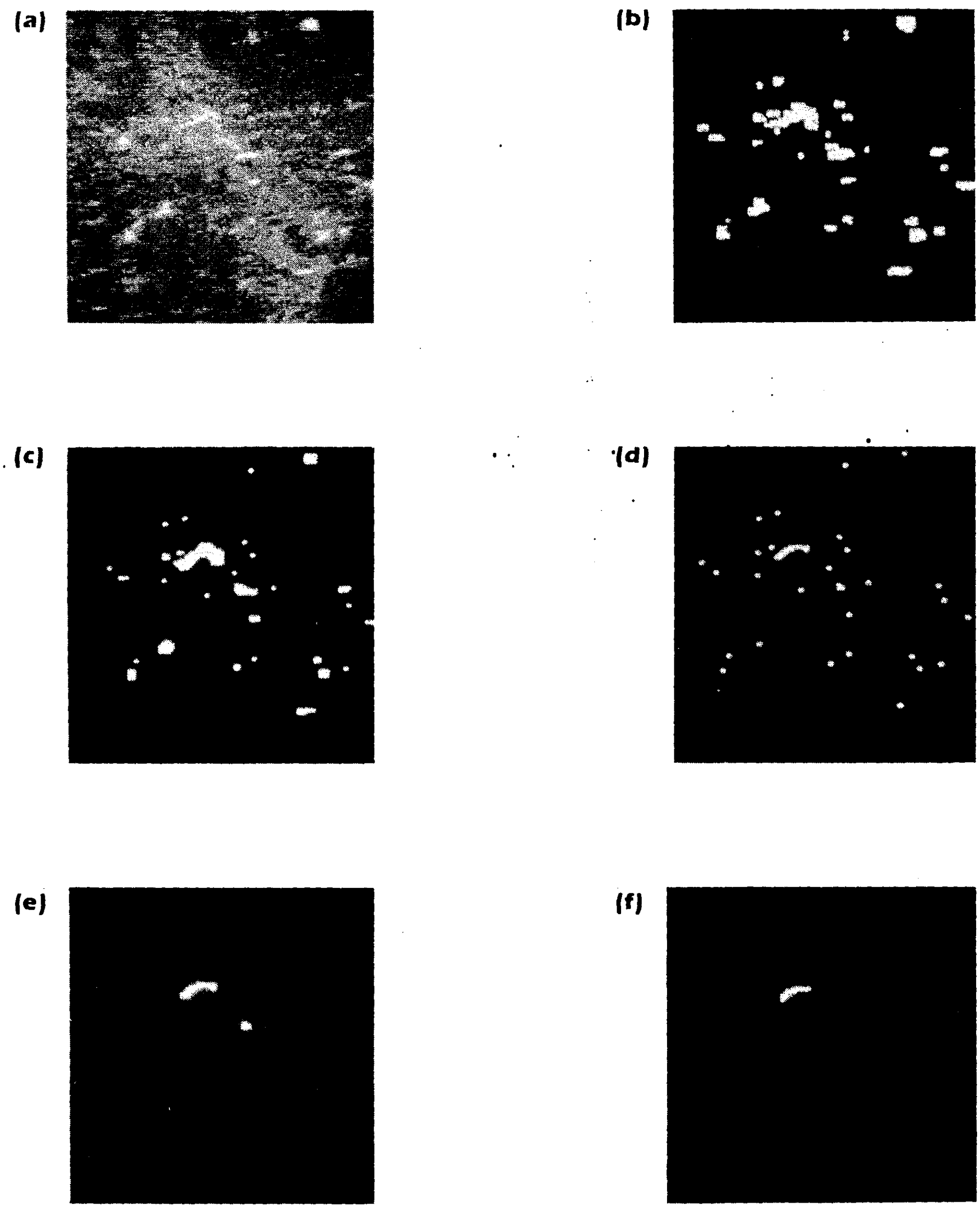


FIGURE 21. Use of neighborhood processing to enhance the image of a tube section, starting with the image before processing, progressing through several enhancement techniques to remove background, and ending with the final image of the discontinuity



An image is analyzed based on these features and a description of the object or image is stored and used for later comparison with images of unknown objects. The purpose of the analysis is to reduce complex images to essential values (a kind of categorizing), so that images may be selected and compared based on the details of interest.

There are three significant points to remember about the SRI algorithms. First, algorithms usually work with a binary image. Therefore all data below the threshold value are defined as zero and all values above the threshold are defined as one. Second, the resulting binary image is analyzed in terms of certain predetermined characteristics (number, size, centroids) of certain predetermined features (holes, lines and so on). Finally, the description is stored for future reference for comparison with unknown images.

The chief limitation of SRI algorithms is the significant amount of data discarded in the generation of the binary image. Also, the severity of the thresholding makes such systems difficult to set up and not very repeatable. It is not easy to digitally manipulate the large amount of video data present in a typical television image. One way to accomplish this is to reduce the number of gray levels from a typical value of 256 to a value of 8. Even eight is too large a number to effectively accommodate the SRI algorithms.

Because of these limitations, other techniques have been developed to expand the number of the gray levels involved in the data processing.

Neighborhood Processing

Neighborhood processing is also known as *cellular automata* and *morphological image processing*.[16] The concept is particularly suitable for industrial nondestructive testing purposes.

In this image processing technique, each pixel in the image is transformed or converted in a particular way that primarily depends on the state of the adjacent or nearest neighbor pixel.

Cellular automata theory was first developed by John von Neuman who is primarily known for developing the algorithms that drive the modern digital computer. Neuman's interest was in simulating in a machine some of the aspects of self-reproduction in biological cells.

As in all electronically processed images, the starting point of neighborhood processing is a large rectangular area of picture cells or pixels, in which the rows and columns are arranged in a standard television format. Typically each pixel has eight neighbors as shown in Fig. 19.

In the normal analog television image, each pixel has a brightness level that corresponds to some shade of gray (typically 256 levels or 8 bits). In digital imaging, the pixel has a binary number that corresponds to the specific gray level. If the computer program word representing a pixel has enough memory capability, additional memory can be used to store other information about that pixel's portion of the image. For example, the most significant bit can be made to indicate that its pixel is part of a discontinuity. A field of all these significant bits forms what is called the *bit plane* of a discontinuity and can be used to indicate the image's discontinuity condition.

In cellular automata, the data in all the pixels are changed according to a transition rule and according to the state of the pixel neighbors (all data change sequentially).

There are four key stages in neighborhood processing. First, the pixel word acquires gray levels in the least significant bits and other information in more significant bits. Second, a series of successive transformations occurs in a carefully determined sequence. Third, when the final transformation has occurred, the important information is located in the most significant bit; irrelevant data are eliminated. Finally, the image is scanned and specific features are studied by examining certain significant bits.

The advantage of the neighborhood processing technique is that it removes background so well (Figs. 20 and 21). After such improvement, it is relatively easy to use spatial gating of a video image system to trigger alarms or other warning devices.

PART 7

EXAMPLES OF PARTIAL AND FULLY AUTOMATED MAGNETIC PARTICLE TESTING SYSTEMS

The magnetic particle system illustrated in Fig. 22 is for billet testing. The system uses a specially developed magnetic particle material that is permanently bonded to the surface of a billet when heated. This allows manual testing to be performed at a later, more convenient time. The processing stages of the test are automated, including multidirectional magnetization, test object bathing and application of heat to fix the magnetic particle indications.

Figure 23 illustrates a system designed to automatically process piston domes using longitudinal coil magnetization at speeds exceeding 200 test objects per hour. The test objects are automatically moved to a pickup point, clamped securely by jaws to a special turnover mechanism, then lifted in an arc and positioned inside the coil. Bath is automatically applied to critical surface areas, coil current is turned on, the bath is shut off and the coil current is then shut off.

Next the test object is returned, dome side down, to the pickup point, with the escapement cycling to push the processed test object onto the exit conveyer, at the same time bringing a new test object into the system for processing. Inspected parts are moved to a testing area where they are visually examined.

FIGURE 22. Fixed indication billet testing system

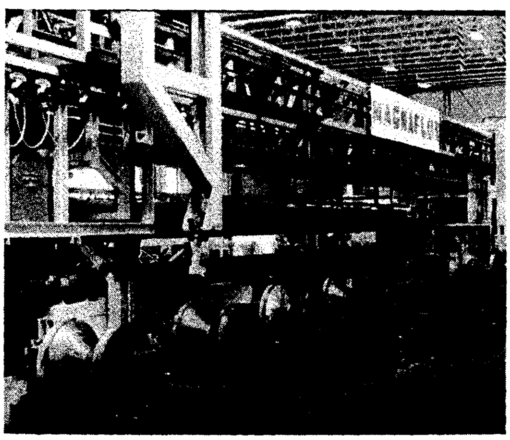


Figure 24 illustrates a system using multidirectional magnetization for processing. Test objects are loaded onto holders and moved into the magnetization area where a

FIGURE 23. Piston dome processing system for magnetic particle tests

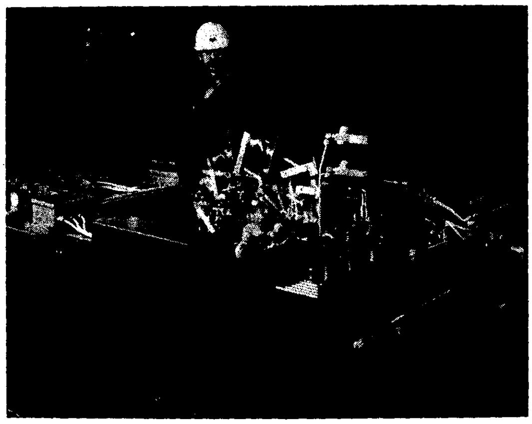


FIGURE 24. Magnetic particle testing unit used for bolt inspection

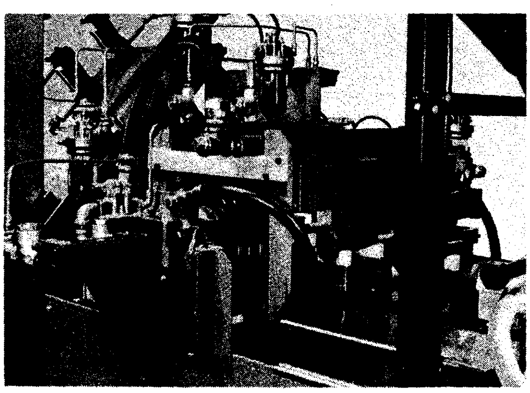


FIGURE 25. Coupling testing unit using a central conductor for circular magnetization

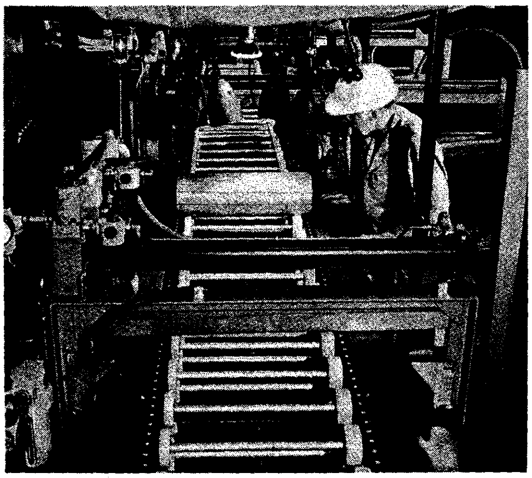
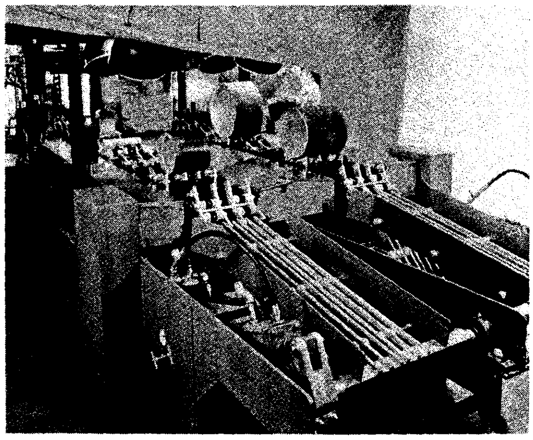


FIGURE 26. Magnetic particle unit for testing bars using residual magnetization (see also Figures 4 and 5)



sequential coil (longitudinal magnetization) and head (circular magnetization) are applied. The bath flows on to the test object during the magnetization cycle and is cut off before the magnetization cycle ends. The test object is then moved to the testing area where it is visually inspected.

Figure 25 shows a system that uses a central conductor to circularly magnetize test objects. Bath is applied during the magnetization cycle and test objects are viewed immediately after bathing. The operator can manually rotate the test object for better observation if necessary.

Residual magnetization is used in the system shown in Fig. 26. This is a fully automatic system. Parts are circularly magnetized two at a time then moved by means of a walking beam conveyer into the testing chamber. There they are rotated two at a time and moved laterally under laser scanning heads. The beams are shaped optically into lines and after scanning, good product moves to the next manufacturing station. Material with discontinuities is automatically removed from the production cycle.

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SECTION 11

RECORDING OF MAGNETIC PARTICLE TEST INDICATIONS

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PART 1

BASIC RECORDING OF MAGNETIC PARTICLE TEST RESULTS

Discontinuity indications formed by the magnetic particle test method may be very visible on the surface of the test object at the time of the test but they are seldom permanent or even durable. In many cases, it is desirable to make a permanent record of these indications. Sometimes, the record is used to document and justify the return of a rejected part and in other cases the recorded indication is used to prove that a discontinuity is small enough to be insignificant.

Indications may be recorded in two basic ways: (1) on the test object itself (often called *fixing*); or (2) on other media for storage remote from the test object. The text that follows includes data on fixing methods, plus details on recording with media separate from the test object, including: drawings and written descriptions, pressure sensitive tape transfers, alginate impressions, magnetic rubber replicas and photography.

Drawings and Written Descriptions

The simplest method of recording test indications is the written description. To be practical and meaningful, this written record must be detailed and descriptive. At the very least, it should include the sizes and locations of test indications. Additional information should be supplied as warranted by the application.

Drawings are often used in place of or as complements to written descriptions. Drawings can provide more information than written descriptions or they can be confusing, depending on the skill and dedication of the illustrator. If large numbers of similar test objects must be recorded by drawing, a master diagram can be prepared and copied. Indication records are then added to the copies by the magnetic particle inspector.

PART 2
PRESSURE SENSITIVE TAPE TRANSFERS

One of the oldest and simplest mechanical methods of recording magnetic particle indications is the tape transfer. This technique uses a piece of pressure sensitive tape pressed over the indication then lifted off and pressed onto a piece of paper that is kept as the test record. It is usually necessary to include some additional descriptive matter covering the location and orientation of the discontinuity on the test object.

In order to make a good tape transfer, the test surface must be clean before the tape is positioned. Dust and dirt deactivate the adhesive if present in excessive amounts, as do water and oil. It is often necessary to clean the surface before the magnetic particle test is performed and again before the indication transfer is made.

Dry Method Tape Transfers

The tape transfer recording method is most easily used with dry magnetic particle tests. Large indications are usually produced with dry techniques and there is no moisture to resist the tape adhesive.

Excess magnetic powder is removed, usually by a gentle air flow, before the transfer is made. Once the indication is formed and the excess powder removed, a piece of tape sufficiently long to cover the desired area is pressed firmly over the indication. The tape is then lifted off the test object and pressed onto the paper backing that is retained as the record.

If fluorescent particles are used, dark colored paper (particularly black photographic paper) is the best backing. Most commercially available pressure sensitive tapes are fluorescent and this greatly reduces contrast between the indication and the backing. If possible, nonfluorescent tape should be obtained and used to make transfers with fluorescent particles.

Wet Method Tape Transfers

Tape transfers can also be made with wet method test indications, but this is not as simple as transfers with the dry method. The first requirement is that the object surface and the test indication be dry before the transfer is taken. The procedure is to form the indication normally, allow the excess bath to drain off and to then dry the surface before making the transfer. Wet surfaces prevent the tape from sticking properly and may dissolve the tape or adhesive.

Water Vehicle Tape Transfers

With water vehicle tests, the drying procedure can be fairly simple. Water dries quickly in a typical testing environment, leaving the test object surface in proper condition for a tape transfer.

If there is not sufficient time for the water vehicle to evaporate, or if the particle background is too dense, the test object can be gently rinsed with acetone. Acetone dissolves water and dries very quickly. It also rinses away some surface particles, performing the function of the dry method air flow. However, caution must be exercised to avoid washing away indications.

Oil Vehicle Tape Transfers

With oil suspensions, the drying problem is more difficult. Oil drains slower than water and dries much slower. With some very volatile oils, it may be possible to wait until the vehicle evaporates, but it is usually necessary to remove excess oil bath with a volatile solvent (petroleum ether, hexane, naphtha or 1,1,1 trichloroethane).

Rinsing with solvents must be done very carefully to avoid loss of the indications and the solvent must be completely dry before the tape is placed.

Caution must be observed when using these solvents since some are very flammable. If possible, it is best to transport the processed test objects to a fume hood to conduct rinsing operations. The area where rinsing is conducted must be well ventilated and free of sparks or other sources of ignition. *Strict storage and handling restrictions apply to all flammable materials.*

Wet Fluorescent Tape Transfers

Since wet method particles are often fluorescent, the procedures and precautions mentioned for dry fluorescent particles must be observed. The use of black paper as a permanent backing for the retained tapes is of particular importance.

Fluorescent indications may sometimes perform as visible light indications but their size and visibility are not ideal (particle concentrations are normally much lower than needed for white light visibility). Therefore, normal tape transfer techniques can provide low quality but usable transfers of fluorescent indications.

Archival Quality of Tape Transfer Records

Tape transfers are fairly durable records of magnetic particle tests, but they do deteriorate with time. The adhesive dries out and becomes brittle, and in some cases, so does the plastic tape base. The transfers then fall off the paper substrate and may be lost.

To minimize this problem, high quality translucent tapes should be used. Tape records should be stored in a cool and moist environment. Wrapping records in aluminum foil retards degradation of the tapes. Good tapes properly stored last at least five years and often longer. Serious deterioration may be expected from the best tape records in about ten years.

PART 3
FIXING COATINGS FOR TEST INDICATIONS

A helpful but seldom used method of recording magnetic particle test indications is the *fixing coating*. These coatings are usually bulk materials that are gently sprayed onto the test object surface. The coatings can fix a discontinuity indication in one of two ways: (1) bind the indication firmly in place on the test object; or (2) lift the indication for preservation elsewhere, much like a tape transfer.

Only certain materials can be used as magnetic particle fixing coatings. Because test surfaces typically contain bath or other materials (scale, oil or water), a coating must adhere to the object surface in spite of contaminants. Specially formulated materials are required for this characteristic.

Application of Fixing Coatings

It is best to have the test object surface as clean and dry as possible before applying the coating. In production operations, this normally requires special drying equipment to complete the recording in a reasonable amount of time. Water baths are probably the easiest to fix because they have shorter drying times than other vehicles and because water does not emit noxious or flammable fumes.

Fixing on the Test Object

One use for fixing coatings is to protect the test indications so that abrasion from mechanical handling does not damage the test result. Coatings designed for this purpose must be durable after drying.

Such coatings are typically applied by spray and may be water based or organic materials. The coating must dry before it can perform its protective function and in the interest of speed, drying equipment must often be provided.

Fixing for Removal from the Test Object

The other type of fixing coating is designed to be stripped off the test object so that the actual indication is preserved elsewhere as a record of the test. These coatings are very special materials containing a release agent that allows the dried coating to be lifted off the object surface. Usually a specially prepared pressure sensitive strip is pressed over the area and used to pick up the coating with its entrapped indication. The strip provides support for the coating and allows easier removal and storage.

With fluorescent indications, the usual precautions apply. Strips and coatings may be fluorescent and can compromise indication visibility.

Archival Quality of Fixing Coatings

Test indications fixed to the test object retain their validity indefinitely while the test object is inactive. The characteristics of a normal service environment can quickly erode or mask typical test results fixed onto the object surface. Fixed indications that are removed from the test object must be stored with the same precautions as tape transfer records. Humidity and temperature controls are needed to extend the life of fixed records.

The pressure sensitive strips used for removing a fixed indication are special grades of expensive materials. Their life expectancy is limited but longer than that of the low grade tapes often used for simple tape transfers. The removed test indications may be mounted on paper backing, wrapped in foil and stored in a cool, moist environment for archival purposes.

PART 4
ALGINATE IMPRESSION RECORDS

Alginate impression compounds are based on mixtures of potassium alginate, calcium sulfate, sequestering agents such as sodium phosphate, and fillers such as silica, diatomaceous earth or calcium carbonate. When the compound is mixed with a prescribed amount of water, a soft paste is formed. In three or four minutes, the paste becomes a rubbery solid with the characteristic of accurately conforming to and replicating, in negative, the surface to which it is applied. This physical record in 1:1 scale has proved valuable in many areas, including dental applications.

The impression solid also absorbs and lifts particulate matter from the object surface and it is this absorption property that makes alginate compounds useful for recording magnetic particle indications. The primary benefit of these compounds is their ability to lift particle indications from test object locations that cannot be directly viewed by the inspector.

Application of Alginate Impression Techniques

To make alginate impressions, the test object is first processed through a typical magnetic particle test procedure. Discontinuity indications are allowed to form normally.

After the test is completed, the alginate impression compound is mixed according to the instructions of the manufacturer. The mixed compound is immediately applied to the inspected part. The test object does not have to be dried before application of the recording media.

If the area of interest is a cavity, it should immediately be filled with the compound paste. If the area of interest is large or has a complex geometry, the recording compound can be applied to a thin polyethylene sheet and the sheet is then smoothed over the full test area. *Movement of the sheet or excessively working the compound will smear the test indications.*

After the paste sets into a solid, the magnetic particles are gently separated from the object by slowly peeling the polyethylene sheet away from the surface or gently dislodging the solid from its cavity. In a successful impression recording, the discontinuity indication is transferred to the compound material in its original size and shape. Test results may then be examined and interpreted at a convenient location remote from the test object surface.

Archival Quality of Alginate Impression Records

Because of their size, impression records are difficult to retain for archival purposes. A common procedure is to use the alginate impression method to retrieve a discontinuity indication from an inaccessible location and to then photograph the indication for filing purposes. Supplementary documentation provides the magnetic particle test method, the impression recording procedure and the photographic data required for complete archival recordkeeping.

PART 5
MAGNETIC RUBBER METHODS

Magnetic rubber recording uses a dispersion of magnetic particles in a rubber base that cures at room temperature. The test object is magnetized with the uncured rubber covering the area of interest. The magnetic particles then migrate to the leakage field caused by a discontinuity. As the rubber cures, discontinuity indications remain in place on the rubber (and over test object) surface.

After curing, the rubber is removed from the test object and the test results are interpreted in a convenient location. Figures 1, 2 and 3 depict the magnetic rubber recording process. Figures 4 and 5 show the preparation for magnetic rubber tests of horizontal and vertical fastener holes.

Magnetic rubber inspection is useful for inaccessible areas such as cavities or bolt holes where test indications cannot be seen. The magnetic rubber method also provides a permanent replica of the test area and indications.

The process is time consuming because special holding dams must often be constructed to keep the rubber in the area of interest. Another disadvantage is that the recording medium must be mixed only at the time of the test and must

FIGURE 1. Typical magnetic rubber inspection using electromagnetism: (a) diagram of rubber application; and (b) cross section of an inspected hole

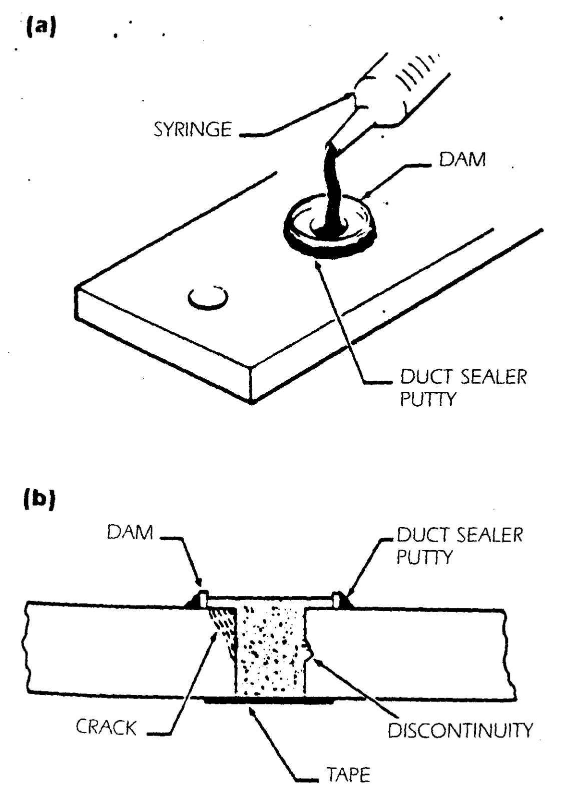


FIGURE 2. A magnetic leakage field at a material discontinuity causes the particles in magnetic rubber to migrate and concentrate over the discontinuity: (a) diagram of yoke positioning; and (b) cross section of an inspected hole

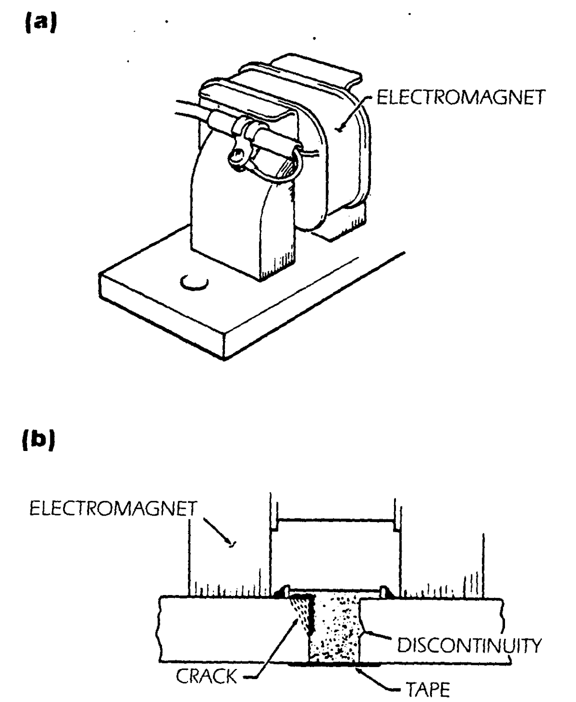


FIGURE 3. After curing, the magnetic rubber replica is removed from the test object, revealing the location of a crack as a vivid dark line; other surface discontinuities and conditions are also shown

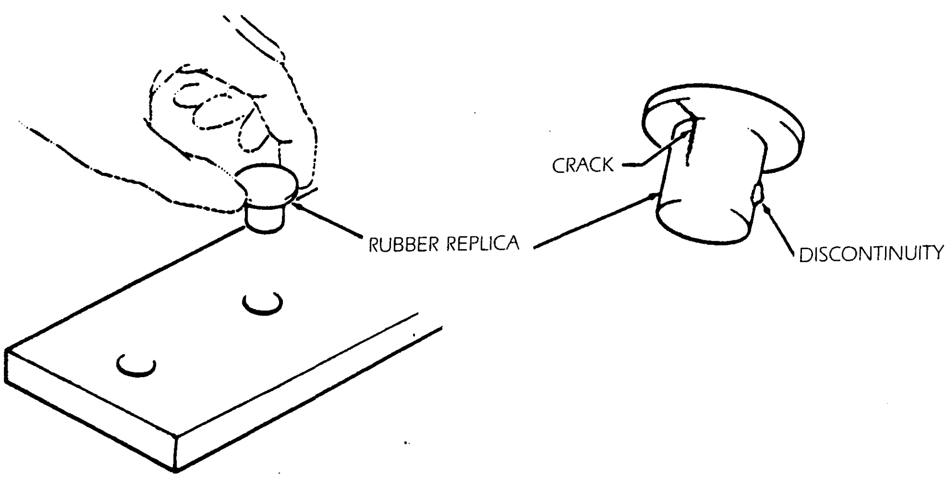


TABLE 1. Materials and accessories for magnetic rubber indication recording

Basic Materials
- Magnetic rubber compound
- Cure and stabilizer
- Dibutyltin dilaurate catalyst
- Duct sealer putty
- Duct tape
- Aluminum foil

Material Preparation Accessories
- Balance (1,000 g capacity capable of reading 0.1 g)
- Disposable syringes (30 to 50 mL capacity)
- Small disposable cups (paper or plastic)
- Disposable stirrers

Optional Special Equipment
- Geometric pole pieces (special design to fit test object)
- Central conductor and dam (assorted sizes)
- Microscope (7× to 10× for viewing very small indications)
- Field meter (electronic or dial probe)
- Heat lamp
- Portable vacuum pump
- Desiccator chamber

be used immediately to avoid premature cure. Furthermore, the rubber medium is very viscous and extremely long magnetization shots are required before indications can form.

Applications of Magnetic Rubber Techniques

Magnetic rubber techniques require special supplies and equipment (see Table 1). Necessary cleaning materials include organic solvents such as acetone, naphtha, xylene or 1,1,1 trichloroethane. These must be able to dissolve oil and grease and must be stored with appropriate precautions. Water and strong detergent may be used for cleaning.

Magnetizing Equipment

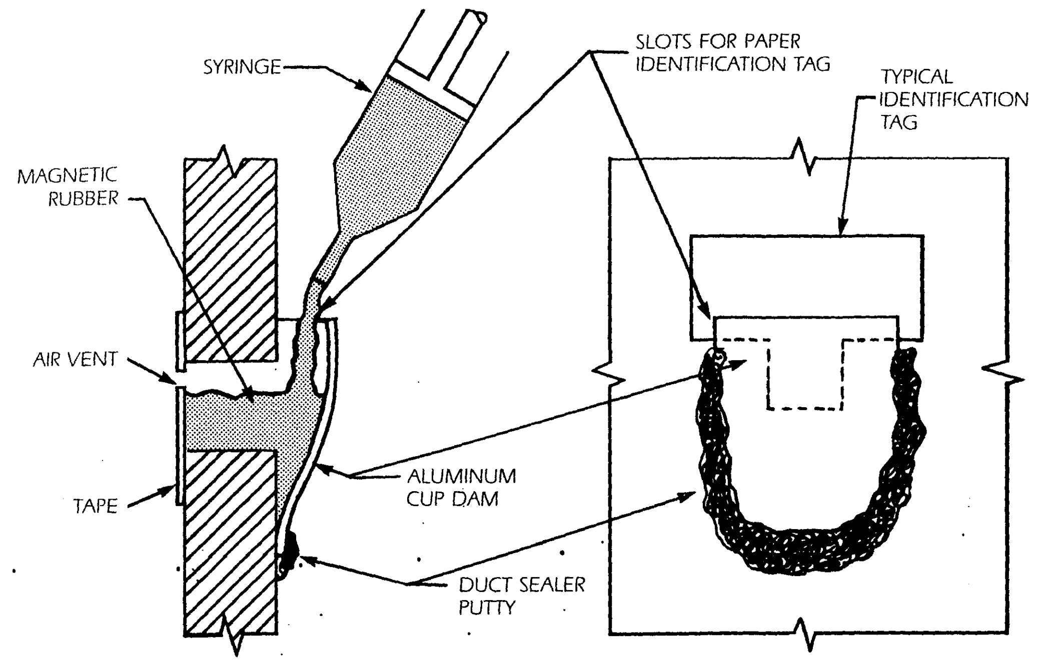
Because of the long magnetizing times, magnetic rubber methods require the same kind of magnetizing systems used for dry method magnetic particle tests. The system may include yokes, prods, clamps, coils or central conductors with alternating or direct current. The direct current yoke is the preferred magnetization method. Permanent magnets may also be used in certain test applications.

Test Object Preparation

Using the chosen cleaning solvent, oil, grease and soil are removed from the test object surface and the area to be tested. Also remove metal burrs, smears and sharp edges. Be sure the surface is dry before proceeding.

If needed, a central conductor and dam assembly (Fig. 6) are then installed and connected. Using tape, foil and duct

FIGURE 4. Horizontal hole preparation for magnetic rubber inspection



sealer putty, a reservoir is formed for the magnetic rubber. Virtually any test object configuration can be prepared for magnetic rubber inspection using a dam assembly. Upside down surfaces may be tested by building a reservoir beneath the test area and pressure filling it with magnetic rubber. A vent hole must be provided in the reservoir to prevent entrapment of air.

Magnetization and Current Parameters

Magnetization may be applied with: (1) portable electromagnets or yokes, (2) central conductors, (3) conventional magnetic particle units with clamps, prods or coils and (4) permanent magnets. Direct current yokes are preferred and, in areas of limited access, steel extensions or pole pieces may be used to transfer magnetism to the test object.

Permanent magnets may be useful in certain specialized situations where test object shape makes magnetization with yokes difficult. The magnetic fields produced by permanent magnets are often quite low and sometimes unreliable. Permanent magnets should be used only if specific procedures have been developed using reference standards with known discontinuities.

Central conductors are best suited for fastener and attachment holes, particularly when there are layers of material requiring replication.

Good magnetic contact is critical. Magnetic field strength is greatly reduced with poor contact between the test object and the magnetizing yoke. To increase contact, auxiliary pole pieces may be machined from soft iron and attached to the poles of electromagnets. Pole pieces should be designed to have the smallest possible reduction of cross section consistent with space requirements. Figures 7 through 10 demonstrate good and bad magnetic contact arrangements and the use of pole pieces.

Magnetic field requirements include both field strength and duration. These are critical to the success of the test because of the high viscosity of the rubber and the long times necessary for migration of the particles to the discontinuity. These requirements are detailed in Table 2.

FIGURE 5. Vertical hole preparation for magnetic rubber inspection

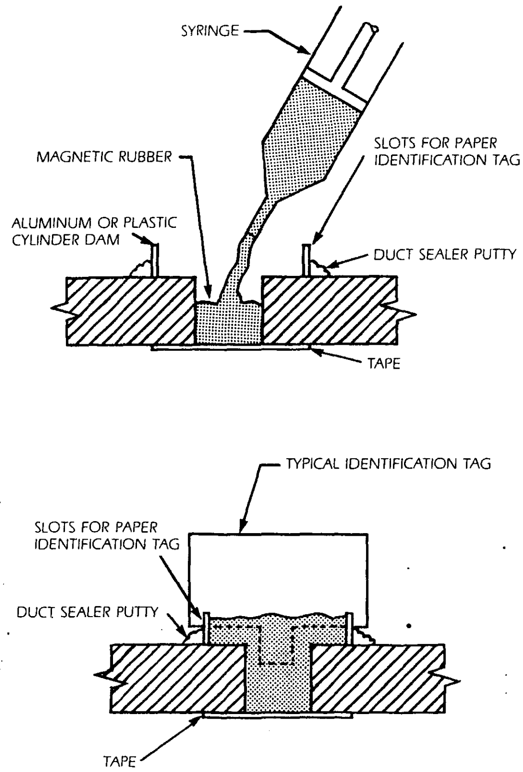


FIGURE 6. Typical central conductor setup for magnetic rubber inspection of horizontal or vertical fastener holes: (a) cutaway view of fastener; and (b) cross section through the fastener hole

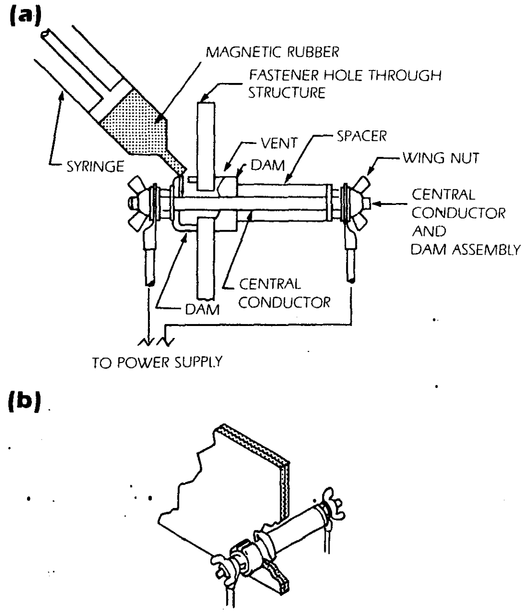


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TABLE 2. Magnetic strengths and durations for magnetic rubber tests

Inspection Area Type	Field Strength millitesla (gauss)	Time (seconds)
Uncoated holes	5 to 7.5 (50 to 75)	30
	2.5 to 5 (25 to 50)	60
	1.5 to 2.5 (15 to 25)	240
Bare surfaces	15 to 25 (150 to 200)	30 to 60
	10 to 15 (100 to 150)	60 to 180
	5 to 10 (50 to 100)	180 to 600
	40 to 50 (40 to 50)	600 to 900
	20 to 40 (20 to 40)	900 to 1,800

VARIATIONS TO THIS TABLE MAY BE NEEDED FOR SPECIFIC APPLICATIONS

Preparation and Use of Magnetic Rubber

Magnetic rubber is prepared according to manufacturer specifications and is only mixed immediately prior to its use.

First, the base rubber is thoroughly mixed to resuspend the magnetic particles (a paint shaker is helpful). Mixing should continue until there are no streaks or color variations in the material.

Weigh or measure the specified amount of magnetic rubber into a paper cup or other disposable container. About 1 g of base material fills 1 mL. Do not measure out more material than can be used within the allowable magnetization period.

FIGURE 7. Good and bad magnetic contact situations for magnetic rubber inspection: (a) very little magnetic flux gets through the aluminum to the steel; (b) a better magnetic field is obtained by leaving alternate steel bolts in place; and (c) the best magnetic field is obtained by magnetizing from the steel side

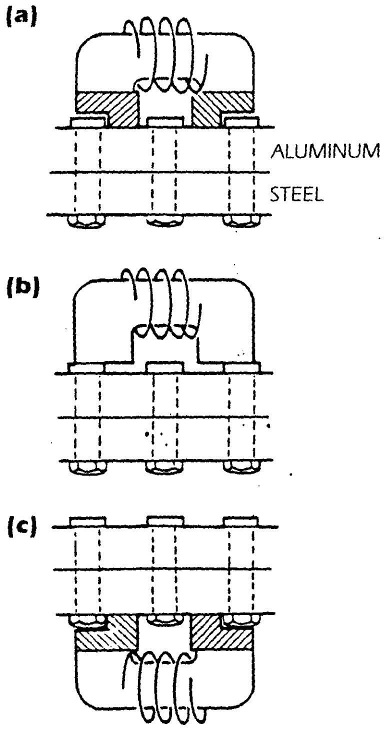
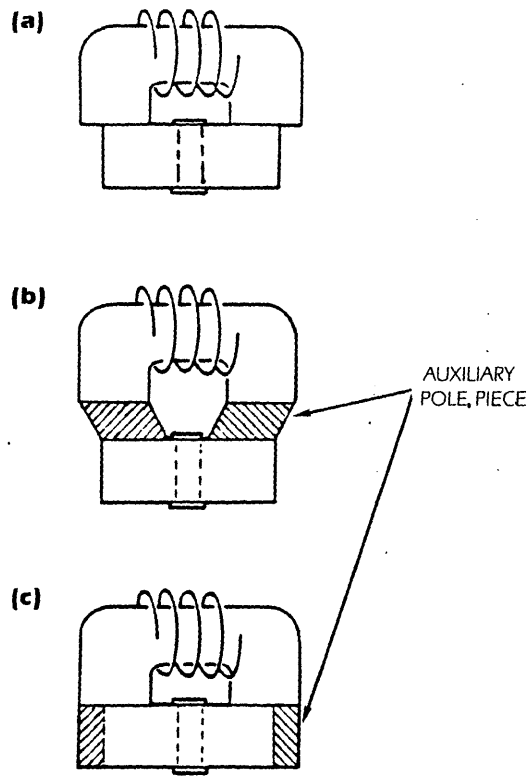


FIGURE 8. Improved contact and improved magnetic field using pole pieces: (a) poor contact (field partially lost); (b) improved field with the addition of pole pieces; and (c) magnetic field and contact are improved with correct pole piece configuration



Deaerate the material if air bubbles are a problem. This is done by placing the mixed material in a vacuum chamber and reducing the pressure to between 85 and 100 kPa (25 to 30 in. Hg) for 60 to 120 s.

Catalyst and Stabilizer

The catalyst and stabilizer are then added as follows. A standard formula is used whenever the magnetization period does not exceed 480 s: 15 drops of dibutyltin dilaurate catalyst and 2 drops of cure stabilizer for each 10 mL of base material. Mix thoroughly, avoiding reintroduction of air bubbles. After about eight minutes, this mixture becomes too thick for magnetic particle migration. Cure is completed in about an hour.

When longer magnetization times are necessary, the cure time may be extended by reducing the amount of catalyst. Five drops of catalyst per 10 mL of base material provides about twenty minutes of usable magnetization time. Final cure is about three hours. One drop of catalyst per 10 mL of base provides about one hour of usable magnetization time and final cure in about eight hours.

Applying the Rubber to the Test Object

When testing holes with scored surfaces, small diameters or unusual configurations, the test area may be coated with a thin layer of petrolatum to aid removal of the replica.

Rubber may be applied by pouring from the disposable container if sufficient access is available. Inaccessible areas

FIGURE 9. Improved contact and improved magnetic field using pole pieces: (a) very poor contact (field partially lost); (b) magnetism in the radius is much improved with the addition of a pole piece

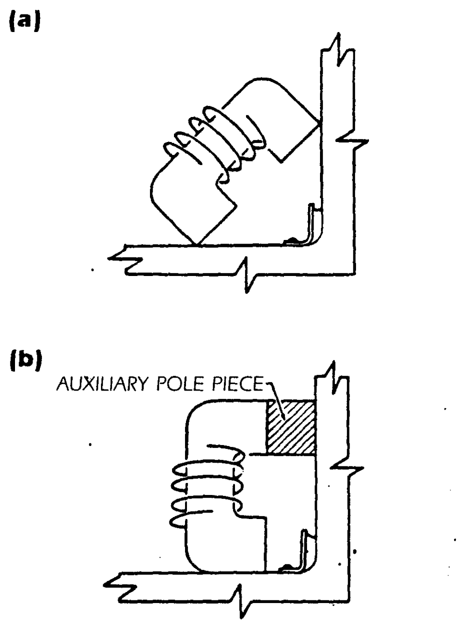
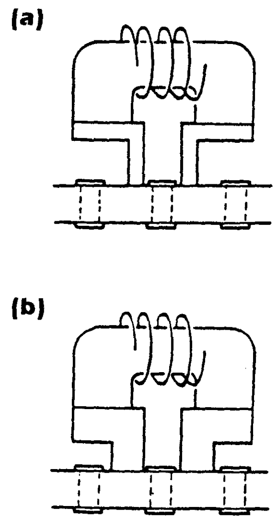


FIGURE 10. Correct positioning of pole pieces: (a) cross section unnecessarily reduced by pole pieces; and (b) greater cross section maintains less loss of field



may be filled with a disposable syringe. Such areas must be equipped with vent holes to allow air to escape and rubber to completely fill the cavity. These vent holes must often be closed with tape or putty after filling to prevent escape of the rubber compound.

Magnetization commences and must be completed in the allotted time. Allow the magnetic rubber to cure for the time specified by the chosen formula. Avoid movement of the test object and contamination of the magnetic rubber during the cure period. To determine that the magnetic rubber is completely cured (tack free), lightly touch the replica or the mixture remaining in the mixing container.

To remove the replica, first remove tape, aluminum dam, duct sealer putty and central conductor dam assembly, then carefully extract the replica from the test area. The replica must be identified by a tag or label or by placing it in a labeled container.

The replica is then visually examined for its condition and discontinuity indications. A low powered microscope may aid in this process. After inspection, test objects may be demagnetized and cleaned with solvent or vapor degreased if necessary.

Archival Quality of Magnetic Rubber Records

The magnetic rubber technique is not a means of recording indications from a typical magnetic particle test. It is a different test procedure, requiring its own test parameters and its own specialized equipment.

One of the advantages of the method is that it provides a permanent replica of the test object surface as well as the particle discontinuity indications. This record may be retained intact for as long as space is available. Magnetic rubber replicas may also be photographed for archival purposes.

PART 6
PHOTOGRAPHY OF MAGNETIC PARTICLE TEST INDICATIONS

Photography is the recommended method for making high quality recordings of magnetic particle test indications, but it is by no means the simplest or least expensive method. Test indication photography is not a point-and-shoot procedure. Specialized equipment is required and the photographer must have a good working knowledge of test object characteristics and magnetic particle testing procedures.

Empirical data are critical to successful indication photography. Considerable experimentation and reshooting is often necessary to obtain quality results, even with appropriate equipment and operator knowledge.

For these reasons, indication photography is normally a labor intensive and expensive recording method. The technique is cost justified because it produces very high quality recordings. Often it is the only method capable of providing the results needed for publication, instruction or permanent records. Figure 11 is a typical photograph of visible magnetic particle indications. Figure 12 is a photograph of fluorescent magnetic particle indications.

One of the difficulties in indication photography is the difference between test result size and test object size.

FIGURE 11. Visible light photograph of a dry magnetic particle indication on a crane hook

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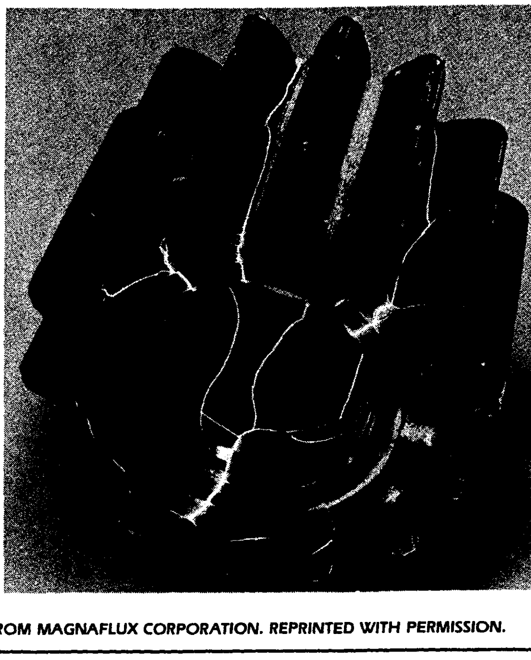
Typical test indications can occupy small areas on comparatively large test objects and it may be possible to accurately record either the entire object configuration or the test indication, but not both in the same frame. It may be necessary to photograph the test object and the test indications separately, with guide marks on the test object. Another solution is to photograph the test object in part, but with sufficient visual detail to show the location and orientation of the indications. Separate close-up photographs are then made to accurately record the test results.

Another difficulty comes with fluorescent test indications. Many magnetic particle tests use particles that are excited by near ultraviolet light and emit fluorescent visible wavelengths. The inspector's eye is sensitive only to the particles' emitted wavelengths, not the ultraviolet light. However, many camera films and photodetectors are sensitive to

FIGURE 12. Ultraviolet photograph of fluorescent wet method indications on a gear



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ultraviolet wavelengths emitted by the light source. If a camera is to record only what the eye sees, then special filters must be used. Producing ultraviolet photographs is a very specialized procedure. Once the technique is learned, it is possible to produce accurate and impressive photographs of fluorescent particle indications.

Cameras for Indication Recording

The most important feature of a camera used for indication photography is the ability to take close-up photographs. This capability is a product of the camera's physical configuration and its lens. Close-up photographs may be taken with a macro lens, bellows or extension rings. Close-up photography also requires that the photographer know exactly what is in the frame and what is in focus. Reflex and view cameras provide this ability while other types do not.

Built-in light meters are another valuable characteristic of cameras used for indication recording. Such meters are standard on many 35 mm systems, but completely automated cameras should be avoided. Because indication exposure parameters are far from normal, most automated cameras must be used in the override mode, allowing manual control and compensation for the extreme conditions.

Accessories for Indication Recording

Lenses

The best lenses for indication photography are those classified as *normal* or *mild telephoto* (50 to 135 mm focal length in the 35 mm format). Wide angle lenses produce distorted images at the short camera-to-subject distances required for small indications. Furthermore, it may be necessary to place a wide angle lens so close to the subject that it prevents proper lighting.

Long telephoto lenses are not often used because their small depth of field sometimes prevents clear focus on the entire area of interest. A long lens is necessary only if it is impossible to closely approach the test object or the particle indication.

Fast lenses are of no particular advantage — most indication photography is done at *f*5.6, *f*8 or even smaller lens openings in order to get acceptable depth of field.

Equipment Supports

Some sort of camera support is usually necessary for test indication photography. This could be a standard tripod, clamp or copy stand. Support is needed because exposures are long in this application and camera movement can be a problem.

Even when a flash unit is used, a camera support allows control of composition and focus while releasing the shutter. In addition to the support, a cable shutter release is recommended for indication photography because it will virtually eliminate camera movement when tripping the shutter.

Choosing Film for Indication Recording

Indication photographs can be made on nearly any kind of film, regular or instant, black and white or color. Special ultraviolet and infrared films are not necessary and are often inappropriate. Even photographs of fluorescent indications rely on visible light and the film must respond to visible light very much as the eye responds.

For highest definition, slower fine grained films are chosen unless exposures become excessively long and a compromise is struck. If there is a choice, exposure indices between 100 and 500 ASA are used. The most common exception is 3000 speed black and white instant film. This is commonly used for quick record photographs not intended for publication.

When using color film, daylight types are normally chosen unless visible indications are being photographed under incandescent (photoflood) illumination. Flash units emit light of approximate daylight balance and natural light requires daylight film. Fluorescent indication photographs are also better with daylight balance film because it has a lower sensitivity to the visible blue and violet light emitted by most ultraviolet sources. Incandescent balance films are very blue sensitive to compensate for the yellowness of the typical incandescent source. Ultraviolet photographs made with incandescent films tend to have an overall blue-green cast.

Instant Films

Instant films may be effectively used for archival indication photographs. Instant film can be chosen from a variety of speeds, color or black and white, depending on the requirements of the testing application.

In some cases, instant films are used to set up the final regular film exposure. Subject, camera and lighting are arranged for the record photograph and a trial exposure is made on instant film. The instant film may be in a different camera or it may be part of a *preview* or *proof exposure pack* mounted on the back of the camera body.

The photographer examines the proof and makes necessary corrections before taking the archival exposures. Much time and expensive film is saved by this procedure. It is very difficult to predict exactly what an indication photograph will register without some sort of trial or extensive exposure bracketing.

Filters for Indication Photography

Filters are often used in indication photography because the available light is seldom what is needed. The purpose of filters is to remove unwanted light or to correct the color balance of the light in use. When using filters, there is a loss of light transmitted to the film and this must be compensated by longer exposure.

Filters for Visible Light Photography

Filters are used with visible light photography to alter color balance, improve contrast and produce special effects. This is a voluminous subject well documented in the literature.

One visible light filtering technique is especially important for test indication recording: the use of polarizing filters to reduce highlights and reflections. Reflections are often a problem with magnetic particle test methods because the test objects are often metallic and highly reflective.

The effect of the polarizing filter is varied by its angle of rotation. If the camera is a reflex or view model, the polarizing effect is seen through the viewer. Otherwise, a manual orientation of the filter is required. Remove the filter from the camera and, staying as close as possible to the expected camera position, view reflections off the test object through the filter while rotating the filter in front of the eye. When the proper filter orientation is determined, the filter is reinstalled on the camera in that position and the exposure is made.

Filters for Fluorescent Indication Photography

Photographic films are responsive to ultraviolet light and this causes serious photographic problems unless the ultraviolet wavelengths are filtered out. Fluorescent indication photography is only possible if a ultraviolet absorbing, visible transmitting filter is placed over the camera lens.

A further requirement for such a filter is that it not be fluorescent itself. A fluorescent filter used in an ultraviolet environment causes fogging of the film image. Since the light emitted by fluorescent indications is visible light, the filter should not change the apparent color of this light, unless the change is done intentionally for special effect.

The filters normally used for indication photographs are called *ultraviolet filters* or *haze filters*. Some of the best are gelatin filters. These are sheets of plastic or acetate containing carefully controlled amounts of dye to produce the desired light transmission. They are produced in sizes from 50 × 50 mm (2 × 2 in.) to 350 × 450 mm (14 × 18 in.). Gelatin filters are sometimes available from commercial photography stores but more often they must be ordered from a manufacturer.

Gelatin filters can be mounted in a filter frame that attaches to the camera lens. For occasional use, they may also be taped over the lens. Gelatin filters are not durable accessories. They are easily scratched or contaminated and are not easily cleaned. In addition, they have little heat resistance and some types fade after extensive exposure to light. Gelatin filters must be inspected and replaced regularly, but they are excellent for their purpose if their limitations are not exceeded.

Types of Photographic Filters

The filters listed below are typical of those produced by many manufacturers and are representative of the types of photographic filters useful for recording magnetic particle test indications (see Table 3 and Fig. 13).

A valuable filter for this kind of photography is one designed to cut off wavelengths at 405 nm. Such a filter transmits no ultraviolet and almost no violet light. It shows test indications in their normal color but does not show the test object very well unless sufficient ambient light is present. The 405 nm filter is excellent when test indications are small and much ultraviolet light is used. It is also a good filter when highly reflective surfaces are present or when the test object has a slightly fluorescent coating. The 405 nm filter can be used with fluorescent tube sources that emit considerable amounts of visible blue and violet light.

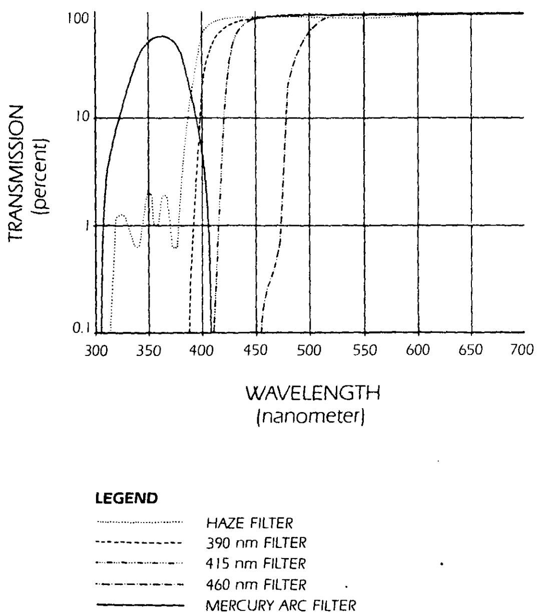
The best all around filter for fluorescent indication photography cuts off at 390 nm and passes the violet 405 nm band of a mercury light source. This band is visible to the eye and the filter uses it to photograph the test object and make it visible along with the indications. The result is a picture closely resembling the image seen by the eye in a

TABLE 3. Filters for fluorescent magnetic particle indication photography

Cut-Off Wavelength (nanometers)	Manufacturers			
	Kodak	B+W	Tiffen	Rolyn
390	2B		UV-15	65-1290
405	2A	420	Color Haze 2	
415	2E	021		65-1300
420	3		Color 3	65-1305
450	4			65-1310
460	8 (K-2)	022	Color 8	

NOTE: FILTERS NOT LISTED ABOVE, INCLUDING KODAK 1A AND B+W 409 FILTERS, MAY TRANSMIT TOO MUCH ULTRAVIOLET LIGHT FOR FLUORESCENT MAGNETIC PARTICLE INDICATION PHOTOGRAPHY

FIGURE 13. Transmission curves of filters used for fluorescent indication photography



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darkened testing booth. This realistic image is produced without a supplementary visible light exposure to show the test object. The high ultraviolet light levels needed to bring out small indications can result in overexposures with this filter. Also, if the background is slightly fluorescent, the 390 nm filter does not provide sufficient contrast.

A pale yellow filter is available to cut off exposures at 415 nm. It does not transmit the 405 nm violet that often produces the image of the test object. Unless the test object is slightly fluorescent or the source contains some blue or green light, only the test indications are shown with the 415 nm filter. If the test object should be photographed, a separate white light exposure is necessary. The 415 nm filter does not alter the color of the indication so it is the correct filter if fluorescent tube sources are used or if background fluorescence is present.

A light yellow filter is designed to cut off exposures at 420 nm. It is similar in use and effect to the 415 nm filter except that it also partially reduces blue wavelengths and makes test indications appear more green. The 420 nm filter may be used where this effect is desired or with black and white film records.

A sharp cut yellow filter limits exposures at 450 nm. No blue is included and indications appear unnaturally yellow. This filter is best restricted to black and white exposures where its background limiting properties may be useful. A separate white light exposure is necessary if the test object is to be photographed.

Another yellow filter has been designed to cut off at 460 nm and to reduce blue-green light at the same time. Indication colors are heavily altered and the test object is not visible at all without a separate white light exposure. The 460 nm filter may be used for black and white work if only the indications must be recorded or if additional visible light exposures are acceptable for photographing the test object.

Other Haze Filters

Many commercial glass covered and ring mounted filters are sold as haze filters. Most of these are a glass sandwich that may be threaded into a filter mount on the camera lens. Some such filters (usually called 1A filters) cannot always be used for recording magnetic particle test indications because they transmit too much ultraviolet light.

However, some commercial haze filters can be used if they are designed to limit the proper wavelengths. It is recommended that test exposures be made to verify the results of a new filter in its intended application. Glass haze filters can have several practical advantages. They are more convenient to use, easier to keep clean, more heat resistant and they last much longer than gelatin filters. Glass filters do not often require markedly increased exposures and they do not noticeably change the color balance of the final photographic image.

Polarizing Filters

In most instances, polarizing filters do not transmit ultraviolet light and can be used in fluorescent indication photography. However, they only transmit 10 to 25 percent of the visible light and greatly extend the lengthy exposure times necessary for fluorescence photography. Polarizing filters can be used if an ultraviolet filter is not available or to reduce blue reflections from a shiny test object.

Figure 13 shows the light transmission of several filters often used for fluorescent indication photography.

Exposure Estimation and Metering

The light meter built into a typical 35 mm camera helps determine proper exposure. Some meters set exposure speed at a chosen lens opening, while other meters set lens opening for a chosen shutter speed. This is a reciprocal relationship: more light from the aperture requires less speed from the shutter. The light meter establishes this relationship by averaging the light striking the whole frame. The light values from the center of the scene are often preferentially weighted by the meter.

Visible Indication Exposures

Visible indication photography requires normal exposures with certain adjustments. Exposures can be estimated with a typical exposure meter but often the meter must be overridden to obtain the desired result. This occurs because the test object (typically filling the frame) is a monotone and is often at a brightness level the meter is not designed to read. Most photographic light meters are designed to give proper exposure of a *17 percent gray* scene. This compromise gray value is a medium tone. In recreational photography, light subjects such as snow or water scenes are underexposed if photographed at the meter settings; dark scenes have overexposed light areas.

Since test objects are mostly monotones and test indications are a very small part of the total area, it is necessary to adjust the exposure to make the subject appear natural. A grayish test object reflecting 15 to 20 percent of the light striking it should be exposed as the meter indicates. A very light colored test object reflecting 70 to 90 percent of the light striking it should be exposed two *f*-stops over the metered value. For example, changing a recommended *f* 11 to an *f* 5.6 setting increases the aperture opening, admits more light and properly exposes a dark test indication in a bright field. A very dark test object reflecting 5 to 10 percent of the light should be exposed one or two *f*-stops under the metered value.

Exposures must be set to compensate for the filters being used. This is done by the meter when using a reflex camera with through-the-lens metering. Otherwise, position the same filter over the meter or use recommended compensation factors to determine exposure settings. Documentation from the filter manufacturer can also recommend exposure changes for the filters in question.

Fluorescent Exposures

Fluorescent indication photography requires more experimentation to get proper exposures from a test indication. Proof exposures are required because of broad variations in the photographic parameters: (1) incident ultraviolet intensity, (2) test object surface reflection, (3) fluorescent background and (4) indication brightness.

Light meters register the visible light emitted by fluorescent particle discontinuity indications. The best estimation of exposure is obtained from a typical light meter equipped with the same type of ultraviolet filter used on the lens. The problem with this is that the measured light intensity may be so low that the meter is not sensitive enough to read it. The ultraviolet intensity can then be increased or estimated mathematically.

Long exposures must be expected for fluorescent indications, particularly since the lens opening should never be larger than *f* 5.6. Limiting the *f*-stop provides adequate sharpness (depth of field) over the pictured area of interest. Even with ASA 400 film, exposures are seldom less than 1/8 second. In many cases exposures are two minutes or more. For this reason, fast films are often chosen at the expense of high grain in the image.

Proper exposure is less difficult for black and white recording, because there is no concern for color accuracy. In color photography, underexposure *and* overexposure can produce images of an indication, but the color will be inaccurate. Underexposed indications usually appear bluish, regardless of their actual color. Overexposed indications are pale or even white.

Changing Exposure Time

Changes are commonly made to exposure time (shutter speed) rather than to the lens opening. For magnetic particle test indications, the aperture is usually limited to *f* 8 and is no larger than *f* 5.6, for proper depth of field. Because of the reciprocal nature of photographic exposures, the remaining option is to change the exposure time. Start at one-half second, make another exposure at one second and possibly another at two seconds.

Most cameras do not automatically time exposures longer than one second. Longer exposures are made by using the *B* setting and timing the exposure manually. Unfortunately, it is difficult to accurately time exposures less than four seconds. Therefore, exposures in the one to four second range should be avoided by using a smaller lens opening and an exposure of four seconds or more.

Reciprocity Failure

Reciprocity failure is a problem caused by the long exposures needed for indication photography. The reciprocity law states that the optical density of a developed photograph is directly proportional to the exposure time and the illumination. Decreases in illumination require corresponding increases in exposure time, and vice versa. Films are balanced for exposure times between 1/10 and 1/1,000 second because most exposures are made in this range. Longer or shorter exposures result in changes of effective exposure index, color balance or both.

Long exposures typically result in a lower exposure index. However, the color balance changes that occur may or may not be compensated by longer exposure. In some cases, only a filter can correct color balance. The only way to ensure proper technique is to run a proof test, making careful notes of all conditions. Once the results are seen, corrections can be made for the archival exposures. This is a tedious and expensive process that should be used only if high quality photographs are required.

Bracketing Exposures

Indication photography is more difficult than scene photography and is typically much less predictable. Even experienced photographers find it necessary to bracket exposures to ensure accurate representations of a test indication. *Bracketing* is the exposure of additional frames with increased or decreased *f*-stops to compensate for unforeseen conditions.

Most photographers routinely bracket critical shots, time and conditions permitting, since the cost of the additional film is much less than the cost of reshooting the session. Bracketing can be safely omitted when the exposure is one of a series done under identical conditions with well known results.

Visible Indication Bracketing

Visible indication photography generally needs little bracketing because meter readings are more trustworthy in this application. A normal visible bracketing series includes a shot with one *f*-stop increased exposure and another with one *f*-stop *decreased* exposure in addition to the shot at the calculated or metered exposure.

The calculated exposure is the exposure including all necessary compensations. Note that moving one *f*-stop doubles or halves the exposure. Photographic films are relatively tolerant of errors smaller than this and smaller increments are necessary only in the most critical cases.

Fluorescent Indication Bracketing

Fluorescent indication photography is much less predictable than visible indication photography and more bracketing is required to ensure a good result. Experience can reduce the amount of bracketing required but at least one or two bracket exposures are typically needed for each subject.

If the test indications are large and bright, one additional shot at one *f*-stop *decreased* exposure may be made. Average size or small indications can often dispense with this decreased exposure. With fluorescent test indications, always make one additional exposure at one *f*-stop *increased* exposure. It is recommended that a second bracketed exposure be made at two *f*-stops increased exposure. For added assurance, still another exposure can be made at a three *f*-stop increase.

Lighting for Test Indication Recording

Daylight Sources

Lighting techniques and light sources are extremely important in photography. The preferred light source for visible test indication photography is daylight. It is readily available, of sufficient intensity, and evenly distributed. Its character does change depending on whether it is direct sunlight, cloud obscured or in shade.

Incandescent Light Sources

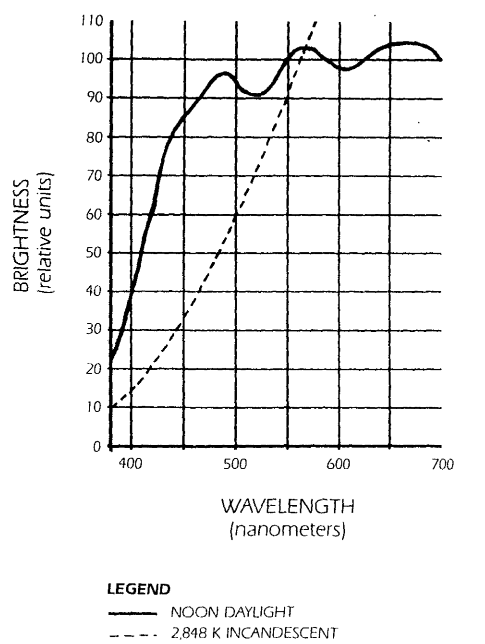
Incandescent light is usually produced by tungsten filament lamps. It is readily available and often of sufficient intensity. Its color varies according to the temperature of the filament but it is always yellower than daylight or fluorescent light. When using incandescent light with color film, special color balance film is required or special blue filters are needed over the lamp or over the camera lens.

Figure 14 shows the spectral distribution of daylight and incandescent sources used for magnetic particle test indication photography.

Fluorescent Light Sources

Fluorescent lamps produce light by bombarding gases with electrons from a cathode and producing ultraviolet energy. This energy excites a fluorescent coating inside the tube which in turn emits several wavelengths of visible and

FIGURE 14. Typical spectral distribution of noon daylight and incandescent light



invisible light. Fluorescent lamps have adequate intensity and very even distribution but their color balance is different from all other sources.

Fluorescent light appears white to the eye but it has a very green tint on film. Filters are available to correct this light to approximate daylight. The filters are a purple color and should always be used when making color photographs under fluorescent light.

Sources for Fluorescent Indication Photography

Fluorescent indication photography is normally done under illumination provided by *mercury vapor* ultraviolet lamps. These lamps are often used for inspection of magnetic particle test objects and may be spot lights or flood lights. For fluorescent photography, the lamps are equipped with a black glass filter that cuts off all visible light except a small amount of violet. Such lamps are often used without a filter for space illumination in factory areas and it may sometimes be necessary to photograph visible indications using this source. Such light is extremely blue and a yellowish filter is required to obtain proper color balance with color films.

Mercury arc ultraviolet sources are often highly directional and spotty when photographed. They illuminate the area of an indication well but may not produce enough distributed light to photograph the rest of a large test object. In such cases, it may be necessary to use a visible light double exposure to show the test object. If this is done, the test object must be underexposed in visible light to retain good images of the indications. Such visible light exposures are made at least two *f*-stops less than normal exposures.

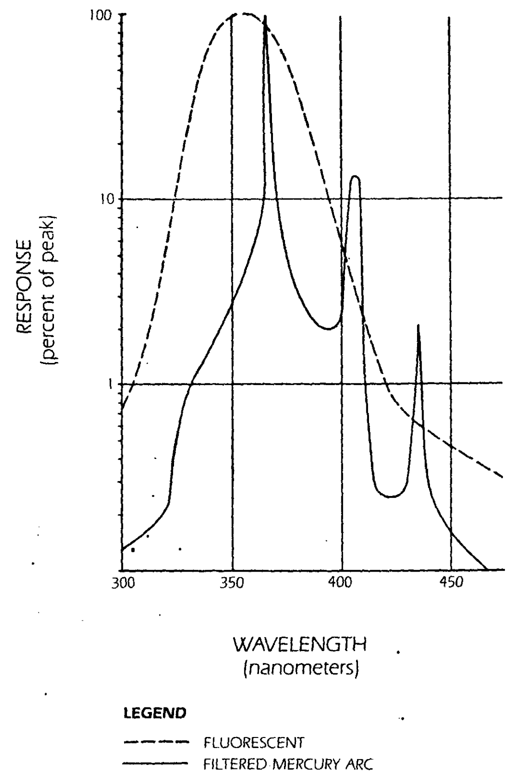
Tubular Black Light Sources

Another light source used for fluorescence photography is sometimes called the *tubular black light*. These are standard fluorescent fixtures equipped with special bulbs containing an ultraviolet emitting phosphor enveloped in ultraviolet transmitting black glass. Such lamps produce a majority of their light in the near ultraviolet spectrum but they also have a considerable output of blue and violet visible light. Their output is not focused so that they illuminate a large area without high intensity in any one spot.

Tubular sources can produce an acceptable photograph of a large area containing large, bright test indications, particularly if the camera is equipped with a filter that cuts off violet light. Such sources are not good for small or dim indications because: (1) they have low spot intensity; and (2) their large visible light output cuts contrast.

Figure 15 shows the spectral emission of several ultraviolet light sources often used in magnetic particle testing.

FIGURE 15. Spectral distribution of mercury arc and fluorescent light sources



Developing Procedures for Test Indication Photographs

Films containing indication photographs can be developed with normal procedures. Special techniques are not necessary although they can be used for some special effects. Color prints produced by commercial processors may be a problem because their processing procedures are often color compensated and based on an easily recognized feature of at least one shot in the series. Few indication photographs have any feature easily recognized by a photoprocessor and color compensation may not be accurately performed.

Instant color films are used for indication photography even though they are subject to serious reciprocity failure at the long exposures needed for fluorescence photography. Normal developing of these films produces a very blue picture. This can be corrected by using one-half to three-quarters of the recommended developing time.

Archival Quality of Indication Photographs

Photographs of magnetic particle test results have two distinct advantages. When properly exposed, photographs have the highest quality reproduction of any of the recording methods.

In addition, photographs can show much more than just the indication's particles. The test object can be completely pictured, with the particle indication in position. The indication's size, shape and intensity can be seen and it is this abundance of information that most recommends the photographic recording method. If stored with a minimum of care, photographs have an indefinite shelf life.

Electronic Recording Techniques

Electronic imaging is regularly used as a test indication recording medium. Black and white and color television cameras have the sensitivity needed to record visible or fluorescent test indications. Sufficient lighting and filtering of unwanted ultraviolet wavelengths are requirements shared with still photography. It is often necessary to adjust illumination levels to obtain the necessary quality for video recordings of test indications.

Video tape exposure time is basically fixed so that the camera's aperture size and gain setting are the controls to adjust for improved exposure. Video tape has a somewhat different color sensitivity than the eye or still films and filtering is adjusted for the individual camera system and the recording conditions. Ultraviolet filtering can be achieved with the same filters used on still cameras.

One distinct advantage of recording discontinuity indications on video tape is the availability of subsequent image processing. Television images may be digitized and processed by computerized image data analysis procedures. These programs are designed to enhance contrast, isolate indications, differentiate signal from noise or use indication characteristics (image density, size or shape) to help determine if an indication is a valid representation of a discontinuity. Automated magnetic particle testing systems use digitized image enhancement as the first step in interpreting test results and determining the actual condition of the test object.

Conclusion

The magnetic particle test method produces visible indications of surface and slightly subsurface discontinuities in ferrous test objects. These indications are visible to the eye in size and location, but they are not durable. If records of magnetic particle tests are necessary, additional procedures for recording the indications are required.

This text summarizes some of the techniques commonly used to produce test records. The inspector must choose a method appropriate for the particular application and must then become proficient in its use. In some cases, new recording procedures must be developed.

In one case, a combination photographic record was required to show the visible outline of the test object and the fluorescent test indications. Because double exposures are difficult with modern cameras, a single exposure was made. Using a polarizing filter and the camera's *B* or bulb setting, the lens was opened in the presence of ambient visible light and a two second exposure was produced. The visible light was then removed and a handheld ultraviolet source introduced to expose the particle indications on the same frame.

This kind of recording may be a unique application, but it is indicative of the flexibility available to the magnetic particle inspector. There are many recording techniques, from drawings and tape transfers to alginate impressions and photography. Each should be considered for certain indication recording situations, and each can be adapted in its own way for producing successful magnetic particle testing archives.

SECTION 12

DEMAGNETIZATION OF TEST OBJECTS

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PART 1
DEMAGNETIZATION AND RESIDUAL MAGNETISM

Demagnetization is the process of removing magnetism from a ferromagnetic material. This is accomplished on the molecular level by establishing or reestablishing random orientations in the material's magnetic domains.

The demagnetizing process is often required in conjunction with magnetic particle testing. However, demagnetization may also be required for reasons other than magnetic particle tests.

Ferromagnetic Materials

Ferromagnetic materials are characterized by a relative ease of magnetization when exposed to a magnetizing force. This can be attributed to the relatively high magnetic permeability μ exhibited by these materials. Once magnetized, ferromagnetic material retains a level of magnetic flux density B after the magnetizing field strength H has been removed. This remanent flux density is commonly referred to as *residual magnetism* or the *residual field*. The magnitude of residual flux density is a function of the following factors: (1) the magnetic characteristics of the material; (2) the immediate history of the material's magnetization; (3) the strength of the applied magnetizing field; (4) the direction of magnetization (longitudinal or circular); and (5) the test object's geometry.

Residually magnetized materials contain magnetic flux Φ measured in webers. In the International System of Units (SI), 1 weber (Wb) passing through 1 m^2 gives a flux density of 1 tesla (T). In the centimeter-gram-second (cgs) system, flux is expressed in maxwells or lines of flux. Flux density is expressed as lines per square centimeter or gauss (G). One weber is equivalent to 10^8 lines and one tesla equals 10^4 gauss.

Depending on the direction of the flux with respect to the surface of the test object, these lines may leave the object at one point and continue their path through air before reentering at another point. The points where magnetic lines of flux leave and reenter a ferromagnetic material are called *magnetic poles*. The north pole is where flux lines leave the material. Flux lines reenter the material at the south pole. Such fields emanating from a test object are called *leakage fields* and are the phenomena responsible for attracting nearby magnetic particles.

Requirement for Demagnetization

Components that retain a relatively strong residual flux density can be a source of problems during subsequent manufacturing processes or during service. Some typical problems are detailed below.

When subsequent machining is performed on a test object, the presence of a strong residual flux density can attract and hold chips or particles. This can adversely affect surface finish or tool life.

In an arc welding operation, the presence of strong leakage fields can deflect the arc away from its intended location. This phenomenon is sometimes called *arc blow*. Electron beam welding is also adversely affected by residual magnetism. Even leakage fields of moderate strength can deflect the electron beam away from its intended target.

Plating quality also can be affected by residual magnetism. In an operation such as chrome plating on a steel surface, the presence of a strong residual magnetic field can divert the plating current away from its intended location. Such mishaps are costly, incorporating the expenses of the first faulty plating, possible repair and a second plating operation.

In-service operation of an object may be impaired if it is the source of excessive leakage fields, attracting metallic chips or tramp particles. This condition can cause malfunctions in rotating assemblies such as bearings or excessive wear on bearing surfaces. Strong residual flux densities also may cause a substantial magnetic attraction between adjacent moving parts. This can produce increased friction or may in other ways interfere with the intended function of the component.

Cleaning operations for the removal of metallic chips and particles can be hampered by the presence of residual fields. This can be of special concern when cleaning objects that have internal openings such as oil passages.

Residual leakage fields can have a direct adverse effect on certain types of instrumentation. The magnetic compass aboard aircraft is an example, as are many electronic components.

Rotating shafts containing residual magnetism may act as electric generators in conjunction with the Earth's magnetic field or other stray fields. The generated electricity can heat the shafts, causing operating losses and other service problems.

Finally, objects sometimes need to be demagnetized before using established magnetizing current levels for magnetic particle testing. The presence of strong residual induction can lead to erroneous results and faulty test procedures.

Demagnetization is *not* required when the test material exhibits very low magnetic remanence. Low carbon or nodular steels are included in this category. If the next manufacturing process calls for the object to be heated above the Curie point, the material becomes nonmagnetic and demagnetization is accomplished by the heating process. At the Curie point, steel temporarily transforms from a ferromagnetic to a paramagnetic state and subsequently cools with zero net induction.

If the part does not require additional machining and its intended function is not compromised by the presence of a residual field, then demagnetization becomes unnecessary.

Common Sources of Residual Magnetic Fields

Ferromagnetic material can become magnetized in a number of ways, intentionally and unintentionally.

Parts may be purposely magnetized to perform magnetic particle tests or to facilitate a magnetic flux leakage test. Magnetization may also come from biasing magnetic fields such as those used to negate the effects of permeability changes in eddy current tests.

Magnetic chucks are a common source of residual fields. Pronounced fields can be left in an object if a chuck's built-in demagnetizing cycle is faulty or inadequate. Prematurely removing test objects before completion of the demagnetizing cycle can also be a source of residual magnetism.

Lift magnets are convenient material handling devices, but because they operate with direct current, they can leave strong residual fields in fabricated objects or in raw material. Physical contact with any permanent magnet or highly magnetized object (a machine table or fixture) can also establish a residual field.

Low frequency induction heating that is abruptly terminated can induce very strong residual flux density. The lower the frequency, the deeper the magnetizing field strength penetrates into the material.

With certain orientations of high amperage cables, an electric arc welding operation can magnetize ferromagnetic material.

Residual magnetization can occur with improper operation of alternating current through a coil demagnetizer. This occurs when the coil current is terminated and the test object is still within the coil or within its influence. Penetration depth is determined by the frequency of the alternating current.

Finally, under certain conditions the Earth's magnetic field can impart a longitudinal residual field. This occurs only with low coercivity steels, usually when the object is shocked or vibrated while its long axis is parallel to the Earth's magnetic field. Such a residual field may become quite significant for long parts subjected to severe vibrations in service or transport. The intensity (horizontal component) of the Earth's field in the United States is about 16 $A{\cdot}m^{-1}$ (0.2 Oe). This is equivalent to the magnetic field strength at the center of a five ampere-turn coil 300 mm (12 in.) in diameter.

Effect of Magnetic Field Origin on Demagnetization

The type of magnetizing source becomes significant when considering the nature of residual induction and its subsequent demagnetization.

Alternating currents tend to flow near the surface of a conductor and this so-called *skin effect* produces residual fields that are surface oriented. Such fields respond well to alternating current demagnetization techniques.

There is practically no skin effect associated with a direct current magnetizing source and consequently the entire cross section of an object can be residually magnetized. Deep seated residual fields in larger objects may not be affected by alternating current demagnetizing techniques because the skin depth is only about 1 mm for steel of relative permeability 100 at 60 Hz.

Types of Residual Magnetic Fields

Longitudinal Magnetic Fields

Materials magnetized by a coil or solenoid sometimes can be left with a longitudinal residual induction. The field is oriented lengthwise in the test object and there is a high concentration of emergent fields at each end. These fields constitute poles, lines of magnetic flux entering or leaving the material.

Longitudinal magnetization is easily detected by field measuring devices such as the gaussmeter or by the attraction of other ferromagnetic materials. While this type of field can adversely affect subsequent machining, it is usually very responsive to demagnetizing techniques.

Circular Magnetic Fields

Unlike longitudinal residual induction, circular residual induction can exhibit little or no external evidence of its presence. The flux may be entirely confined within the material, depending to some extent on part geometry and the magnetizing procedure.

For example, if magnetizing current is passed through a homogeneous length of ferromagnetic bar stock having a circular cross section, the resulting circular residual flux density is for all practical purposes undetectable without altering the bar in some manner. Virtually no leakage fields emanate from its surface because the magnetic flux path is closed within the object. Because of this, the internal residual flux density B may be much stronger than if the test object had been magnetized longitudinally in a coil or solenoid having a comparable magnetic field strength H.

The circular residual flux density becomes an apparent problem when the geometry of the object is altered by subsequent machining. For example, if a keyway is cut in a piece of shafting that is circularly magnetized, the circular field becomes quite evident. Strong leakage fields (north and south magnetic poles) occur on either side of the keyway. All holes or slots cutting through a circular field produce magnetic poles that can attract materials such as chips or dust from subsequent machining.

Without special equipment, demagnetization of a circularly magnetized object can be very difficult. Confirmation of an adequate demagnetization level is an additional problem. Leakage field measuring devices are ineffective since there may not be an external leakage field to monitor. In this case, reorientation of the circular field into a longitudinal field prior to demagnetization may be advantageous in some instances when such a procedure is compatible with part geometry and size.

Multiple Magnetic Poles

Multiple magnetic poles can be induced in and retained by ferromagnetic material that has been exposed to direct current magnetization, as in a magnetic chuck or lift magnet. These fields can be pronounced and take the form of alternate north and south poles at relatively close intervals. Demagnetization of multiple poles may be difficult using conventional alternating current through-coil procedures.

PART 2
PRINCIPLES OF DEMAGNETIZATION

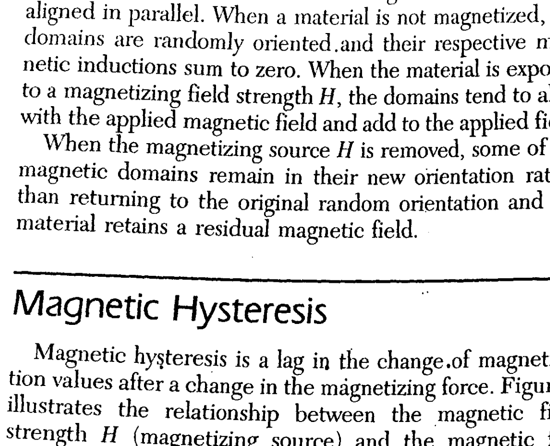
Ferromagnetic material differs from other material in that it contains magnetic domains, localized regions in which the atomic or molecular magnetic moments are aligned in parallel. When a material is not magnetized, the domains are randomly oriented and their respective magnetic inductions sum to zero. When the material is exposed to a magnetizing field strength H, the domains tend to align with the applied magnetic field and add to the applied field.

When the magnetizing source H is removed, some of the magnetic domains remain in their new orientation rather than returning to the original random orientation and the material retains a residual magnetic field.

Magnetic Hysteresis

Magnetic hysteresis is a lag in the change of magnetization values after a change in the magnetizing force. Figure 1 illustrates the relationship between the magnetic field strength H (magnetizing source) and the magnetic flux density B (level of magnetization). When an unmagnetized material is magnetized by gradually increasing H from zero to $+H_m$, the level of magnetization B increases along the virgin magnetization curve to a maximum value corresponding to $+B_m$.

FIGURE 1. Magnetic hysteresis curve



As H is reduced to zero, the level of B falls to $+B_r$ rather than zero. This level of retained magnetization ($+B_r$) is the remanent or residual field remaining in the material. As negative values of H (opposite polarity) are applied, the curve passes through $-H_c$ and on to $-H_m$ and reaches a magnetization level of $-B_m$. Reversing the applied field to a value of $+H_m$ completes the magnetic hysteresis loop.

Retentivity and Coercive Force

The value H_c is the coercive force and is an indicator of the difficulty involved in demagnetizing a material. The value of B_r is the material's retentivity and indicates the residual induction within a section of the material. As a rule, high coercive forces are associated with harder materials and low coercive forces with softer materials. Therefore, harder materials usually offer more resistance to demagnetization and require a higher demagnetizing field than softer materials.

No definition has been made for the dividing line between hard and soft materials. However, if $H_c \geq 8{,}000$ A•m^{-1} (100 Oe), then the material is typically considered hard. If $H_c \leq 400$ A•m^{-1} (5 Oe), then the material is considered soft. Coercive forces as large as 8×10^5 A•m^{-1} (10^4 Oe) and as small as 0.08 A•m^{-1} (10^{-3} Oe) have been observed.

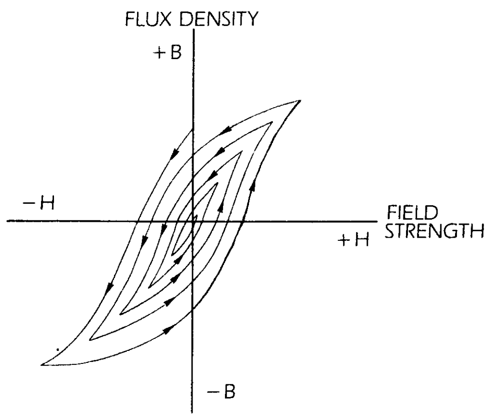
The fact that an object retains a strong residual field B_r is not necessarily indicative of a high coercive force H_c. Some materials retain an appreciable residual induction and yet are easily demagnetized (transformer steels are an example). On the other hand, some materials that retain relatively weak residual fields can be extremely difficult to demagnetize because of a high coercive force.

Basic Principle of Demagnetization

Practically all demagnetizing methods are based on a common procedure. A magnetizing field strength H, sufficiently high to overcome the initial coercive force H_c, is alternately reversed in polarity and gradually reduced to zero. The diminishing hysteresis curve shown in Fig. 2 illustrates this principle.

The value of the total coercive force H_c is often unknown and varies with proximity to the test object's ends. However,

FIGURE 2. Diminishing hysteresis curve



it is always less than the maximum magnetizing force H_m value. This may serve as a guide in cases where the magnetizing field strength H_m is known, as is sometimes the case in magnetic particle testing. Successful demagnetization procedures often start with an initial demagnetizing field which equals or exceeds that of the magnetizing force H_m.

An object may also be demagnetized by raising its temperature above the Curie point. Although this method provides thorough demagnetization, it is often impractical.

PART 3
SUMMARY OF DEMAGNETIZATION PROCEDURES

Alternating Current Demagnetization

Through-Coil Method

The simplicity of the alternating current through-coil method makes it one of the most prevalent demagnetization techniques. The method uses a coil powered from a current source alternating at line frequency (usually 60 Hz in the United States). Operating at a fixed amplitude, the coil produces a continuously reversing magnetic field because of the cyclic nature of the current. As a test object is conveyed through the coil, it is subjected to the most intense magnetic field while within the confines of the coil.

The strength of the field is gradually reduced to zero as the object exits the coil and reaches a point beyond the influence of the coil's field. The coil should not be deenergized until the test object has reached this point, three or four coil diameters away or about 1 m (3 ft). This rule applies to most demagnetizing coils in industry, where peak values of the field at the center of the coil are about 1.2×10^5 to 2.4×10^5 A•m^{-1}. Small test objects can be hand held, placed within the coil and withdrawn. Field penetration may be several skin depths.

The magnitude of the field can also be reduced by withdrawing a coil such as a cable coil away from a stationary test object. This method is advantageous for high production rates since a properly designed coil can be continuously energized while a steady stream of test objects is conveyed through the coil opening. Typical alternating current through-coil demagnetizers are shown in Figs. 3 and 4.

Demagnetization of test shims may be performed by removing them slowly from one pole of an alternating current yoke.

FIGURE 3. Manually operated alternating current coil demagnetizer with roller carriage and automatic timer

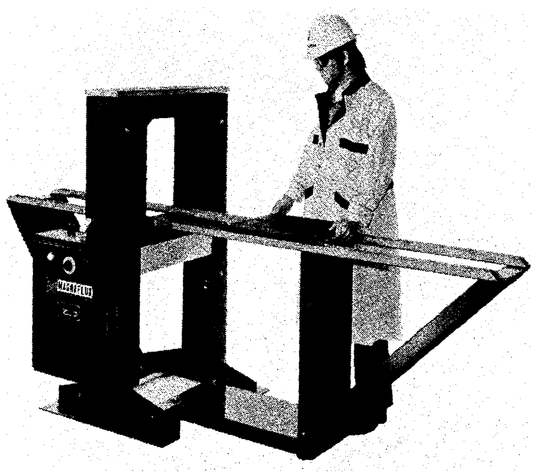


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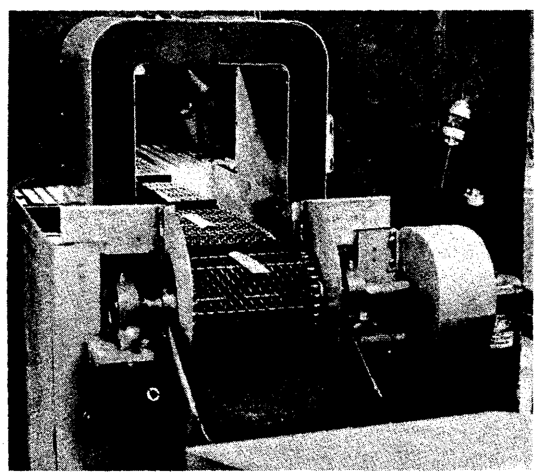
FIGURE 4. Production alternating current coil demagnetizer incorporated into conveyorized magnetic particle testing unit



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Cable Wrap Method

There are applications (such as large or immobile test objects) where a cable wrap, in conjunction with an appropriate high amperage alternating current power source, can provide a convenient means of demagnetization. The high amperage power source must also incorporate a suitable current control to facilitate the gradual reduction of current from maximum to zero.

Portable or mobile alternating current power packs are available for such applications. Equipment of this type usually features stepless solid state current control. Some units incorporate special current decay circuitry that automatically reduces the current from maximum to zero in a matter of three or four seconds.

Through-Current Method

Through-current demagnetization is a contact method. High amperage alternating current is caused to flow directly through a test object starting at contact electrodes. The current control system must provide gradual reduction of current as required for demagnetization. A portable alternating current power pack used for cable wrap demagnetization may also be used for the through-current method.

Through-current demagnetization is used on horizontal wet magnetic particle testing units that have comparable current control systems. Because of part configuration and the accessibility of alternating current, the through-current method can have real advantages for certain applications.

Direct Current Demagnetization

Reversing Direct Current Contact Coil Method

Reversing direct current contact coil demagnetization is usually associated with relatively large test objects that have been magnetized using a direct current magnetic field. It is also applicable in certain instances where alternating current demagnetization proves ineffective.

The method requires high amperage direct current or full-wave rectified alternating current that can be directed to a coil or contact plate. There must also be provisions for reversing the polarity of the current and suitable means for gradually reducing its amplitude to zero.

The direct current is alternately reversed in polarity (direction) and reduced in amplitude to zero. Although fewer steps may provide satisfactory results, greater reliability is achieved by using about thirty reversals and current reductions to approach zero asymptotically.

The cycle is usually controlled automatically and requires about thirty seconds to complete. When using a coil, the test object should remain stationary within the coil until the demagnetizing cycle has been completed. When the contact method is used, contact should be maintained until the cycle is completed. The direct current method provides deep penetration and is usually very successful on objects that are otherwise difficult to demagnetize.

Because of economic considerations, the reversing direct current demagnetizing feature is usually incorporated into the design of direct current horizontal wet magnetic particle testing units or relatively large stationary power packs.

Reversing Cable Wrap Method

This method is used for demagnetizing objects too large or heavy to process on a horizontal wet testing unit. The object to be demagnetized is wrapped with multiple turns of high amperage flexible cable (such as 4/0) connected to a stationary direct current power pack.

The current is alternately reversed in direction and reduced in amplitude through multiple steps until the current reaches zero. This is usually accomplished using built-in automatic circuitry similar to that designed into some wet testing units. Power packs that lack an automatic demagnetizing cycle can sometimes be used to accomplish demagnetization by manually interchanging cable connections (current reversal) and manipulating manual current controls (current reduction). However, this is time consuming and requires an appropriately fine current control to be successful.

Pulsating Reversing Method

A high amperage direct current coil demagnetizer has been designed to produce alternate pulses of positive and negative current. The pulses are generated at a fixed amplitude and a repetition rate of five to ten cycles per second. This permits relatively small objects to be demagnetized by the through-coil method.

The object is subjected to a constantly reversing magnetic field as it passes through the coil and the magnitude of the effective field is reduced to zero as the object is gradually withdrawn from the coil. This mode of operation is identical to the alternating current through-coil method described above, except for the reduced repetition rate (five to ten cycles per second compared to sixty cycles per second).

The lower repetition rate substantially reduces the skin effect with a corresponding increase in magnetic field penetration. Therefore, the method provides additional demagnetizing capabilities on some relatively small test objects with thick cross sections that are difficult to handle with line frequency coil demagnetizers. Another standard mode of operation allows the object to remain stationary within the coil while the current gradually decays to zero.

Specialized Demagnetization Procedures

There is a wide variety of miscellaneous demagnetizing techniques that have specific applications designed around a specific test object.

Demagnetization with Yokes

A yoke configuration is sometimes used to demagnetize small objects having high coercive force. Yokes are also used for demagnetization of objects with small length-to-diameter (*L/D*) ratios, including spheres with near-perfect *L/D* ratios of 1. Yokes are usually designed for a specific type or range of test objects.

Some alternating current yokes are similar in operation to the alternating current coil method, where the test object is passed between or across the surfaces of the pole faces (maximum field strength) and then withdrawn. Direct current yokes are sometimes used with the reversing direct current method on specific objects requiring deep penetration. However, this is an inherently slow process because of the associated high inductance of the circuit.

Some coil or yoke arrangements use damped oscillation to obtain the required reversing and diminishing field. The oscillation is derived from a special circuit design based on specific values of capacitance, inductance and resistance.

Demagnetization of Oil Field Tubes

Various testing processes involving direct current magnetization leave the test object with a significant longitudinal residual field. Demagnetization is usually required to eliminate any possibility of the field having an adverse effect on subsequent machining or welding operations. Some tubular products have lengths of 9 to 15 m (30 to 50 ft) and this presents a formidable challenge to standard demagnetization procedures. Some unusual methods have been used when facilities for overall (full length) demagnetization are not available.

One such procedure applies a bucking (opposite polarity) field at the ends of the object using a direct current coil positioned near the ends. By trial and error, magnetizing current to the coil is increased until external field readings are reduced to an acceptable level. The result is a redistribution of the field at each end of the tube. Unfortunately, mechanical agitation subsequent to this procedure, from handling or transport, can result in the redistribution of the longitudinal field and can reestablish strong leakage fields at the ends of the test object.

Another specialized demagnetization procedure uses a full length internal conductor in conjunction with a unidirectional current pulse to reorient the longitudinal field and form a circular field. The magnitude of the circularly magnetizing current is increased until acceptable external field readings are achieved. While this is *not* demagnetization, it does reduce leakage fields to a level suitable for butt welding operations. It also creates the undesirable conditions associated with circular magnetization and hinders subsequent operations, including weld preparation or threading.

Overall demagnetization is the best solution for long tubes and this is usually carried out using some form of reversing direct current. For static conditions, an internal conductor is used in conjunction with a conventional reversing direct current cycle. A cable, wrapped to give several internal conductors, could be used in place of the central conductor. However, when object's length is taken into consideration, the central conductor approach is much more time efficient.

The advent of pulsating direct current equipment has lead to dynamic demagnetizing systems for overall demagnetization of long test objects. In such systems, the object is conveyed through a special coil arrangement at speeds up to 1.5 m per second (300 ft per minute). The coil current consists of constant amplitude pulses of direct current alternating relative to polarity (positive and negative) at a rate of about five cycles per second.

PART 4

SELECTING A DEMAGNETIZATION PROCEDURE

Selecting a suitable demagnetization procedure is a matter of matching capabilities with the specific application. Each of the procedures discussed above has advantages and limitations based on test object size, hardness, production rate and source of magnetization (see Table 1).

Limitations of Alternating Current Methods

The alternating current through-coil method is probably the most widely used demagnetization technique because of its simplicity and its adaptability to high production rates. However, the skin effect associated with alternating current magnetic fields results in limited penetration capabilities. Consequently, alternating current demagnetization methods may be ineffective for removing deep residual fields such as those associated with direct current magnetization.

This becomes a significant factor on large test objects. As a rule, alternating current methods can effectively demagnetize most objects with a cross section less than 50 mm (2 in.), regardless of the original magnetizing source. Larger test objects with deep residual fields usually require some form of reversing direct current demagnetization. If alternating current is the only source of magnetization, alternating current demagnetization is effective regardless of test object size.

Maximum Effective Field Strength

The maximum effective field strength H_m of a particular demagnetization procedure is an important indicator of the procedure's capability. Basically, the H_m value must be sufficient to overcome the coercive force H_c associated with the material to be demagnetized. Generally, H_c increases with hardness.

Test object size and geometry (including the *L/D* ratio) are also factors that influence field strength requirements. The demagnetization potential of a procedure inherently increases with field strength capabilities. When related to various alternating current coil sizes with equal ampere-turn ratings, the field strength increases as coil size decreases.

Reversing Direct Current

Reversing direct current procedures are usually required when alternating current techniques prove inadequate. For those difficult applications, reversing direct current has unexcelled demagnetization capabilities. Almost any object can be demagnetized to an acceptable level with reversing direct current. While production rate capabilities are limited, this is usually not a significant hindrance; since larger objects are often involved, the associated production rates are relatively low.

TABLE 1. Demagnetizing method selection guide based on test object size, hardness and production rate for residual fields from direct current magnetizing source

	Test Object Size			Material Hardness			Production Rate		
	Small[1]	Medium[2]	Large[3]	Soft	Medium	Hard	Low	Medium	High
Alternating Current (50/60 Hz)									
Through-coil	A	Q	N	A	A	N	A	A	A
Cable wrap	N	Q	Q	A	A	N	A	N	N
Through-current (30 point step down)	N	A	N	A	A	N	A	Q	N
Through-current (current decay)	N	A	N	A	A	N	A	Q	N
Yoke	A	N	N	A	A	Q	A	N	N
Reversing Direct Current									
Through-coil (pulsating)	A	A	A	A	A	A	A	A	A
Coil (30 point step down)	A	A	Q	A	A	A	A	A	N
Cable wrap (30 point step down)	N	Q	A	A	A	A	A	N	N
Through-current (30 point step down)	N	A	A	A	A	A	A	Q	N

1. HAND HELD
2. LESS THAN 50 mm (2 in.) DIAMETER
3. MORE THAN 50 mm (2 in.) DIAMETER

LEGEND
Q = QUESTIONABLE
A = APPLICABLE
N = NOT APPLICABLE

PART 5
MEASURING EXTERNAL FIELD STRENGTH

In SI units, magnetic flux density B is measured in tesla or webers per square meter. In cgs units, magnetic flux density is measured in gauss or as magnetic lines of force per square centimeter. One tesla is equivalent to 10^4 gauss. In SI, the magnetic field strength H is measured in amperes per meter ($A{\bullet}m^{-1}$); in cgs, the unit is oersted (Oe). One ampere per meter is equivalent to 0.013 oersted.

Flux density and field strength are related to each other and to magnetic permeability by the following equation:

$$B = \mu_o \mu H \qquad \text{(Eq. 1)}$$

Where:

μ_o = the permeability of free space; and
μ = the relative permeability.

The value of permeability is not affected by the choice of units. Permeability values in customary units are the same magnitude as those of relative permeabilities in SI units. Because gauss and oersted have by definition the same magnitude in air, the μ_o factor is not used in the equation for customary units.

By itself, the permeability of a material has no meaning. Its value at specific values of H or B does have meaning.

Field Indicators

Theory of Operation

The field indicator is a hand held instrument used to measure the relative strength of magnetic leakage fields. The construction of a typical field indicator is shown in Fig. 5 and its theory of operation is relatively simple. As illustrated, an elliptically shaped soft iron vane is attached to a pointer that is free to pivot. A rectangular permanent magnet is mounted in a fixed position directly above the soft iron vane.

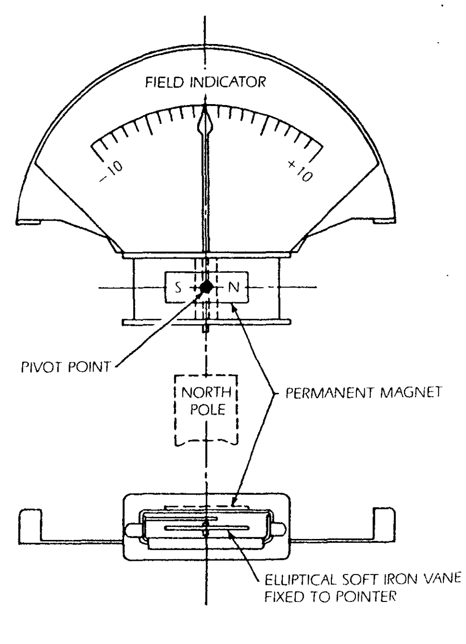
Because the vane is under the influence of the magnet, it tends to align its long axis in the direction of the leakage field emanating from the magnet. In so doing, the vane becomes magnetized and has a magnetic pole induced at each end of its long axis.

On the end of the vane below the south pole of the magnet, a north pole is induced. Correspondingly, a south pole is induced at the opposite end of the vane below the north pole of the magnet. In the absence of external fields, the pointer indicates zero on the graduated scale.

When the magnetic north pole of a residually magnetized object is moved close to the pivot end of the pointer, the south pole of the vane is attracted toward the object and the north pole of the vane is repelled. The resulting torque causes the pointer to rotate in the positive or plus direction. The restraining torque is provided by the tendency of the vane to remain aligned with the leakage field of the permanent magnet.

Sensitivity of the field indicator is primarily a function of the permanent magnet's characteristics and the spacing between the magnet and the vane. The device can be calibrated in relative units, milliteslas or gauss. Calibration is only valid when the device is subjected to a uniform

FIGURE 5. Typical magnetic field indicator construction.



magnetic field such as that found at the center of a large coil or Helmholtz coil arrangement.

The pattern of external fields emanating from a residually magnetized object is anything but uniform and varies with changes in part geometry. In view of this, readings obtained with a field indicator are effectively in relative units but still useful for comparative purposes.

Use of the Field Indicator

The relative strength of an external field is measured by bringing the field indicator near the object and noting the deflection of the pointer. The edge of the field indicator at the pivot end of the pointer should be closest to the object under investigation.

The required degree of demagnetization is usually specified as a maximum field indicator reading (in terms of divisions, tesla or gauss) for a specific device. Leakage field patterns of very small objects may be too limited for detection by a field indicator — the sensing element (soft iron vane) is located approximately 12 mm (0.5 in.) from the edge of the device's casing.

The field indicator is the most common device used in industry for monitoring the effectiveness of demagnetizing processes. It is convenient, easy to operate and inexpensive.

Laboratory Instruments

The Hall effect gaussmeter is the most common laboratory instrument used to measure the strength of leakage fields quantitatively. The sensing element is located in a remote hand held probe connected to the basic instrument by a flexible multiconductor electrical cable. This permits leakage field measurements right at the surface of a test object, and consequently, the readings are substantially greater compared to those obtained with a field indicator.

In the past, use of the gaussmeter was confined to laboratory work because of instrument cost, complicated operating procedures and the delicate nature of the probe. However, gaussmeters are now widely used in many ways, such as qualifying demagnetization procedures for small or unusual test objects; establishing maximum permissible field indicator readings; and verifying field indicator calibration procedures.

Measuring Techniques

Leakage field measurements are undertaken to ascertain the level of residual magnetic fields emanating from an object. To increase the accuracy and repeatability of such measurements, it is good practice to isolate the object magnetically to eliminate the influence of extraneous magnetic fields or other ferromagnetic material. This can be accomplished by moving the test object to an appropriate area and supporting it manually or by placing it on a suitable nonferromagnetic platform.

Caution should be exercised to keep certain types of field indicators at a safe distance from demagnetizing fields. Such exposure can partially demagnetize the internal permanent magnet and effectively change the calibration of the device. If this occurs, the sensitivity of the device increases substantially. In strong fields, remagnetization of the device's internal magnet may occur, rendering it unfit for future use.

PART 6
TYPICAL DEMAGNETIZATION PROBLEMS

Demagnetizing Field Strength Too Weak

Demagnetizing capability is directly related to the technique's magnetic field strength. Higher field intensities increase the variety of objects that can be successfully demagnetized.

Conventional alternating current coils are usually rated in terms of ampere-turns. However, for the same applied ampere-turns, the strength of the field increases as coil diameter decreases. It should be noted that the field strength within a coil is greater near the inside wall than at the center.

Alternating Current Demagnetization and Direct Current Magnetization

Objects magnetized by a direct current source can be difficult if not impossible to adequately demagnetize with an alternating current process. This is more prevalent in test objects with diameters greater than 50 mm (2 in.) because of the pronounced skin effect associated with alternating current fields.

Deep interior residual magnetism remains unaffected by surface oriented alternating current fields. On such objects, some form of reversing direct current demagnetization must be used.

Test Object Orientation

Improper test object orientation relative to an alternating current demagnetizing coil can have an adverse effect on the demagnetization process. For the best results, a test object should be passed through the coil lengthwise or with its longest axis parallel to the coil's central axis.

Ring shaped test objects such as bearing races can be rolled through an alternating current coil to obtain the desired results. In a similar manner, objects with a complex configuration may require some form of rotation as they are passed through a demagnetizing coil.

Poor Length-to-Diameter Ratio

The ratio of an object's length to its diameter (the *L/D* ratio) is as important to coil demagnetization as it is to coil magnetization. Values below 3:1 can be a problem, but the situation may be corrected by effectively increasing the *L/D* ratio.

This correction is done by adding ferromagnetic pole pieces at both ends of the object. Pole pieces should be about 150 mm (6 in.) long and nearly the same diameter as the object. With pole pieces in place, the assembly can be passed through the demagnetizing coil in the usual manner. For large lots, it is sometimes convenient to pass the objects through the demagnetizing coil end to end in a chain.

Magnetic Shielding

Whenever possible, it is desirable to demagnetize an object before its assembly with other components. Once assembled, the test object may be adjacent to or surrounded by other ferromagnetic material. In such cases, the demagnetizing field may be shunted through the adjacent material rather than through the object itself and demagnetization will be ineffective.

Small objects should not be passed through a demagnetizing coil in bundles or layered in handling baskets. Test objects in the center of a stack are shielded from the demagnetizing field by the outer layer of material. Ferromagnetic baskets or trays are objectionable for the same reason.

Calibration of Field Indicators

Field indicators are convenient devices for monitoring the effectiveness of a demagnetization process but obscure changes in calibration can cause problems when verifying the demagnetization procedure.

Inadvertently subjecting the device to a demagnetizing field can partially demagnetize the field indicator's internal permanent magnet and significantly increase the device's sensitivity. Subsequent measurements would then indicate the erroneous conclusion that an established demagnetization process is inadequate. In such cases, the results of demagnetization should be verified with another device known to be accurate.

Demagnetization Specifications

Stringent demagnetization specifications can be a source of serious production problems. Specifications are often written without accommodation to the practical limitations of the demagnetization process and its verification. For example, objects exhibiting a field indicator reading around 0.3 mT (3 G) usually will not have an adverse effect on subsequent machining or welding, instrumentation or end use.

Strictly specified limitations should be placed only on a limited number of demagnetization applications (particular test objects manufactured for specific service) as required by experience or laboratory data.

To eliminate ambiguity, a specification should define how a reading is made — on the surface with a Hall effect meter or with a field indicator of a specific design.

PART 7
DEMAGNETIZING EQUIPMENT

Summary of Alternating Current Demagnetization Equipment

Alternating current coil demagnetizers function only as demagnetizers. They are designed for operation at line voltage and line frequency. Most of the units are rated for intermittent duty but some are available for continuous duty. A variety of coil openings are commercially available.

Portable alternating current half-wave units are lightweight magnetization and demagnetization units used to power high amperage cables. Solid state stepless current control permits demagnetization by coil, cable wrap or contact methods. Limited alternating current output usually restricts application of these systems to relatively small or medium sized objects.

Mobile alternating current half-wave units are heavy duty, dual output systems used in conjunction with high amperage cables. Newer designs have solid state current control and built-in current decay circuitry. Relatively large test objects can be demagnetized by the coil, cable wrap or contact methods.

The *horizontal wet alternating current units* with solid state current control feature current decay circuitry that can be used for demagnetizing either by the coil method or the contact method.

Summary of Reversing Direct Current Demagnetization Equipment

Equipment for reversing direct current demagnetization is often expensive. The reversing feature is commonly offered as an option on direct current magnetization equipment but separate units are also available. Some typical units are listed below.

Coil demagnetizers are designed for demagnetization only. A constant amplitude, high amperage direct current is directed through a fixed coil. The polarity of the current is continuously reversed at a fixed rate. Relatively small test objects may be demagnetized dynamically with the through-coil method or statically with modified current decay techniques. Coil sizes may be limited.

Horizontal wet magnetization and demagnetization units permit objects to be magnetized, tested and demagnetized in place on the system. Demagnetization is based on automatic polarity reversal and a step down cycle using coil or contact methods. These systems are suitable for relatively large test objects.

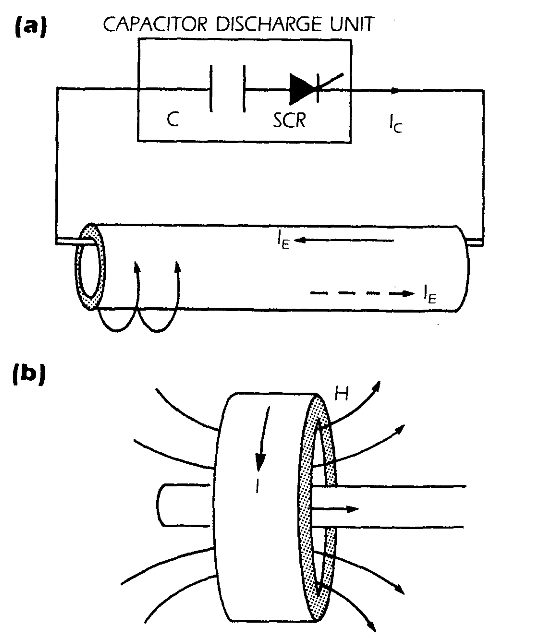
Stationary magnetization and demagnetization power packs produce high amperage directed to the test object through flexible high amperage cables. Either the contact or cable wrap method can be used to demagnetize large objects. The reversing direct current demagnetization process is automatically controlled through a fixed cycle.

Specially designed systems are available for applications that require high rates of productivity. Special power pack and coil configurations are available to demagnetize 9 to 15 m (30 to 50 ft) lengths of tubing on a continuous basis at rates up to 1.5 m per second (300 ft per minute).

PART 8
DEMAGNETIZATION OF ELONGATED TEST OBJECTS

Much finished or semifinished tubular product is tested for surface breaking tight discontinuities by the magnetic flux leakage method. In the case of ferromagnetic oil field tubes, for example, the ends of the tube might first be tested for transversely oriented discontinuities, with the magnetic flux being induced by placing the end of the tube in a coil. The tube is then tested for longitudinal discontinuities using circumferential induction resulting from a current pulse along an internally placed conductor connected to a capacitor discharge system. Both of these methods are shown in Fig. 6.

FIGURE 6. Magnetization of elongated products as commonly practiced for oil field tubular tests: (a) circumferential magnetization of a tube using the capacitor discharge internal conductor method; and (b) longitudinal magnetization of an end region using an encircling coil



In some testing specifications, it is also required that the external longitudinal magnetic fields close to the ends of the tubular product (especially oil field transmission line pipe) be reduced to a value below a specified minimum following magnetic flux leakage testing.[1] This is generally done so that such materials can more easily be field welded.

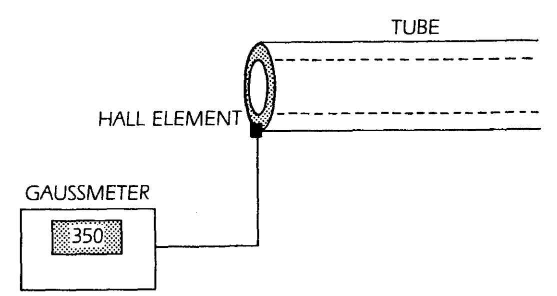
Typically a specification might require that not more than 800 A•m^{-1} (10 Oe) be measured with a gaussmeter at the ends of the material. After magnetic flux leakage testing for transversely oriented discontinuities, the magnetic field intensities emerging from the ends of tubes might easily be 40 kA•m^{-1} (500 Oe) and it is essential that some form of demagnetization be applied.

In the text below, commonly used forms of demagnetization or remagnetization are outlined.

Circumferential Remagnetization

In some cases, after longitudinal magnetization has been established and transverse discontinuity testing completed, it is necessary to remagnetize only in the circumferential direction. The resulting magnetization then causes little or no external field. This is easy to accomplish in tubes by using the internal conductor method[2] shown in Fig. 6a. The

FIGURE 7. Hall element gaussmeter measuring longitudinal magnetic field in air close to the end of a tube



remaining longitudinal field strength can be measured easily with a gaussmeter as shown in Fig. 7.

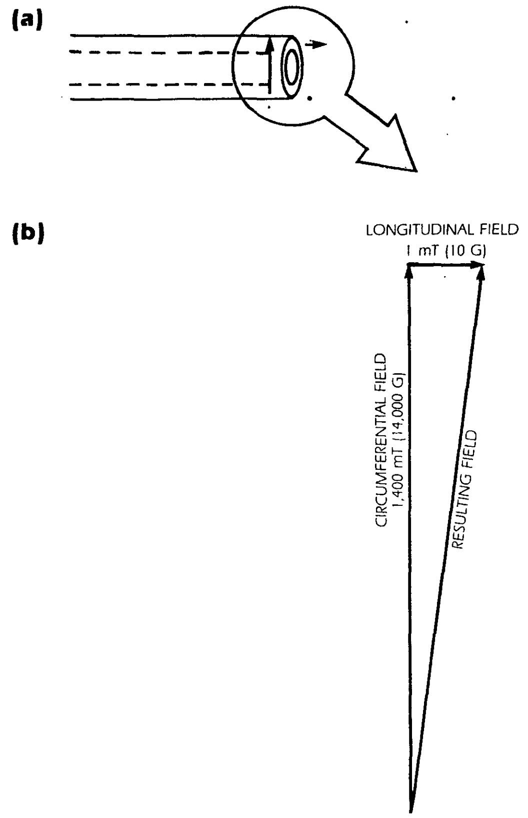
In this test, a calibrated gaussmeter is used to measure the maximum value of the magnetic field strength at the end of the material. If it exceeds a specified value, additional shots from the capacitor discharge internal conductor are applied to reduce this emergent field. For this application, a gaussmeter capable of reading up to 100 mT (1,000 G) is preferred over other types of field indicator.

Angled Nature of the Resulting Field

The presence of some small axial field strength at the end of a tube (or other elongated part) does not indicate that the tube is not circumferentially magnetized.[3] It merely indicates that the circumferential and axial flux densities involved obey a vector relationship such as that shown in Fig. 8.

In this particular example, the material just inside the end of the tube is saturated with magnetic flux that is virtually circumferential at a value very close to the remanence B_r for the steel. Suppose that an external flux density of 1 mT (10 G) occurs for a material with a remanence of 1,400 mT (14 kG). This flux density measurement was made with a gaussmeter after attempted circumferential magnetization by the method outlined above. Its value indicates that the direction of the flux inside the material is only $\tan^{-1}$ (1/1,400) or 0.04 degrees from being perfectly circumferential.

FIGURE 8. Possible magnetic flux density configuration at the end of a tube: (a) the emergent flux density is measurable with a gaussmeter but the circumferential component is not; and (b) the resulting field within the tube in this case is almost circumferential

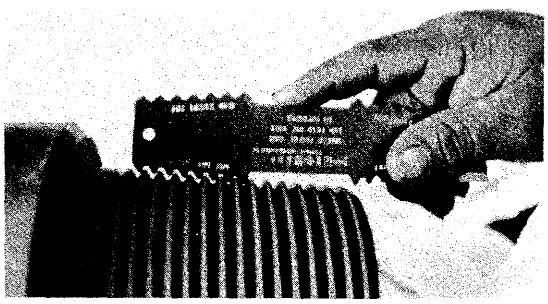


Drill Pipe End Area Tests

A commonly practiced magnetic flux leakage test is that of longitudinally magnetizing the ends of drill pipe (Fig. 6b) and looking for thread root cracks with wet fluorescent magnetic particle techniques. Figure 9 illustrates an example of pin thread stretching, the roots of these threads being particularly prone to cracking.[4] Following such a test, the rotation of the flux into the circumferential direction might require several pulses from a capacitor discharge internal conductor system. Under such circumstances, longer pulses (25 ms) are more effective than shorter ones (3 ms).

In the resulting circumferential magnetization, the drill stem can be tested for longitudinally oriented discontinuities and the tool joints can be tested for heat-check cracks with magnetic particle tests. The threads are also relatively easy to clean of particles.

FIGURE 9. Pin stretch on used drill pipe threads; wet magnetic particle tests are often used to detect fatigue cracking on these thread roots



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Upset Area Problems

It is generally necessary to apply only 3.2 to 4 kA•m^{-1} (40 to 50 Oe) circumferentially to magnetize oil field tubular materials to a point near saturation. This is especially true of the region between the ends of the material (*QR* in Fig. 10). Some materials may require higher field strength values to cause saturation (the *B-H* curve for the material should be consulted).

However, prior to threading the ends of such tubes, it is sometimes necessary to bell or upset the ends (*PQ* and *RS*) of the material. This process may lock in existing magnetic fluxes from earlier tests, the result being that the flux density at the ends can require a higher demagnetizing circumferential field than is required for the central regions of the tube. This is due to ineffective or incomplete stress relief at the ends after upsetting, which also causes the *B-H* properties to differ from those of the central regions.

When this situation is encountered, a gaussmeter can indicate the number of pulses required to rotate the flux within the upset areas.

Alternating Current Coil Demagnetization

After tubes have been longitudinally magnetized to saturation, lowering the remaining induction is usually done with alternating current or direct current through a centralized, surrounding coil. With the alternating current technique, it is critical to know that, for a frequency of 60 Hz, the skin depth being demagnetized is only about 1 mm (0.04 in.). The effect of this form of demagnetization is dependent on: (1) the strength of the demagnetizing field at the surface of the test object; (2) the thickness of the material; and (3) the material's *B-H* properties.

In traditional demagnetization with alternating current, it is required that the test object be slowly removed axially from the demagnetizing coil and that the strength of the field be sufficient to produce saturation in the direction opposed to the existing magnetization direction.

Because of the skin effect, the field strength at any point within the material is lower than that at the surface. If sufficiently high fields are to penetrate the material to cause demagnetization at that given point, the surface field amplitude must be several times higher than that required to cause saturation. At five skin depths (about 5 mm) one percent of the surface field remains. It is clear that the alternating current technique is confined to relatively thin or thin walled test objects and that some other form of demagnetization is needed for thicker materials.

FIGURE 10. Different circumferential magnetic field B-H curves: (a) at the belled or upset ends of tubes; and (b) the unworked center section of a tube; curve (a) shows lower B_r and higher H_c than curve (b)

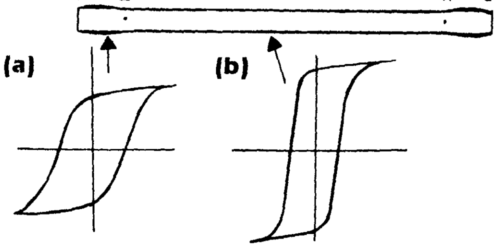
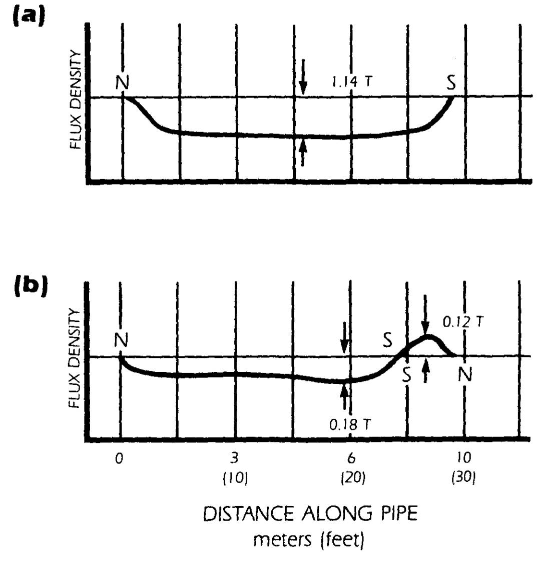


FIGURE 11. The axial bulk flux density in a 10 m (30 ft) long tube: (a) after longitudinal magnetization to saturation; and (b) after direct current coil demagnetization using a constant current; note the remanent flux density (1.14 T), the opposed dipole effect caused by the demagnetization process, and the values of the flux densities in the tube after this form of demagnetization



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Direct Current Coil Demagnetization

Partial demagnetization of tubes is often accomplished by passing the tube through a coil in which the field strength H opposes the direction of the residual induction in the material. Demagnetization current settings are obtained by trial and error since only the external fields at the ends of the tube are available to the inspector. Currently accepted practice is to adjust the demagnetizing field strength to provide the minimum fields at either end of the test object. As shown in Fig. 11, this process leaves the flux density within the material at a relatively high level.

The actual value of the axial flux density in the material is governed by two factors. The first is the local magnetic property or, in effect, just how high a value of flux density B can be sustained. The second is the proximity of the ends of the material (this affects the flux density through the demagnetizing field). The latter factor is very important within about 1 m of the tube ends and has a considerable effect on the local B-H properties. The general effect is to lower the local permeability, due to the internal demagnetizing field inside the test object.

As an example, the effect of direct current coil demagnetization on the axial flux density in a typical 10 m (30 ft) tube is shown in Fig. 11. As illustrated in Fig. 11a, the axial flux density of the tube after magnetization is relatively constant at 1.14 T (11.4 kG) except within about 1 m of either end. This value is close to the remanence for the material, which varies with localized stress, chemical composition and other factors.

After demagnetization, in which only the external field is sampled at both ends of the tube, the remaining flux density within the material is as shown in Fig. 11b. The flux density for the majority of the material is relatively low and in the same direction as the saturated state. However, at one end of the tube the direction of the flux has been reversed by the coil field for roughly 1.4 m (4.4 ft). The demagnetized material then exists in an opposing dipole configuration, with poles as shown in the illustration.

If this form of demagnetization is used, the inspector must consider each application individually. The direct current required depends on the wall thickness of the tube. Passage of the material through an alternating current coil, perhaps of low frequency, further lowers the contained flux.

Flux Sensed Demagnetization

Traditional alternating current and direct current demagnetization techniques do not totally demagnetize an object. They merely reduce the bulk flux density to the value at which emergent fields are low enough not to hinder subsequent metalworking processes. The following information is provided to show that lower bulk fluxes can be obtained by sensing the remaining flux and adjusting the demagnetization current to make the flux as small as possible.

A commonly used method for sensing the flux density level in an elongated object is to jerk a loosely fitting coil from a position of flux linkage with the part to a position of no flux linkage. This is shown in Fig. 12. With the coil in position-1, the flux linkage with the magnetized object is given by:

$$N\Phi = N \times \int \overline{B} \cdot \hat{n} dA \qquad \text{(Eq. 2)}$$

Where:

$N\Phi$ = the flux linkage (weber-turns);
N = the number of turns on the coil;
$\overline{B}$ = the flux density of the test object in the coil (webers per square meter or tesla); and
$\hat{n}dA$ = the area of the coil perpendicular to B (square meters).

With the coil in position-2, the flux linkage is zero and the net change in flux linkage is $N\int \overline{B} \cdot \hat{n}dA$. When the voltage induced in the coil during this process is integrated with a fluxmeter, the output (suitably compensated for the value of A and N) is the average value of the flux density in the test object directly inside the coil at position-1.

Applying this theory to the demagnetization process, the test object is passed through a sensing coil and the output of the fluxmeter is used to electronically compensate the current through the demagnetizing coil. This compensation produces a net flux density in the sensing coil, and therefore in the object, as close to zero as possible. This is shown schematically in Fig. 13.

FIGURE 12. Measurement of the flux at a specific position close to the end of an elongated test object; a search coil is taken from position-1 to position-2 and the resulting voltage is integrated within a fluxmeter; the fluxmeter output is proportional to the flux at position-1

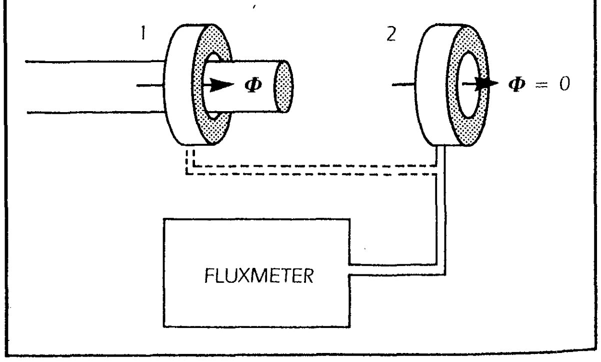
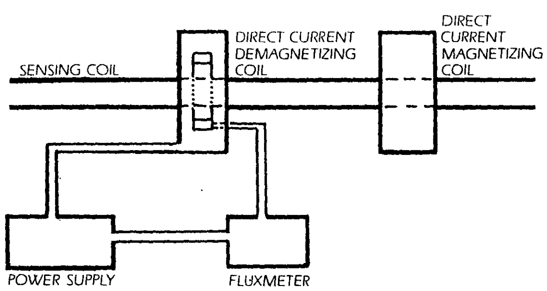


FIGURE 13. Diagram for optimizing the direct current demagnetization of an elongated test object; the sensing coil develops voltage as a magnetized material passes through it and the voltage is fed to a fluxmeter; the meter's signal is proportional to the flux density within the test object and is used to control the programmable power supply of the demagnetizing coil



Problems Associated with Partial Demagnetization

Partial demagnetization can lead to field problems when the material later appears to be highly magnetized. Because of the skin effect, surface demagnetization by the alternating current method is at best a temporary measure so that the bulk magnetization of the test object may eventually lead to large external fields.

The alternative practice is that of local application of a direct current field which, while it may remove the flux from a small region of a test object, does not leave the entire part demagnetized. Unless the entire object can be demagnetized totally, presently accepted practice will continue: the flux is reduced in certain regions of the object so that externally applied field indicators show a low field. The end user will continue to accept material that is highly magnetized even though it appears to be demagnetized. No specifications appear to exist for demagnetization procedures that lead to bulk flux reduction in previously magnetized objects. Below are examples of situations where the lack of demagnetization can cause problems at a later date.

A common practice in the testing of oil field tubes is to reduce the bulk flux to the condition shown in Fig. 11b. Subsequent transportation and other mechanical vibrations can cause the external field to rise to levels unacceptable to the end user. Such levels cannot be caused by the Earth's magnetic field (only 0.02 mT or 0.2 G) because the field strength required to magnetize these materials is much larger than 0.02 mT.

A second common practice is to pass a longitudinally magnetized tube or rod through an alternating current coil carrying 50 or 60 Hz current. Skin depth considerations reveal the volume of material actually demagnetized. The material is left in a highly magnetized state, apart from a surface layer. Subsequent handling causes the reappearance of high external fields.

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SECTION 12

DEMAGNETIZATION OF TEST OBJECTS

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PART 1

DEMAGNETIZATION AND RESIDUAL MAGNETISM

Demagnetization is the process of removing magnetism from a ferromagnetic material. This is accomplished on the molecular level by establishing or reestablishing random orientations in the material's magnetic domains.

The demagnetizing process is often required in conjunction with magnetic particle testing. However, demagnetization may also be required for reasons other than magnetic particle tests.

Ferromagnetic Materials

Ferromagnetic materials are characterized by a relative ease of magnetization when exposed to a magnetizing force. This can be attributed to the relatively high magnetic permeability μ exhibited by these materials. Once magnetized, ferromagnetic material retains a level of magnetic flux density B after the magnetizing field strength H has been removed. This remanent flux density is commonly referred to as *residual magnetism* or the *residual field*. The magnitude of residual flux density is a function of the following factors: (1) the magnetic characteristics of the material; (2) the immediate history of the material's magnetization; (3) the strength of the applied magnetizing field; (4) the direction of magnetization (longitudinal or circular); and (5) the test object's geometry.

Residually magnetized materials contain magnetic flux Φ measured in webers. In the International System of Units (SI), 1 weber (Wb) passing through 1 m^2 gives a flux density of 1 tesla (T). In the centimeter-gram-second (cgs) system, flux is expressed in maxwells or lines of flux. Flux density is expressed as lines per square centimeter or gauss (G). One weber is equivalent to 10^8 lines and one tesla equals 10^4 gauss.

Depending on the direction of the flux with respect to the surface of the test object, these lines may leave the object at one point and continue their path through air before reentering at another point. The points where magnetic lines of flux leave and reenter a ferromagnetic material are called *magnetic poles*. The north pole is where flux lines leave the material. Flux lines reenter the material at the south pole. Such fields emanating from a test object are called *leakage fields* and are the phenomena responsible for attracting nearby magnetic particles.

Requirement for Demagnetization

Components that retain a relatively strong residual flux density can be a source of problems during subsequent manufacturing processes or during service. Some typical problems are detailed below.

When subsequent machining is performed on a test object, the presence of a strong residual flux density can attract and hold chips or particles. This can adversely affect surface finish or tool life.

In an arc welding operation, the presence of strong leakage fields can deflect the arc away from its intended location. This phenomenon is sometimes called *arc blow*. Electron beam welding is also adversely affected by residual magnetism. Even leakage fields of moderate strength can deflect the electron beam away from its intended target.

Plating quality also can be affected by residual magnetism. In an operation such as chrome plating on a steel surface, the presence of a strong residual magnetic field can divert the plating current away from its intended location. Such mishaps are costly, incorporating the expenses of the first faulty plating, possible repair and a second plating operation.

In-service operation of an object may be impaired if it is the source of excessive leakage fields, attracting metallic chips or tramp particles. This condition can cause malfunctions in rotating assemblies such as bearings or excessive wear on bearing surfaces. Strong residual flux densities also may cause a substantial magnetic attraction between adjacent moving parts. This can produce increased friction or may in other ways interfere with the intended function of the component.

Cleaning operations for the removal of metallic chips and particles can be hampered by the presence of residual fields. This can be of special concern when cleaning objects that have internal openings such as oil passages.

Residual leakage fields can have a direct adverse effect on certain types of instrumentation. The magnetic compass aboard aircraft is an example, as are many electronic components.

Rotating shafts containing residual magnetism may act as electric generators in conjunction with the Earth's magnetic field or other stray fields. The generated electricity can heat the shafts, causing operating losses and other service problems.

Finally, objects sometimes need to be demagnetized before using established magnetizing current levels for magnetic particle testing. The presence of strong residual induction can lead to erroneous results and faulty test procedures.

Demagnetization is *not* required when the test material exhibits very low magnetic remanence. Low carbon or nodular steels are included in this category. If the next manufacturing process calls for the object to be heated above the Curie point, the material becomes nonmagnetic and demagnetization is accomplished by the heating process. At the Curie point, steel temporarily transforms from a ferromagnetic to a paramagnetic state and subsequently cools with zero net induction.

If the part does not require additional machining and its intended function is not compromised by the presence of a residual field, then demagnetization becomes unnecessary.

Common Sources of Residual Magnetic Fields

Ferromagnetic material can become magnetized in a number of ways, intentionally and unintentionally.

Parts may be purposely magnetized to perform magnetic particle tests or to facilitate a magnetic flux leakage test. Magnetization may also come from biasing magnetic fields such as those used to negate the effects of permeability changes in eddy current tests.

Magnetic chucks are a common source of residual fields. Pronounced fields can be left in an object if a chuck's built-in demagnetizing cycle is faulty or inadequate. Prematurely removing test objects before completion of the demagnetizing cycle can also be a source of residual magnetism.

Lift magnets are convenient material handling devices, but because they operate with direct current, they can leave strong residual fields in fabricated objects or in raw material. Physical contact with any permanent magnet or highly magnetized object (a machine table or fixture) can also establish a residual field.

Low frequency induction heating that is abruptly terminated can induce very strong residual flux density. The lower the frequency, the deeper the magnetizing field strength penetrates into the material.

With certain orientations of high amperage cables, an electric arc welding operation can magnetize ferromagnetic material.

Residual magnetization can occur with improper operation of alternating current through a coil demagnetizer. This occurs when the coil current is terminated and the test object is still within the coil or within its influence. Penetration depth is determined by the frequency of the alternating current.

Finally, under certain conditions the Earth's magnetic field can impart a longitudinal residual field. This occurs only with low coercivity steels, usually when the object is shocked or vibrated while its long axis is parallel to the Earth's magnetic field. Such a residual field may become quite significant for long parts subjected to severe vibrations in service or transport. The intensity (horizontal component) of the Earth's field in the United States is about 16 $A{\cdot}m^{-1}$ (0.2 Oe). This is equivalent to the magnetic field strength at the center of a five ampere-turn coil 300 mm (12 in.) in diameter.

Effect of Magnetic Field Origin on Demagnetization

The type of magnetizing source becomes significant when considering the nature of residual induction and its subsequent demagnetization.

Alternating currents tend to flow near the surface of a conductor and this so-called *skin effect* produces residual fields that are surface oriented. Such fields respond well to alternating current demagnetization techniques.

There is practically no skin effect associated with a direct current magnetizing source and consequently the entire cross section of an object can be residually magnetized. Deep seated residual fields in larger objects may not be affected by alternating current demagnetizing techniques because the skin depth is only about 1 mm for steel of relative permeability 100 at 60 Hz.

Types of Residual Magnetic Fields

Longitudinal Magnetic Fields

Materials magnetized by a coil or solenoid sometimes can be left with a longitudinal residual induction. The field is oriented lengthwise in the test object and there is a high concentration of emergent fields at each end. These fields constitute poles, lines of magnetic flux entering or leaving the material.

Longitudinal magnetization is easily detected by field measuring devices such as the gaussmeter or by the attraction of other ferromagnetic materials. While this type of field can adversely affect subsequent machining, it is usually very responsive to demagnetizing techniques.

Circular Magnetic Fields

Unlike longitudinal residual induction, circular residual induction can exhibit little or no external evidence of its presence. The flux may be entirely confined within the material, depending to some extent on part geometry and the magnetizing procedure.

For example, if magnetizing current is passed through a homogeneous length of ferromagnetic bar stock having a circular cross section, the resulting circular residual flux density is for all practical purposes undetectable without altering the bar in some manner. Virtually no leakage fields emanate from its surface because the magnetic flux path is closed within the object. Because of this, the internal residual flux density B may be much stronger than if the test object had been magnetized longitudinally in a coil or solenoid having a comparable magnetic field strength H.

The circular residual flux density becomes an apparent problem when the geometry of the object is altered by subsequent machining. For example, if a keyway is cut in a piece of shafting that is circularly magnetized, the circular field becomes quite evident. Strong leakage fields (north and south magnetic poles) occur on either side of the keyway. All holes or slots cutting through a circular field produce magnetic poles that can attract materials such as chips or dust from subsequent machining.

Without special equipment, demagnetization of a circularly magnetized object can be very difficult. Confirmation of an adequate demagnetization level is an additional problem. Leakage field measuring devices are ineffective since there may not be an external leakage field to monitor. In this case, reorientation of the circular field into a longitudinal field prior to demagnetization may be advantageous in some instances when such a procedure is compatible with part geometry and size.

Multiple Magnetic Poles

Multiple magnetic poles can be induced in and retained by ferromagnetic material that has been exposed to direct current magnetization, as in a magnetic chuck or lift magnet. These fields can be pronounced and take the form of alternate north and south poles at relatively close intervals. Demagnetization of multiple poles may be difficult using conventional alternating current through-coil procedures.

PART 2
PRINCIPLES OF DEMAGNETIZATION

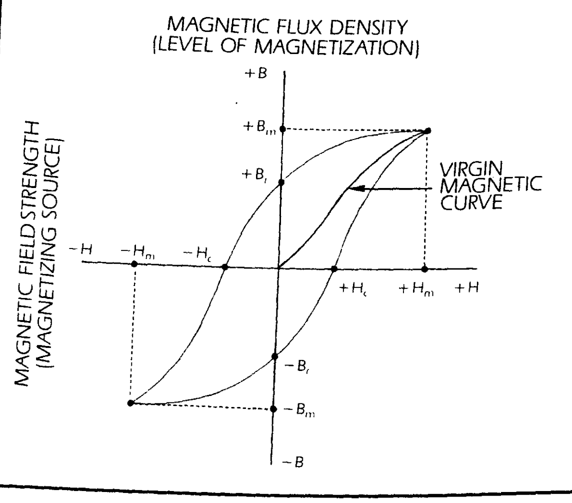
Ferromagnetic material differs from other material in that it contains magnetic domains, localized regions in which the atomic or molecular magnetic moments are aligned in parallel. When a material is not magnetized, the domains are randomly oriented and their respective magnetic inductions sum to zero. When the material is exposed to a magnetizing field strength H, the domains tend to align with the applied magnetic field and add to the applied field.

When the magnetizing source H is removed, some of the magnetic domains remain in their new orientation rather than returning to the original random orientation and the material retains a residual magnetic field.

Magnetic Hysteresis

Magnetic hysteresis is a lag in the change of magnetization values after a change in the magnetizing force. Figure 1 illustrates the relationship between the magnetic field strength H (magnetizing source) and the magnetic flux density B (level of magnetization). When an unmagnetized material is magnetized by gradually increasing H from zero to $+H_m$, the level of magnetization B increases along the virgin magnetization curve to a maximum value corresponding to $+B_m$.

FIGURE 1. Magnetic hysteresis curve



As H is reduced to zero, the level of B falls to $+B_r$ rather than zero. This level of retained magnetization ($+B_r$) is the remanent or residual field remaining in the material. As negative values of H (opposite polarity) are applied, the curve passes through $-H_c$ and on to $-H_m$ and reaches a magnetization level of $-B_m$. Reversing the applied field to a value of $+H_m$ completes the magnetic hysteresis loop.

Retentivity and Coercive Force

The value H_c is the coercive force and is an indicator of the difficulty involved in demagnetizing a material. The value of B_r is the material's retentivity and indicates the residual induction within a section of the material. As a rule, high coercive forces are associated with harder materials and low coercive forces with softer materials. Therefore, harder materials usually offer more resistance to demagnetization and require a higher demagnetizing field than softer materials.

No definition has been made for the dividing line between hard and soft materials. However, if $H_c \geq 8{,}000$ A•m^{-1} (100 Oe), then the material is typically considered hard. If $H_c \leq 400$ A•m^{-1} (5 Oe), then the material is considered soft. Coercive forces as large as 8×10^5 A•m^{-1} (10^4 Oe) and as small as 0.08 A•m^{-1} (10^{-3} Oe) have been observed.

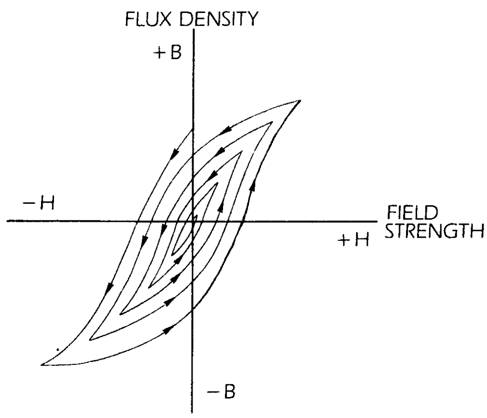
The fact that an object retains a strong residual field B_r is not necessarily indicative of a high coercive force H_c. Some materials retain an appreciable residual induction and yet are easily demagnetized (transformer steels are an example). On the other hand, some materials that retain relatively weak residual fields can be extremely difficult to demagnetize because of a high coercive force.

Basic Principle of Demagnetization

Practically all demagnetizing methods are based on a common procedure. A magnetizing field strength H, sufficiently high to overcome the initial coercive force H_c, is alternately reversed in polarity and gradually reduced to zero. The diminishing hysteresis curve shown in Fig. 2 illustrates this principle.

The value of the total coercive force H_c is often unknown and varies with proximity to the test object's ends. However,

FIGURE 2. Diminishing hysteresis curve



it is always less than the maximum magnetizing force H_m value. This may serve as a guide in cases where the magnetizing field strength H_m is known, as is sometimes the case in magnetic particle testing. Successful demagnetization procedures often start with an initial demagnetizing field which equals or exceeds that of the magnetizing force H_m.

An object may also be demagnetized by raising its temperature above the Curie point. Although this method provides thorough demagnetization, it is often impractical.

PART 3
SUMMARY OF DEMAGNETIZATION PROCEDURES

Alternating Current Demagnetization

Through-Coil Method

The simplicity of the alternating current through-coil method makes it one of the most prevalent demagnetization techniques. The method uses a coil powered from a current source alternating at line frequency (usually 60 Hz in the United States). Operating at a fixed amplitude, the coil produces a continuously reversing magnetic field because of the cyclic nature of the current. As a test object is conveyed through the coil, it is subjected to the most intense magnetic field while within the confines of the coil.

The strength of the field is gradually reduced to zero as the object exits the coil and reaches a point beyond the influence of the coil's field. The coil should not be deenergized until the test object has reached this point, three or four coil diameters away or about 1 m (3 ft). This rule applies to most demagnetizing coils in industry, where peak values of the field at the center of the coil are about 1.2×10^5 to 2.4×10^5 A•m^{-1}. Small test objects can be hand held, placed within the coil and withdrawn. Field penetration may be several skin depths.

The magnitude of the field can also be reduced by withdrawing a coil such as a cable coil away from a stationary test object. This method is advantageous for high production rates since a properly designed coil can be continuously energized while a steady stream of test objects is conveyed through the coil opening. Typical alternating current through-coil demagnetizers are shown in Figs. 3 and 4.

Demagnetization of test shims may be performed by removing them slowly from one pole of an alternating current yoke.

FIGURE 3. Manually operated alternating current coil demagnetizer with roller carriage and automatic timer

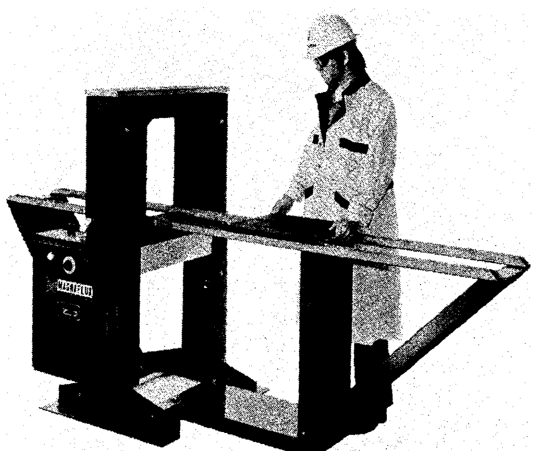


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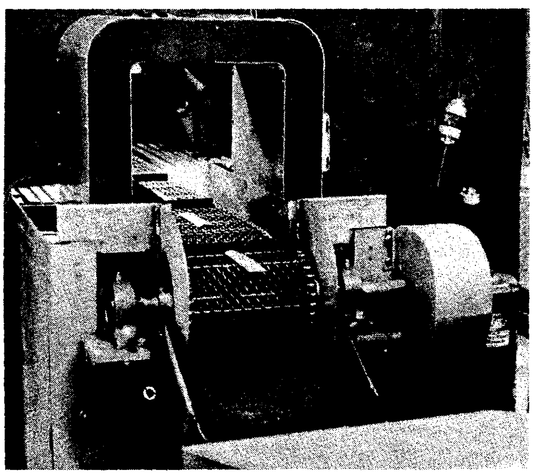
FIGURE 4. Production alternating current coil demagnetizer incorporated into conveyorized magnetic particle testing unit



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Cable Wrap Method

There are applications (such as large or immobile test objects) where a cable wrap, in conjunction with an appropriate high amperage alternating current power source, can provide a convenient means of demagnetization. The high amperage power source must also incorporate a suitable current control to facilitate the gradual reduction of current from maximum to zero.

Portable or mobile alternating current power packs are available for such applications. Equipment of this type usually features stepless solid state current control. Some units incorporate special current decay circuitry that automatically reduces the current from maximum to zero in a matter of three or four seconds.

Through-Current Method

Through-current demagnetization is a contact method. High amperage alternating current is caused to flow directly through a test object starting at contact electrodes. The current control system must provide gradual reduction of current as required for demagnetization. A portable alternating current power pack used for cable wrap demagnetization may also be used for the through-current method.

Through-current demagnetization is used on horizontal wet magnetic particle testing units that have comparable current control systems. Because of part configuration and the accessibility of alternating current, the through-current method can have real advantages for certain applications.

Direct Current Demagnetization

Reversing Direct Current Contact Coil Method

Reversing direct current contact coil demagnetization is usually associated with relatively large test objects that have been magnetized using a direct current magnetic field. It is also applicable in certain instances where alternating current demagnetization proves ineffective.

The method requires high amperage direct current or full-wave rectified alternating current that can be directed to a coil or contact plate. There must also be provisions for reversing the polarity of the current and suitable means for gradually reducing its amplitude to zero.

The direct current is alternately reversed in polarity (direction) and reduced in amplitude to zero. Although fewer steps may provide satisfactory results, greater reliability is achieved by using about thirty reversals and current reductions to approach zero asymptotically.

The cycle is usually controlled automatically and requires about thirty seconds to complete. When using a coil, the test object should remain stationary within the coil until the demagnetizing cycle has been completed. When the contact method is used, contact should be maintained until the cycle is completed. The direct current method provides deep penetration and is usually very successful on objects that are otherwise difficult to demagnetize.

Because of economic considerations, the reversing direct current demagnetizing feature is usually incorporated into the design of direct current horizontal wet magnetic particle testing units or relatively large stationary power packs.

Reversing Cable Wrap Method

This method is used for demagnetizing objects too large or heavy to process on a horizontal wet testing unit. The object to be demagnetized is wrapped with multiple turns of high amperage flexible cable (such as 4/0) connected to a stationary direct current power pack.

The current is alternately reversed in direction and reduced in amplitude through multiple steps until the current reaches zero. This is usually accomplished using built-in automatic circuitry similar to that designed into some wet testing units. Power packs that lack an automatic demagnetizing cycle can sometimes be used to accomplish demagnetization by manually interchanging cable connections (current reversal) and manipulating manual current controls (current reduction). However, this is time consuming and requires an appropriately fine current control to be successful.

Pulsating Reversing Method

A high amperage direct current coil demagnetizer has been designed to produce alternate pulses of positive and negative current. The pulses are generated at a fixed amplitude and a repetition rate of five to ten cycles per second. This permits relatively small objects to be demagnetized by the through-coil method.

The object is subjected to a constantly reversing magnetic field as it passes through the coil and the magnitude of the effective field is reduced to zero as the object is gradually withdrawn from the coil. This mode of operation is identical to the alternating current through-coil method described above, except for the reduced repetition rate (five to ten cycles per second compared to sixty cycles per second).

The lower repetition rate substantially reduces the skin effect with a corresponding increase in magnetic field penetration. Therefore, the method provides additional demagnetizing capabilities on some relatively small test objects with thick cross sections that are difficult to handle with line frequency coil demagnetizers. Another standard mode of operation allows the object to remain stationary within the coil while the current gradually decays to zero.

Specialized Demagnetization Procedures

There is a wide variety of miscellaneous demagnetizing techniques that have specific applications designed around a specific test object.

Demagnetization with Yokes

A yoke configuration is sometimes used to demagnetize small objects having high coercive force. Yokes are also used for demagnetization of objects with small length-to-diameter (*L/D*) ratios, including spheres with near-perfect *L/D* ratios of 1. Yokes are usually designed for a specific type or range of test objects.

Some alternating current yokes are similar in operation to the alternating current coil method, where the test object is passed between or across the surfaces of the pole faces (maximum field strength) and then withdrawn. Direct current yokes are sometimes used with the reversing direct current method on specific objects requiring deep penetration. However, this is an inherently slow process because of the associated high inductance of the circuit.

Some coil or yoke arrangements use damped oscillation to obtain the required reversing and diminishing field. The oscillation is derived from a special circuit design based on specific values of capacitance, inductance and resistance.

Demagnetization of Oil Field Tubes

Various testing processes involving direct current magnetization leave the test object with a significant longitudinal residual field. Demagnetization is usually required to eliminate any possibility of the field having an adverse effect on subsequent machining or welding operations. Some tubular products have lengths of 9 to 15 m (30 to 50 ft) and this presents a formidable challenge to standard demagnetization procedures. Some unusual methods have been used when facilities for overall (full length) demagnetization are not available.

One such procedure applies a bucking (opposite polarity) field at the ends of the object using a direct current coil positioned near the ends. By trial and error, magnetizing current to the coil is increased until external field readings are reduced to an acceptable level. The result is a redistribution of the field at each end of the tube. Unfortunately, mechanical agitation subsequent to this procedure, from handling or transport, can result in the redistribution of the longitudinal field and can reestablish strong leakage fields at the ends of the test object.

Another specialized demagnetization procedure uses a full length internal conductor in conjunction with a unidirectional current pulse to reorient the longitudinal field and form a circular field. The magnitude of the circularly magnetizing current is increased until acceptable external field readings are achieved. While this is *not* demagnetization, it does reduce leakage fields to a level suitable for butt welding operations. It also creates the undesirable conditions associated with circular magnetization and hinders subsequent operations, including weld preparation or threading.

Overall demagnetization is the best solution for long tubes and this is usually carried out using some form of reversing direct current. For static conditions, an internal conductor is used in conjunction with a conventional reversing direct current cycle. A cable, wrapped to give several internal conductors, could be used in place of the central conductor. However, when object's length is taken into consideration, the central conductor approach is much more time efficient.

The advent of pulsating direct current equipment has lead to dynamic demagnetizing systems for overall demagnetization of long test objects. In such systems, the object is conveyed through a special coil arrangement at speeds up to 1.5 m per second (300 ft per minute). The coil current consists of constant amplitude pulses of direct current alternating relative to polarity (positive and negative) at a rate of about five cycles per second.

PART 4
SELECTING A DEMAGNETIZATION PROCEDURE

Selecting a suitable demagnetization procedure is a matter of matching capabilities with the specific application. Each of the procedures discussed above has advantages and limitations based on test object size, hardness, production rate and source of magnetization (see Table 1).

Limitations of Alternating Current Methods

The alternating current through-coil method is probably the most widely used demagnetization technique because of its simplicity and its adaptability to high production rates. However, the skin effect associated with alternating current magnetic fields results in limited penetration capabilities. Consequently, alternating current demagnetization methods may be ineffective for removing deep residual fields such as those associated with direct current magnetization.

This becomes a significant factor on large test objects. As a rule, alternating current methods can effectively demagnetize most objects with a cross section less than 50 mm (2 in.), regardless of the original magnetizing source. Larger test objects with deep residual fields usually require some form of reversing direct current demagnetization. If alternating current is the only source of magnetization, alternating current demagnetization is effective regardless of test object size.

Maximum Effective Field Strength

The maximum effective field strength H_m of a particular demagnetization procedure is an important indicator of the procedure's capability. Basically, the H_m value must be sufficient to overcome the coercive force H_c associated with the material to be demagnetized. Generally, H_c increases with hardness.

Test object size and geometry (including the *L/D* ratio) are also factors that influence field strength requirements. The demagnetization potential of a procedure inherently increases with field strength capabilities. When related to various alternating current coil sizes with equal ampere-turn ratings, the field strength increases as coil size decreases.

Reversing Direct Current

Reversing direct current procedures are usually required when alternating current techniques prove inadequate. For those difficult applications, reversing direct current has unexcelled demagnetization capabilities. Almost any object can be demagnetized to an acceptable level with reversing direct current. While production rate capabilities are limited, this is usually not a significant hindrance; since larger objects are often involved, the associated production rates are relatively low.

TABLE 1. Demagnetizing method selection guide based on test object size, hardness and production rate for residual fields from direct current magnetizing source

	Test Object Size			Material Hardness			Production Rate		
	Small[1]	Medium[2]	Large[3]	Soft	Medium	Hard	Low	Medium	High
Alternating Current (50/60 Hz)									
Through-coil	A	Q	N	A	A	N	A	A	A
Cable wrap	N	Q	Q	A	A	N	A	N	N
Through-current (30 point step down)	N	A	N	A	A	N	A	Q	N
Through-current (current decay)	N	A	N	A	A	N	A	Q	N
Yoke	A	N	N	A	A	Q	A	N	N
Reversing Direct Current									
Through-coil (pulsating)	A	A	A	A	A	A	A	A	A
Coil (30 point step down)	A	A	Q	A	A	A	A	A	N
Cable wrap (30 point step down)	N	Q	A	A	A	A	A	N	N
Through-current (30 point step down)	N	A	A	A	A	A	A	Q	N

1. HAND HELD
2. LESS THAN 50 mm (2 in.) DIAMETER
3. MORE THAN 50 mm (2 in.) DIAMETER

LEGEND
Q = QUESTIONABLE
A = APPLICABLE
N = NOT APPLICABLE

PART 5
MEASURING EXTERNAL FIELD STRENGTH

In SI units, magnetic flux density B is measured in tesla or webers per square meter. In cgs units, magnetic flux density is measured in gauss or as magnetic lines of force per square centimeter. One tesla is equivalent to 10^4 gauss. In SI, the magnetic field strength H is measured in amperes per meter ($A{\bullet}m^{-1}$); in cgs, the unit is oersted (Oe). One ampere per meter is equivalent to 0.013 oersted.

Flux density and field strength are related to each other and to magnetic permeability by the following equation:

$$B = \mu_o \mu H \qquad \text{(Eq. 1)}$$

Where:

μ_o = the permeability of free space; and
μ = the relative permeability.

The value of permeability is not affected by the choice of units. Permeability values in customary units are the same magnitude as those of relative permeabilities in SI units. Because gauss and oersted have by definition the same magnitude in air, the μ_o factor is not used in the equation for customary units.

By itself, the permeability of a material has no meaning. Its value at specific values of H or B does have meaning.

Field Indicators

Theory of Operation

The field indicator is a hand held instrument used to measure the relative strength of magnetic leakage fields. The construction of a typical field indicator is shown in Fig. 5 and its theory of operation is relatively simple. As illustrated, an elliptically shaped soft iron vane is attached to a pointer that is free to pivot. A rectangular permanent magnet is mounted in a fixed position directly above the soft iron vane.

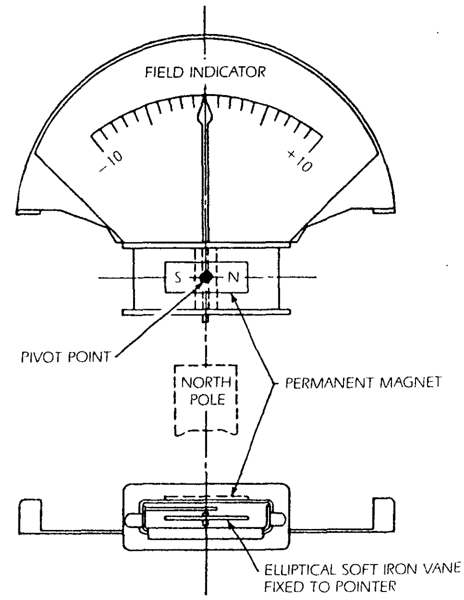
Because the vane is under the influence of the magnet, it tends to align its long axis in the direction of the leakage field emanating from the magnet. In so doing, the vane becomes magnetized and has a magnetic pole induced at each end of its long axis.

On the end of the vane below the south pole of the magnet, a north pole is induced. Correspondingly, a south pole is induced at the opposite end of the vane below the north pole of the magnet. In the absence of external fields, the pointer indicates zero on the graduated scale.

When the magnetic north pole of a residually magnetized object is moved close to the pivot end of the pointer, the south pole of the vane is attracted toward the object and the north pole of the vane is repelled. The resulting torque causes the pointer to rotate in the positive or plus direction. The restraining torque is provided by the tendency of the vane to remain aligned with the leakage field of the permanent magnet.

Sensitivity of the field indicator is primarily a function of the permanent magnet's characteristics and the spacing between the magnet and the vane. The device can be calibrated in relative units, milliteslas or gauss. Calibration is only valid when the device is subjected to a uniform

FIGURE 5. Typical magnetic field indicator construction.



magnetic field such as that found at the center of a large coil or Helmholtz coil arrangement.

The pattern of external fields emanating from a residually magnetized object is anything but uniform and varies with changes in part geometry. In view of this, readings obtained with a field indicator are effectively in relative units but still useful for comparative purposes.

Use of the Field Indicator

The relative strength of an external field is measured by bringing the field indicator near the object and noting the deflection of the pointer. The edge of the field indicator at the pivot end of the pointer should be closest to the object under investigation.

The required degree of demagnetization is usually specified as a maximum field indicator reading (in terms of divisions, tesla or gauss) for a specific device. Leakage field patterns of very small objects may be too limited for detection by a field indicator — the sensing element (soft iron vane) is located approximately 12 mm (0.5 in.) from the edge of the device's casing.

The field indicator is the most common device used in industry for monitoring the effectiveness of demagnetizing processes. It is convenient, easy to operate and inexpensive.

Laboratory Instruments

The Hall effect gaussmeter is the most common laboratory instrument used to measure the strength of leakage fields quantitatively. The sensing element is located in a remote hand held probe connected to the basic instrument by a flexible multiconductor electrical cable. This permits leakage field measurements right at the surface of a test object, and consequently, the readings are substantially greater compared to those obtained with a field indicator.

In the past, use of the gaussmeter was confined to laboratory work because of instrument cost, complicated operating procedures and the delicate nature of the probe. However, gaussmeters are now widely used in many ways, such as qualifying demagnetization procedures for small or unusual test objects; establishing maximum permissible field indicator readings; and verifying field indicator calibration procedures.

Measuring Techniques

Leakage field measurements are undertaken to ascertain the level of residual magnetic fields emanating from an object. To increase the accuracy and repeatability of such measurements, it is good practice to isolate the object magnetically to eliminate the influence of extraneous magnetic fields or other ferromagnetic material. This can be accomplished by moving the test object to an appropriate area and supporting it manually or by placing it on a suitable nonferromagnetic platform.

Caution should be exercised to keep certain types of field indicators at a safe distance from demagnetizing fields. Such exposure can partially demagnetize the internal permanent magnet and effectively change the calibration of the device. If this occurs, the sensitivity of the device increases substantially. In strong fields, remagnetization of the device's internal magnet may occur, rendering it unfit for future use.

PART 6
TYPICAL DEMAGNETIZATION PROBLEMS

Demagnetizing Field Strength Too Weak

Demagnetizing capability is directly related to the technique's magnetic field strength. Higher field intensities increase the variety of objects that can be successfully demagnetized.

Conventional alternating current coils are usually rated in terms of ampere-turns. However, for the same applied ampere-turns, the strength of the field increases as coil diameter decreases. It should be noted that the field strength within a coil is greater near the inside wall than at the center.

Alternating Current Demagnetization and Direct Current Magnetization

Objects magnetized by a direct current source can be difficult if not impossible to adequately demagnetize with an alternating current process. This is more prevalent in test objects with diameters greater than 50 mm (2 in.) because of the pronounced skin effect associated with alternating current fields.

Deep interior residual magnetism remains unaffected by surface oriented alternating current fields. On such objects, some form of reversing direct current demagnetization must be used.

Test Object Orientation

Improper test object orientation relative to an alternating current demagnetizing coil can have an adverse effect on the demagnetization process. For the best results, a test object should be passed through the coil lengthwise or with its longest axis parallel to the coil's central axis.

Ring shaped test objects such as bearing races can be rolled through an alternating current coil to obtain the desired results. In a similar manner, objects with a complex configuration may require some form of rotation as they are passed through a demagnetizing coil.

Poor Length-to-Diameter Ratio

The ratio of an object's length to its diameter (the *L/D* ratio) is as important to coil demagnetization as it is to coil magnetization. Values below 3:1 can be a problem, but the situation may be corrected by effectively increasing the *L/D* ratio.

This correction is done by adding ferromagnetic pole pieces at both ends of the object. Pole pieces should be about 150 mm (6 in.) long and nearly the same diameter as the object. With pole pieces in place, the assembly can be passed through the demagnetizing coil in the usual manner. For large lots, it is sometimes convenient to pass the objects through the demagnetizing coil end to end in a chain.

Magnetic Shielding

Whenever possible, it is desirable to demagnetize an object before its assembly with other components. Once assembled, the test object may be adjacent to or surrounded by other ferromagnetic material. In such cases, the demagnetizing field may be shunted through the adjacent material rather than through the object itself and demagnetization will be ineffective.

Small objects should not be passed through a demagnetizing coil in bundles or layered in handling baskets. Test objects in the center of a stack are shielded from the demagnetizing field by the outer layer of material. Ferromagnetic baskets or trays are objectionable for the same reason.

Calibration of Field Indicators

Field indicators are convenient devices for monitoring the effectiveness of a demagnetization process but obscure changes in calibration can cause problems when verifying the demagnetization procedure.

Inadvertently subjecting the device to a demagnetizing field can partially demagnetize the field indicator's internal permanent magnet and significantly increase the device's sensitivity. Subsequent measurements would then indicate the erroneous conclusion that an established demagnetization process is inadequate. In such cases, the results of demagnetization should be verified with another device known to be accurate.

Demagnetization Specifications

Stringent demagnetization specifications can be a source of serious production problems. Specifications are often written without accommodation to the practical limitations of the demagnetization process and its verification. For example, objects exhibiting a field indicator reading around 0.3 mT (3 G) usually will not have an adverse effect on subsequent machining or welding, instrumentation or end use.

Strictly specified limitations should be placed only on a limited number of demagnetization applications (particular test objects manufactured for specific service) as required by experience or laboratory data.

To eliminate ambiguity, a specification should define how a reading is made — on the surface with a Hall effect meter or with a field indicator of a specific design.

PART 7
DEMAGNETIZING EQUIPMENT

Summary of Alternating Current Demagnetization Equipment

Alternating current coil demagnetizers function only as demagnetizers. They are designed for operation at line voltage and line frequency. Most of the units are rated for intermittent duty but some are available for continuous duty. A variety of coil openings are commercially available.

Portable alternating current half-wave units are lightweight magnetization and demagnetization units used to power high amperage cables. Solid state stepless current control permits demagnetization by coil, cable wrap or contact methods. Limited alternating current output usually restricts application of these systems to relatively small or medium sized objects.

Mobile alternating current half-wave units are heavy duty, dual output systems used in conjunction with high amperage cables. Newer designs have solid state current control and built-in current decay circuitry. Relatively large test objects can be demagnetized by the coil, cable wrap or contact methods.

The *horizontal wet alternating current units* with solid state current control feature current decay circuitry that can be used for demagnetizing either by the coil method or the contact method.

Summary of Reversing Direct Current Demagnetization Equipment

Equipment for reversing direct current demagnetization is often expensive. The reversing feature is commonly offered as an option on direct current magnetization equipment but separate units are also available. Some typical units are listed below.

Coil demagnetizers are designed for demagnetization only. A constant amplitude, high amperage direct current is directed through a fixed coil. The polarity of the current is continuously reversed at a fixed rate. Relatively small test objects may be demagnetized dynamically with the through-coil method or statically with modified current decay techniques. Coil sizes may be limited.

Horizontal wet magnetization and demagnetization units permit objects to be magnetized, tested and demagnetized in place on the system. Demagnetization is based on automatic polarity reversal and a step down cycle using coil or contact methods. These systems are suitable for relatively large test objects.

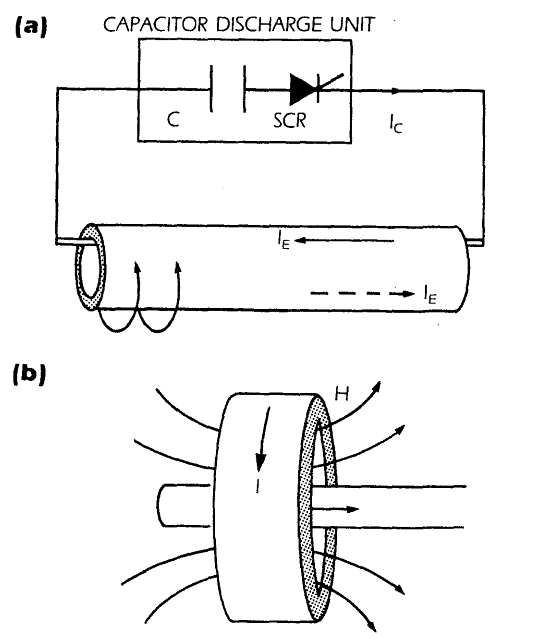
Stationary magnetization and demagnetization power packs produce high amperage directed to the test object through flexible high amperage cables. Either the contact or cable wrap method can be used to demagnetize large objects. The reversing direct current demagnetization process is automatically controlled through a fixed cycle.

Specially designed systems are available for applications that require high rates of productivity. Special power pack and coil configurations are available to demagnetize 9 to 15 m (30 to 50 ft) lengths of tubing on a continuous basis at rates up to 1.5 m per second (300 ft per minute).

PART 8
DEMAGNETIZATION OF ELONGATED TEST OBJECTS

Much finished or semifinished tubular product is tested for surface breaking tight discontinuities by the magnetic flux leakage method. In the case of ferromagnetic oil field tubes, for example, the ends of the tube might first be tested for transversely oriented discontinuities, with the magnetic flux being induced by placing the end of the tube in a coil. The tube is then tested for longitudinal discontinuities using circumferential induction resulting from a current pulse along an internally placed conductor connected to a capacitor discharge system. Both of these methods are shown in Fig. 6.

FIGURE 6. Magnetization of elongated products as commonly practiced for oil field tubular tests: (a) circumferential magnetization of a tube using the capacitor discharge internal conductor method; and (b) longitudinal magnetization of an end region using an encircling coil



In some testing specifications, it is also required that the external longitudinal magnetic fields close to the ends of the tubular product (especially oil field transmission line pipe) be reduced to a value below a specified minimum following magnetic flux leakage testing.[1] This is generally done so that such materials can more easily be field welded.

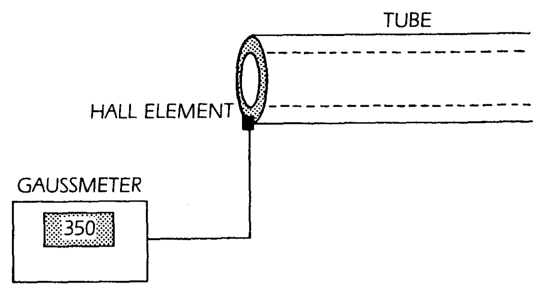
Typically a specification might require that not more than 800 A•m^{-1} (10 Oe) be measured with a gaussmeter at the ends of the material. After magnetic flux leakage testing for transversely oriented discontinuities, the magnetic field intensities emerging from the ends of tubes might easily be 40 kA•m^{-1} (500 Oe) and it is essential that some form of demagnetization be applied.

In the text below, commonly used forms of demagnetization or remagnetization are outlined.

Circumferential Remagnetization

In some cases, after longitudinal magnetization has been established and transverse discontinuity testing completed, it is necessary to remagnetize only in the circumferential direction. The resulting magnetization then causes little or no external field. This is easy to accomplish in tubes by using the internal conductor method[2] shown in Fig. 6a. The

FIGURE 7. Hall element gaussmeter measuring longitudinal magnetic field in air close to the end of a tube



remaining longitudinal field strength can be measured easily with a gaussmeter as shown in Fig. 7.

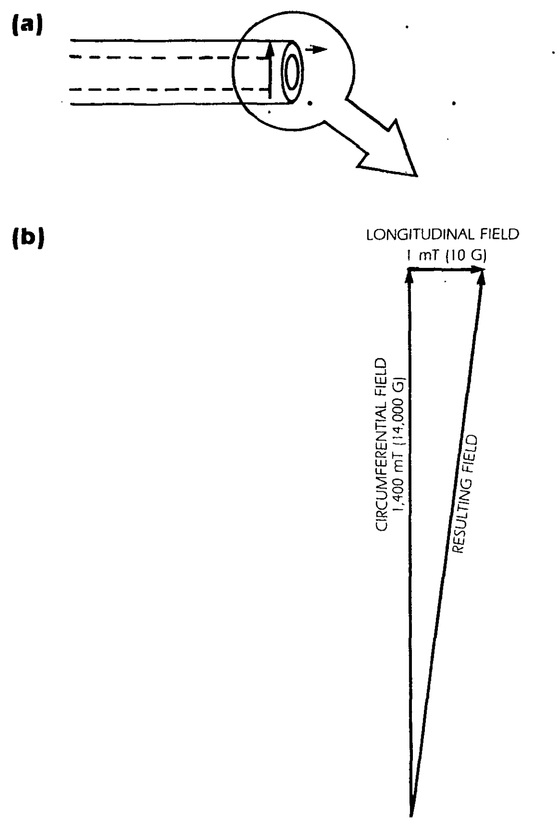
In this test, a calibrated gaussmeter is used to measure the maximum value of the magnetic field strength at the end of the material. If it exceeds a specified value, additional shots from the capacitor discharge internal conductor are applied to reduce this emergent field. For this application, a gaussmeter capable of reading up to 100 mT (1,000 G) is preferred over other types of field indicator.

Angled Nature of the Resulting Field

The presence of some small axial field strength at the end of a tube (or other elongated part) does not indicate that the tube is not circumferentially magnetized.[3] It merely indicates that the circumferential and axial flux densities involved obey a vector relationship such as that shown in Fig. 8.

In this particular example, the material just inside the end of the tube is saturated with magnetic flux that is virtually circumferential at a value very close to the remanence B_r for the steel. Suppose that an external flux density of 1 mT (10 G) occurs for a material with a remanence of 1,400 mT (14 kG). This flux density measurement was made with a gaussmeter after attempted circumferential magnetization by the method outlined above. Its value indicates that the direction of the flux inside the material is only $\tan^{-1}$ (1/1,400) or 0.04 degrees from being perfectly circumferential.

FIGURE 8. Possible magnetic flux density configuration at the end of a tube: (a) the emergent flux density is measurable with a gaussmeter but the circumferential component is not; and (b) the resulting field within the tube in this case is almost circumferential

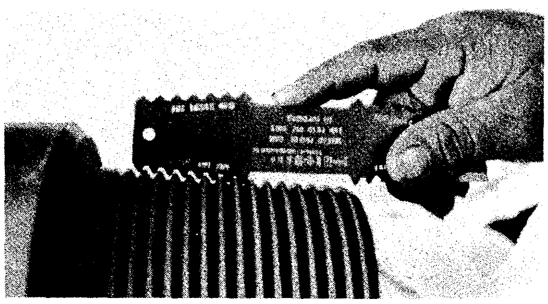


Drill Pipe End Area Tests

A commonly practiced magnetic flux leakage test is that of longitudinally magnetizing the ends of drill pipe (Fig. 6b) and looking for thread root cracks with wet fluorescent magnetic particle techniques. Figure 9 illustrates an example of pin thread stretching, the roots of these threads being particularly prone to cracking.[4] Following such a test, the rotation of the flux into the circumferential direction might require several pulses from a capacitor discharge internal conductor system. Under such circumstances, longer pulses (25 ms) are more effective than shorter ones (3 ms).

In the resulting circumferential magnetization, the drill stem can be tested for longitudinally oriented discontinuities and the tool joints can be tested for heat-check cracks with magnetic particle tests. The threads are also relatively easy to clean of particles.

FIGURE 9. Pin stretch on used drill pipe threads; wet magnetic particle tests are often used to detect fatigue cracking on these thread roots



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Upset Area Problems

It is generally necessary to apply only 3.2 to 4 kA•m^{-1} (40 to 50 Oe) circumferentially to magnetize oil field tubular materials to a point near saturation. This is especially true of the region between the ends of the material (*QR* in Fig. 10). Some materials may require higher field strength values to cause saturation (the *B-H* curve for the material should be consulted).

However, prior to threading the ends of such tubes, it is sometimes necessary to bell or upset the ends (*PQ* and *RS*) of the material. This process may lock in existing magnetic fluxes from earlier tests, the result being that the flux density at the ends can require a higher demagnetizing circumferential field than is required for the central regions of the tube. This is due to ineffective or incomplete stress relief at the ends after upsetting, which also causes the *B-H* properties to differ from those of the central regions.

When this situation is encountered, a gaussmeter can indicate the number of pulses required to rotate the flux within the upset areas.

Alternating Current Coil Demagnetization

After tubes have been longitudinally magnetized to saturation, lowering the remaining induction is usually done with alternating current or direct current through a centralized, surrounding coil. With the alternating current technique, it is critical to know that, for a frequency of 60 Hz, the skin depth being demagnetized is only about 1 mm (0.04 in.). The effect of this form of demagnetization is dependent on: (1) the strength of the demagnetizing field at the surface of the test object; (2) the thickness of the material; and (3) the material's *B-H* properties.

In traditional demagnetization with alternating current, it is required that the test object be slowly removed axially from the demagnetizing coil and that the strength of the field be sufficient to produce saturation in the direction opposed to the existing magnetization direction.

Because of the skin effect, the field strength at any point within the material is lower than that at the surface. If sufficiently high fields are to penetrate the material to cause demagnetization at that given point, the surface field amplitude must be several times higher than that required to cause saturation. At five skin depths (about 5 mm) one percent of the surface field remains. It is clear that the alternating current technique is confined to relatively thin or thin walled test objects and that some other form of demagnetization is needed for thicker materials.

FIGURE 10. Different circumferential magnetic field B-H curves: (a) at the belled or upset ends of tubes; and (b) the unworked center section of a tube; curve (a) shows lower B_r and higher H_c than curve (b)

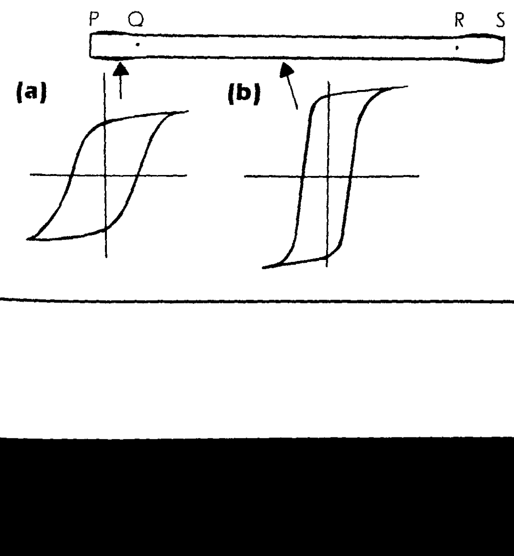
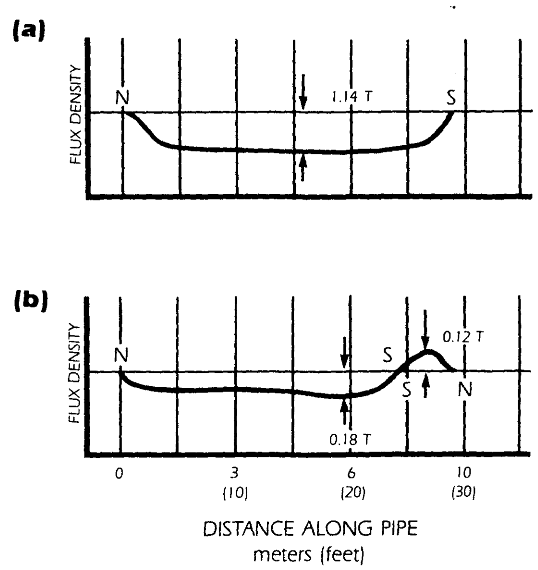


FIGURE 11. The axial bulk flux density in a 10 m (30 ft) long tube: (a) after longitudinal magnetization to saturation; and (b) after direct current coil demagnetization using a constant current; note the remanent flux density (1.14 T), the opposed dipole effect caused by the demagnetization process, and the values of the flux densities in the tube after this form of demagnetization



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Direct Current Coil Demagnetization

Partial demagnetization of tubes is often accomplished by passing the tube through a coil in which the field strength H opposes the direction of the residual induction in the material. Demagnetization current settings are obtained by trial and error since only the external fields at the ends of the tube are available to the inspector. Currently accepted practice is to adjust the demagnetizing field strength to provide the minimum fields at either end of the test object. As shown in Fig. 11, this process leaves the flux density within the material at a relatively high level.

The actual value of the axial flux density in the material is governed by two factors. The first is the local magnetic property or, in effect, just how high a value of flux density B can be sustained. The second is the proximity of the ends of the material (this affects the flux density through the demagnetizing field). The latter factor is very important within about 1 m of the tube ends and has a considerable effect on the local B-H properties. The general effect is to lower the local permeability, due to the internal demagnetizing field inside the test object.

As an example, the effect of direct current coil demagnetization on the axial flux density in a typical 10 m (30 ft) tube is shown in Fig. 11. As illustrated in Fig. 11a, the axial flux density of the tube after magnetization is relatively constant at 1.14 T (11.4 kG) except within about 1 m of either end. This value is close to the remanence for the material, which varies with localized stress, chemical composition and other factors.

After demagnetization, in which only the external field is sampled at both ends of the tube, the remaining flux density within the material is as shown in Fig. 11b. The flux density for the majority of the material is relatively low and in the same direction as the saturated state. However, at one end of the tube the direction of the flux has been reversed by the coil field for roughly 1.4 m (4.4 ft). The demagnetized material then exists in an opposing dipole configuration, with poles as shown in the illustration.

If this form of demagnetization is used, the inspector must consider each application individually. The direct current required depends on the wall thickness of the tube. Passage of the material through an alternating current coil, perhaps of low frequency, further lowers the contained flux.

Flux Sensed Demagnetization

Traditional alternating current and direct current demagnetization techniques do not totally demagnetize an object. They merely reduce the bulk flux density to the value at which emergent fields are low enough not to hinder subsequent metalworking processes. The following information is provided to show that lower bulk fluxes can be obtained by sensing the remaining flux and adjusting the demagnetization current to make the flux as small as possible.

A commonly used method for sensing the flux density level in an elongated object is to jerk a loosely fitting coil from a position of flux linkage with the part to a position of no flux linkage. This is shown in Fig. 12. With the coil in position-1, the flux linkage with the magnetized object is given by:

$$N\Phi = N \times \int \overline{B} \cdot \hat{n}dA \qquad \text{(Eq. 2)}$$

Where:

$N\Phi$ = the flux linkage (weber-turns);
N = the number of turns on the coil;
$\overline{B}$ = the flux density of the test object in the coil (webers per square meter or tesla); and
$\hat{n}dA$ = the area of the coil perpendicular to B (square meters).

With the coil in position-2, the flux linkage is zero and the net change in flux linkage is $N\int\overline{B} \cdot \hat{n}dA$. When the voltage induced in the coil during this process is integrated with a fluxmeter, the output (suitably compensated for the value of A and N) is the average value of the flux density in the test object directly inside the coil at position-1.

Applying this theory to the demagnetization process, the test object is passed through a sensing coil and the output of the fluxmeter is used to electronically compensate the current through the demagnetizing coil. This compensation produces a net flux density in the sensing coil, and therefore in the object, as close to zero as possible. This is shown schematically in Fig. 13.

FIGURE 12. Measurement of the flux at a specific position close to the end of an elongated test object; a search coil is taken from position-1 to position-2 and the resulting voltage is integrated within a fluxmeter; the fluxmeter output is proportional to the flux at position-1

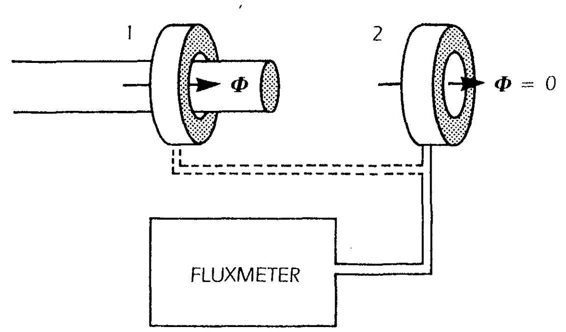
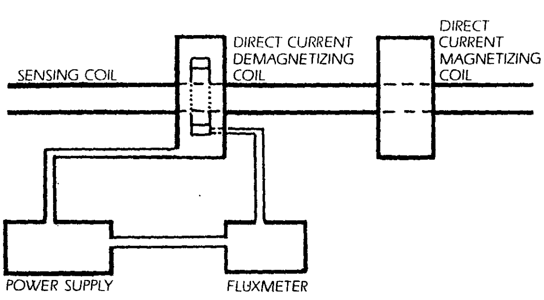


FIGURE 13. Diagram for optimizing the direct current demagnetization of an elongated test object; the sensing coil develops voltage as a magnetized material passes through it and the voltage is fed to a fluxmeter; the meter's signal is proportional to the flux density within the test object and is used to control the programmable power supply of the demagnetizing coil



Problems Associated with Partial Demagnetization

Partial demagnetization can lead to field problems when the material later appears to be highly magnetized. Because of the skin effect, surface demagnetization by the alternating current method is at best a temporary measure so that the bulk magnetization of the test object may eventually lead to large external fields.

The alternative practice is that of local application of a direct current field which, while it may remove the flux from a small region of a test object, does not leave the entire part demagnetized. Unless the entire object can be demagnetized totally, presently accepted practice will continue: the flux is reduced in certain regions of the object so that externally applied field indicators show a low field. The end user will continue to accept material that is highly magnetized even though it appears to be demagnetized. No specifications appear to exist for demagnetization procedures that lead to bulk flux reduction in previously magnetized objects. Below are examples of situations where the lack of demagnetization can cause problems at a later date.

A common practice in the testing of oil field tubes is to reduce the bulk flux to the condition shown in Fig. 11b. Subsequent transportation and other mechanical vibrations can cause the external field to rise to levels unacceptable to the end user. Such levels cannot be caused by the Earth's magnetic field (only 0.02 mT or 0.2 G) because the field strength required to magnetize these materials is much larger than 0.02 mT.

A second common practice is to pass a longitudinally magnetized tube or rod through an alternating current coil carrying 50 or 60 Hz current. Skin depth considerations reveal the volume of material actually demagnetized. The material is left in a highly magnetized state, apart from a surface layer. Subsequent handling causes the reappearance of high external fields.

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SECTION 14

REFERENCE STANDARDS AND ARTIFICIAL DISCONTINUITY INDICATIONS

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PART 1

FUNDAMENTALS OF REFERENCE STANDARDS FOR MAGNETIC PARTICLE TESTING

Nondestructive tests are typically designed to reveal the presence of discontinuities or to measure specific properties in a structure or material. The discontinuity may be an anomaly in a homogeneous material or a change in one of the material's properties (thickness, hardness or density, for example).

Before testing, some form of artificial discontinuity or reference standard is commonly used to verify the operation of a magnetic particle testing system. This verification is performed in order to (1) provide a sensitivity check of the testing procedure; and (2) establish a known correlation between the response of the test system, the magnitude of the material property or the severity of a discontinuity.

Magnetic particle testing uses magnetic fields to inspect ferromagnetic materials. Discontinuities in the material cause disturbances in the magnetic field and this in turn produces a leakage flux. It is this leakage flux that permits the formation of particle indications. Both the direction and intensity of the magnetic field are critical in determining the sensitivity of the test procedure. Both of these factors are in turn affected by the nature of the material, the test object geometry and the way in which the magnetic field is induced.

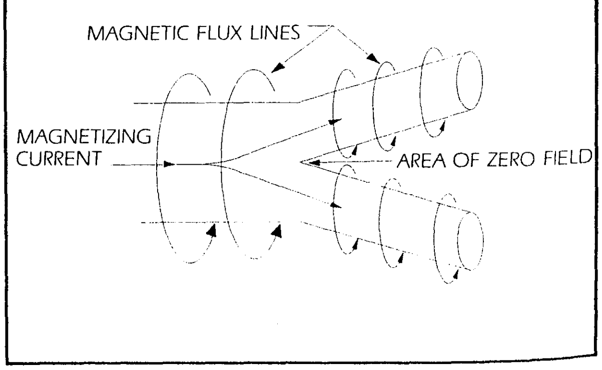
All of these parameters are interrelated to determine the direction and intensity of the magnetic field in a particular location in a test object. The mathematics of these interrelationships does not lend itself to straightforward, closed form solutions even for relatively simple geometries. A generalized solution for more complex test objects has not been obtained and would probably not completely solve the problem of establishing magnetic particle testing procedures.

Empirical Rules for Using Reference Standards

Perhaps more than any other nondestructive technique, magnetic particle testing has based its procedures on empirical data (rules of thumb) developed by trial and error in the early days of the method. These rules have persisted through the years in various standards and specifications. The reliance on empirical data occurred because of the enormous complexity of magnetic fields and their interactions with ferromagnetic components. Unfortunately, rules of thumb have sometimes been used exclusively for determining the adequacy of certain test setups. As with most empirical data, the rules developed for magnetic particle testing should be used with caution and with an understanding of their limits. Caution dictates that regular system monitoring be used to verify acceptable test sensitivity — most existing formulas ensure over-magnetization in some test objects.

It is easy to demonstrate the connection between misused rules of magnetization and inaccurate testing. Figure 1 shows where a null field is produced at the fork in a simple test object configuration. Failure to use some form of field strength indicator to verify the presence of a valid magnetic flux could lead to inadequate testing of this critical area. Measurements with the means described here have shown a variation from 0.3 to 8.5 mT (3 to 85 G) within the same test object, because of its geometric differences.

FIGURE 1. Magnetic particle testing problem area in a simple part geometry



Reliability Studies

The absence of verification has led to widely varying effectiveness. Two often cited reliability studies are excellent examples of the problems associated with the lack of a sensitivity check. The first of the studies[1] was the result of a round-robin among four major aerospace contractors, two jet engine manufacturers, three landing gear manufacturers, one major forging supplier and a commercial test lab. Each company processed and tested twenty-four pedigreed specimens with known discontinuities. All of the discontinuities were considered detectable at that time in the method's development. Figure 2 shows the results of that study.

The companies varied from less than 20 percent detection to over 90 percent. Only one of the eleven companies scored better than 60 percent of the discontinuities. At the time of its completion, the study drew few conclusions about the cause for this variability.

In another study,[2] it was concluded that the maximum probability of detection was 55 percent on jet turbine blades made of magnetic alloys (Fig. 3). The reasons for the poor results were not individually assessed.

Needs for a Known Indicator

The goal of system monitoring is to verify that the system is performing in the desired way and at the desired sensitivity. The most direct way to achieve this goal is to verify the system's ability to detect one or more known discontinuities. Ideally this would be done with a discontinuity of the smallest critical size in an exact duplicate of the test piece. This ideal is rarely if ever practical.

More often, some form of artificial discontinuity indicator is used. This so-called *reference standard* is designed to help evaluate several aspects of a magnetic particle system's performance, including: (1) testing the magnetizing equipment; (2) checking the sensitivity of the magnetic particle compound; and (3) verifying the adequacy of a test procedure for detecting discontinuities of a predetermined magnitude.

System Evaluation

Unlike other nondestructive testing methods, magnetic particle testing systems give little evidence of malfunction. The absence of a test indication could mean that (1) tests were properly performed on samples without discontinuities; or (2) the testing system was not working and therefore not locating existing discontinuities.

As a result, some form of reference standard is needed to determine proper system performance and adequate sensitivity. Such a system evaluation tool should check for contamination of the magnetic particle bath, material visibility (loss of fluorescence on fluorescent oxides), particle concentration (for wet methods), adequate particle mobility, and the ability to generate an appropriate magnetic field.

System Standardization

When multiple variables can affect the outcome of a test, a means should be used to normalize or standardize the test. This ensures that consistent, repeatable results are achieved, independent of the machine, the operator or the time of the test.

The most direct way to achieve consistent results is to regularly use a reference standard to compare system sensitivity to preestablished tolerances. If the desired sensitivity is not achieved, testing should be stopped to allow required system adjustments.

FIGURE 2. Magnetic particle discontinuity detection survey results

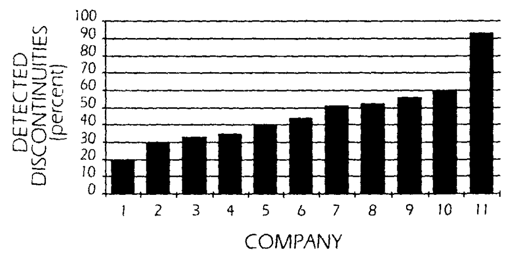
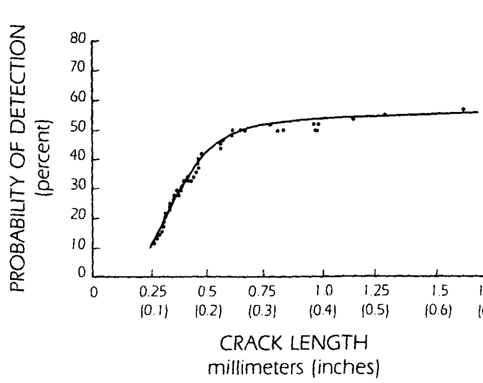


FIGURE 3. Magnetic particle testing discontinuity detection probability



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Parametric Evaluations

It is at times useful to examine a system's sensitivity to changes in one or more variables. For example, to evaluate the effectiveness of magnetic particle testing on chromium plated components, it would be appropriate to investigate: (1) the effect of various plating thicknesses; (2) the sensitivity of the test to changes in current levels or field strength; and (3) the effect of changes in the particle type or bath concentration.

Reference standards are used to study these changing parameters. Indications of the known discontinuities help determine the effect of the individual parameters on test sensitivity. The results of such studies are used to generate or modify testing procedures for the material and geometry of interest.

Technique Development

In the past, it was common for some operators to rely solely on empirical rules for establishing magnetic particle testing procedures. This practice frequently lead to overmagnetization, poor coverage, inappropriate selection of test geometries or some combination of all three disadvantages.

The selection of an appropriate test technique may be the single most important factor in the success of a magnetic particle test. The use of reference standards and artificial indications can significantly improve system performance and may also reduce the cost of testing by eliminating unnecessary configurations or scrappage caused by excessive current. The use of reference standards during technique development can quickly verify the completeness of coverage, the direction of magnetizing fields and the level of field strengths.

In many cases, it can be demonstrated that common rules of thumb produce field strengths far in excess of those necessary for detecting particular discontinuities. Excessive field strength might *appear* to provide a margin of safety for unknown effects of test object material and geometry. However, in many cases, this excess produces a significant field component normal to the test object surface. This in turn reduces particle mobility, increases particle background and actually reduces rather than enhances the sensitivity of the test. Reference standards are often used to regulate field strength to avoid excess flux while achieving accurate indications.

Two kinds of artificial discontinuities are used for magnetic particle test systems: (1) those designed to indicate the adequacy of the field in an unknown test object; and (2) those designed to measure the effectiveness of the testing system independent of the test object.

PART 2
REFERENCE STANDARDS FOR SYSTEM EVALUATION

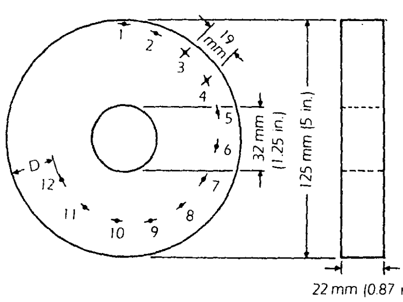
Reference standards may be used to evaluate the functionality or performance of a magnetic particle testing system. On a periodic basis, reference standards are used as test objects in order to monitor the system for changes in magnetic field production, particle concentration, visibility or contamination. It is helpful to have graduated discontinuities so that a numerical indicator of the system performance can be recorded and monitored.

Tool Steel Ring Standard

The tool steel ring is a commonly used and universally recognized reference standard for magnetic particle testing systems (see Fig. 4 and Table 1), but it essentially indicates only particle efficacy. It appears in virtually all US codes and specifications as the means for checking magnetic particle performance. The ring was first used in 1941[3].

Since that time, its use has expanded for both wet and dry methods, to the point that the ring is widely used for measuring system performance. It is important, however, to recognize the ring's limits. For example, a current density level less than 20 percent of that usually applied (Table 2) is all that is needed to indicate a surface discontinuity 0.25 mm (0.01 in.) in length.

FIGURE 4. Tool steel ring standard (see Table 1)



Using the Ring Standard

The ring standard is used by passing a specified direct current through a conductor which in turn passes through the ring's center. The magnetic particle testing procedure (or system) is evaluated based on the number of holes detected at various current levels. The number of holes that should be detected at a particular current level is provided by written specifications (see Table 2).[4]

Standard test objects such as the ring have proven to be a valuable aid in controlling magnetic particle test system

TABLE 1. Comparative dimensions for a tool steel ring standard (see Figure 4)

Hole Number	Diameter millimeters (inches)	Distance from Edge to Center of Hole millimeters (inches)
1	1.78 (0.07)	1.8 (0.07)
2	1.78 (0.07)	3.6 (0.14)
3	1.78 (0.07)	5.3 (0.21)
4	1.78 (0.07)	7.1 (0.28)
5	1.78 (0.07)	9.0 (0.35)
6	1.78 (0.07)	10.7 (0.42)
7	1.78 (0.07)	12.5 (0.49)
8	1.78 (0.07)	14.2 (0.56)
9	1.78 (0.07)	16.0 (0.63)
10	1.78 (0.07)	17.8 (0.70)
11	1.78 (0.07)	19.6 (0.77)
12	1.78 (0.07)	21.4 (0.84)

TABLE 2. Test indications required when using the tool steel ring standard

Type of Magnetic Particles Used	Current* (amperes)	Minimum Number of Holes Indicated
Wet suspension**	1,400	6
	2,500	7
	3,400	7
Dry powder	1,400	7
	2,500	9
	3,400	9

*FULL-WAVE DIRECT CURRENT AT CENTRAL CONDUCTOR
**VISIBLE OR FLUORESCENT

parameters.[5] However, in addition to magnetizing current level, other factors influence test results, including the properties of the particles, operator skill, magnetization level, direction of the magnetic fields produced, and particle concentration. An evaluation of all the contributing factors requires the development of mathematical models[6] to describe their effect on the formation of test indications.[7]

Ring Standard Magnetic Fields

All magnetic leakage fields are a superposition of dipolar fields. This dipole character is usually evident when the field from the discontinuity is measured.[8,9] The field arising from a long cylindrical discontinuity in a linear isotropic medium can be exactly calculated and has a pure dipolar character. Referring to the coordinate system defined in Fig. 5, the applied field has a value of H_o and is in the X direction.

This is a classic problem in magnetostatics[10] whose solution in the region of permeability μ_1 consists of the vector sum of the applied field H_o with a dipole field centered at the origin. The dipole field can be written in polar coordinates as:

$$H_r = -m \frac{\cos \theta}{r^2} \quad \text{(Eq. 1)}$$

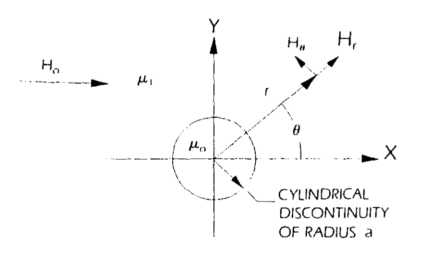
$$H_\theta = -m \frac{\sin \theta}{r^2} \quad \text{(Eq. 2)}$$

Here, m is a dipole moment per unit of length along the cylinder axis and is given by:

$$m = \frac{\mu_1 - \mu_o}{\mu_1 + \mu_o} H_o a^2 \quad \text{(Eq. 3)}$$

The field from the cylindrical discontinuity is exactly that which would be obtained from a magnetic dipole of strength m per unit length centered at the origin and pointing in the negative X direction (since $\mu_1 > \mu_o$), or that which would be obtained from a current dipole with a current separation product of $2\pi m$ pointing in the negative Y direction.

FIGURE 5. Coordinate system for cylindrical discontinuities



Influence of a Boundary

The field from a cylindrical discontinuity next to a plane boundary can be obtained using the method of images. The field above the plane surface is the sum of the fields from a dipole at the center of a discontinuity with strength as given by Eg. 3 and an infinite series of images as illustrated in Fig. 6. To a good approximation, when $h > 2a$, all image dipoles are assumed to be at the center of the cylinder.[11] The field above the surface can then be described by Eqs. 1 and 2 (rather than by Eg. 3), with m given by:

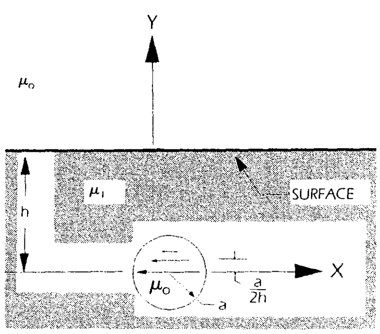
$$m = \left(\frac{2\mu_1}{\mu_1 + \mu_o}\right)\left[1 + \left(\frac{\mu_1 - \mu_o}{\mu_1 + \mu_o}\right)^2 \left(\frac{a}{2h}\right)^2\right]\left(\frac{\mu_1 - \mu_o}{\mu_1 + \mu_o}\right) H_o a^2 \quad \text{(Eq. 4)}$$

Magnetic particle test materials generally have $\mu_1 \gg \mu_o$. The major effect of the surface is an approximate doubling of the effective dipolar field from the first term on the right of Eg. 4 and a small increase from the second term (about 7 percent when $h = 2a$).

Sample Leakage Field Calculation

The calculated field from a subsurface cylindrical discontinuity (as obtained by Eqs. 1, 2 and 4) has the familiar form illustrated in Fig. 7. The illustration shows the components tangential and perpendicular to the surface (the most commonly measured components).

FIGURE 6. Dipole images for the field from a cylindrical discontinuity next to a plane surface

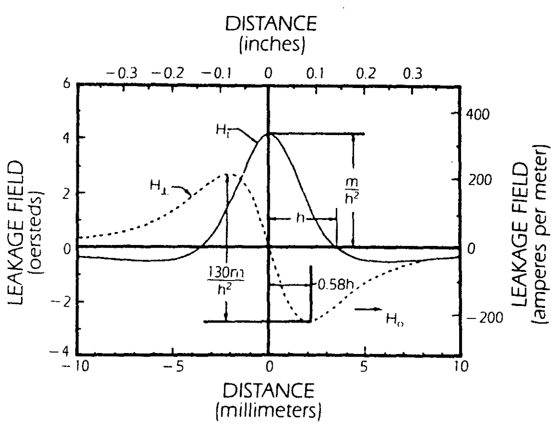


The numerical values are based on the hole depth (h = 3.56 mm or 0.14 in.) and hole radius (a = 0.89 mm or 0.03 in.) of hole 2 in the ring, with a central conductor current of 1,000 A. This corresponds to an H_o value of 2.5 kA•m^{-1} (31.5 Oe). This calculation applies to the ideal case of a linear isotropic magnetic medium with a high permeability, a two-dimensional geometry (a cylindrical discontinuity of infinite length) and a plane parallel boundary. Although the test ring of Fig. 4 deviates considerably from this ideal condition, comparison of measured leakage fields with the form shown in Fig. 7 reveals that the leakage fields from the ring can be closely approximated by Eqs. 1 and 2.

Limitations of the Ring Standard

A 1986 study revealed a lack of uniformity among ring standards used around the United States.[12] When tested in a prescribed manner, the rings were found to produce indications anywhere from 4 to 11 holes, while indicating no difference in hardness or spectrographic analysis. The data appear to cluster around two sensitivities, one at 5 to 6 holes (40 percent of the rings) and the other at 9 to 10 holes (46 percent of the rings).

FIGURE 7. Calculated components of the magnetic leakage field at the surface of a subsurface cylindrical discontinuity in a linear isotropic magnetic medium with high permeability and with the applied field in the positive X direction



A ring that showed 5 holes at a given current density produced 9 holes in a repeat of the sensitivity test after annealing. Standardization efforts are being pursued to control this problem.

Reference Standard Test Blocks

Split Prism Test Block

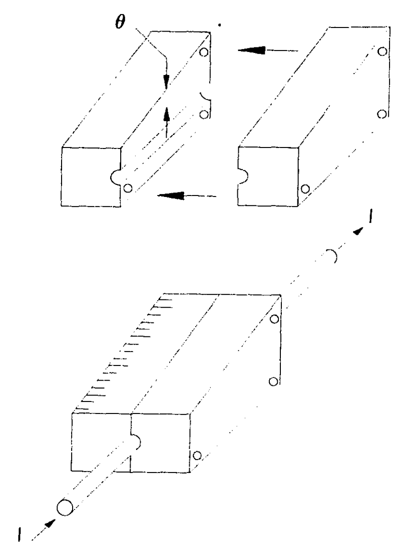
The prism block shown in Fig. 8 is another reference standard containing an artificial discontinuity.[13] Truncated half-prisms are built with one face at an angle and when two such components are bolted together, an artificial crack is formed. The sloped surface of the block can be positioned at variable distances from the conductor.

When current is passed through the conductor, the leakage field from the crack gradually weakens along the prism face. A specified amperage is applied through the conductor and the length of the magnetic particle indication is used to measure the test sensitivity.

Magnetized Test Blocks

Another version of the block standard consists of two ground steel blocks forming an artificial crack at their

FIGURE 8. Prism sensitivity indicator



contact surfaces (see Fig. 9), similar to the discontinuity formation in the split prism test block. On one of the face ends, a small permanent magnet is fixed below a brass cover, causing magnetic flux leakage from the artificial discontinuity. This leakage field decreases with greater distance from the magnet, so that longer discontinuity indications reveal higher test sensitivity.

This same task can be fulfilled by another block standard using a slightly different test principle: a residually magnetized block is manufactured to contain a network of many different crack widths on its surface (see Fig. 10). A typical standard of this type is 50 mm (2 in.) in diameter and 10 mm (0.4 in.) thick. Very fine cracks are situated between grosser discontinuities across the block standard's face. As an example of this standard's use, the loss of indications for the fine cracks (or their appearance as points rather than lines) indicates that the magnetic particle bath is no longer usable.

FIGURE 9. Block standard containing a permanent magnet

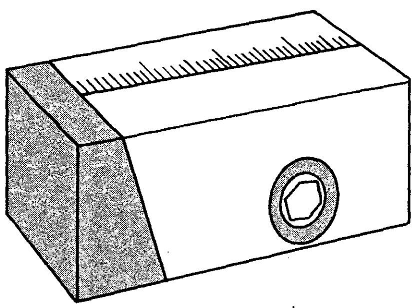


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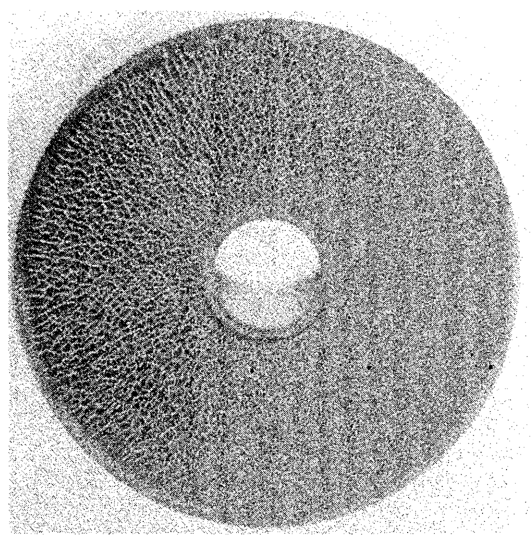
FIGURE 10. Residually magnetized block standard



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PART 3
MAGNETIC DISCONTINUITY STANDARDS

Artificial discontinuity standards and magnetic field indicators of the shared flux type all have some common characteristics. The basic shared flux gage was developed by Dr. B. Berthold and was first used in Germany in the late 1930s to indicate magnetic field direction. Refinements have resulted in the pie gage, widely used in weld testing applications (specified by NavShips 271), and in the so-called magnetic penetrameter or raised cross indicator. Both of these devices respond to applied magnetic fields, regardless of the test object or lack thereof.

On flat ferromagnetic surfaces, the shared flux devices respond well and verify magnetic field strengths capable of detecting surface discontinuities about 0.025 mm in length and 0.01 mm deep. On complex test objects with convex surfaces, the value of shared flux devices is limited and invariably results in over-magnetization when so applied.

Shared flux discontinuity standards should only be used in conjunction with the continuous method of particle application. When the continuous method is *not* used, commercial pie gages may indicate a magnetic field, but this is evidently residual magnetism in some gages or possibly even physical entrapment of particles.

All artificial discontinuity standards can produce results comparable to a Hall effect gaussmeter. A shim with 30 percent discontinuity depth and pie gages can indicate discontinuities 0.25 × 0.05 mm (0.01 × 0.002 in.) at 0.9 to 1.5 mT (9 to 15 G), depending on the permeability of the test object material.

Pie Gages and Raised Cross Indicators

Pie gages are disks of high permeability material divided into triangular segments separated by known gaps (see Fig. 11a). The gaps are typically filled with a nonmagnetic material, to protect the integrity of the gap and to strengthen the disk. The testing surface is coated with a nonmagnetic layer. The pie gage contains eight segments separated by gaps up to 0.75 mm (0.03 in.). The gaps run the full depth of the gage.

Raised cross indicators contain four gaps (in the shape of a cross) approximately 0.13 mm (0.5 in.) in width. The segments are cut away so that the known gap is raised a fixed distance off the test object surface (see Fig. 11b).

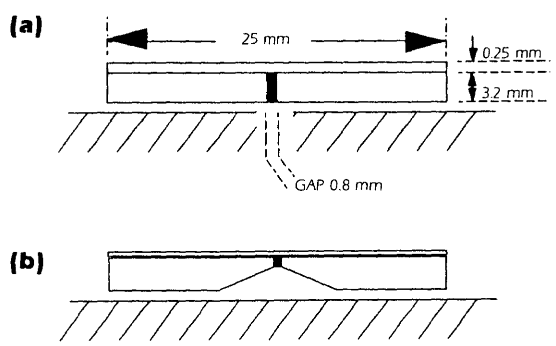
Both of these devices are used to determine the approximate orientation and, to a limited extent, indicate the adequacy of field strength. However, they do not measure the internal field strength of the test object. They merely detect external fields in the vicinity of the test object. The presence of multiple gaps at different orientations helps reveal the approximate orientation of the magnetic flux. Slots perpendicular to the flux lines produce the most distinct indications. Slots parallel to the flux lines produce little or nothing.

Limitations of Pie Gages and Raised Cross Indicators

The raised cross indicator is designed to have a large liftoff (the discontinuity distance from the testing surface). Yet because of this, there is some question about what the raised cross device actually detects during residual induction tests. The pie gage sits closer to the testing surface and generally performs better than a raised cross indicator at the same point. This occurs for two reasons.

Both devices attract and hold magnetic particles, as determined by the leakage fields from the test object. The gap in the raised cross is farther from the testing surface than the slot in the pie gage and it is exposed to less ambient field than the slot in the pie gage. Also, being thinner, the raised cross gap causes less flux leakage at the slot, mainly because such slot fields are width dependent.

FIGURE 11. Gap indicators for magnetic field measurements: (a) pie gage and (b) raised cross indicator



Shim Discontinuity Standards

Shim indicators are thin foils of high permeability material containing well-controlled notch discontinuities (see Fig. 12). Frequently, multiple shims are used at different locations and different orientations on the test object to examine the magnetic field distribution.

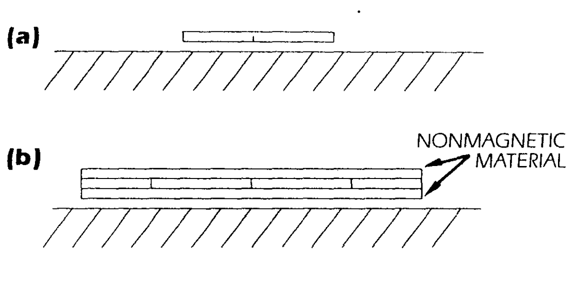
One popular version of the shim indicator is a strip of high permeability magnetic material containing three slots of different widths. The strip is placed in contact with the testing surface and shares flux with the test object. For the purposes of producing test indications, the slots in the strip act as if they were cracks in the test object. A principle limitation of this standard is that a 50 mm (2 in.) gage length is needed.

Another type of shim (sometimes called a *block*) has been used in Japan since the 1960s (see Fig. 13). As described in Japanese Industrial Standard G 05665, these indicators are used for examining the "performance of the apparatus, magnetic particles and suspension, and the strength and direction of effective magnetic field on the surface of the test article."

The blocks are available in a variety of thicknesses and slot depths. Linear and circular slots are available. Circular slots are particularly effective when the direction of the magnetic flux is not known. The shims are taped to the test object (slotted side in close contact with the part), in areas where the strength and direction of the magnetic field are in question. The slots share magnetic flux with the test object and simulate slightly subsurface discontinuities.

An American version of the Japanese shim is manufactured in 0.05 mm (0.002 in.) and 0.1 mm (0.004 in.) thicknesses, with discontinuity depths of 15, 30 and 60 percent of the shim thickness. The controlled discontinuities are available as either linear grooves or circular grooves. The circular discontinuities have the added advantage of indicating the direction of maximum field strength and the angular tolerance of sensitivity. Such shim standards can be used when setting up multidirectional magnetization, to ensure that balanced fields exist in all directions during the magnetizing cycle at any given point in the test object.

FIGURE 12. Shim indicators for magnetic field verification: (a) simple shim and (b) slotted strip



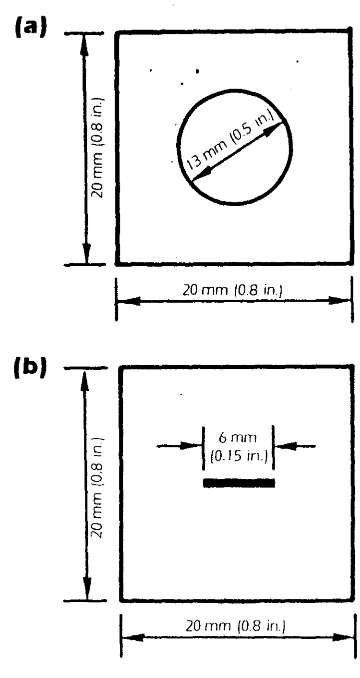
Application of Shims

Shims are sometimes called *paste-on discontinuities* because they must be attached to the test object with pressure sensitive tape. Shims are used most often during the development of test procedures, where they help indicate the relative strength and direction of a magnetic field for a particular test configuration.

Because shims are often made of high permeability foils, they are generally small and flexible enough to fit into fairly complex test object geometries to help determine the adequacy of field strength in these critical areas.

Once the field distribution is found adequate, the testing procedure is recorded and the components are tested with the parameters established by the shims.

FIGURE 13. Japanese type A standard test shims: (a) circular and (b) linear



PART 4
ELECTRONIC REFERENCE STANDARDS

Hall Effect Meters

Hall effect devices are commonly used to measure the strength of the magnetizing force tangential to the surface of a test object. Though often called a *gaussmeter*, the device does not actually measure the magnetic flux B within the component. Rather, it measures the magnetic field strength H adjacent to the test object. The Hall effect meter is a relatively effective indicator and is in widespread use for establishing magnetic particle testing procedures. They effectively measure residual fields and indicate the direction of the remanence.

Various specifications call for the use of different tesla (gauss) or ampere per meter (oersted) values in particular applications. In air, the nonmetric gauss and oersted units are numerically equal in value. Required values commonly range from 1.6 kA•m^{-1} (20 Oe) to 4.8 kA•m^{-1} (60 Oe) when the residual method is used. A residual field less than 240 A•m^{-1} (3 Oe) usually does not attract conventional magnetic particles.

Eddy Current Devices

The ability of a material to store electromagnetic energy in the form of eddy currents is a function of both the conductivity and permeability of the material. Because the permeability of a ferromagnetic material changes as the material is magnetized (from a relatively low initial permeability through a higher maximum value), the eddy current coil impedance also changes.

Several eddy current procedures have been developed to detect this change in permeability and thereby indicate the degree of magnetization. Because of poor repeatability, few of these procedures are widely used. The repeatability problem stems from the large number of variables that can affect eddy current response in a ferromagnetic material.

A magnetization level indicator has been developed to detect imbalance in the permeability along the lines of flux compared with the permeability transverse to the lines of flux as the material approaches magnetic saturation.

Conclusion

Magnetic particle testing historically relied on empirical guidelines for the development of test procedures. This practice led to widely varying discontinuity detection capabilities. Various codes and specifications have perpetuated the problem by citing rules of thumb for establishing procedures.

Several forms of reference standards are available for verifying procedures and for evaluating the performance of a magnetic particle testing system (as a whole or by components). Reference standards for this purpose are usually made of high permeability materials containing controlled graduations of artificial discontinuities. Reference standards are also available for evaluating the effectiveness of a magnetic particle test for a particular test object. These devices include a variety of shim configurations containing known discontinuities.

Electronic reference standards such as Hall effect meters and eddy current devices can also be used to evaluate the adequacy of a test procedure.

Widespread use of reference standards and test discontinuities is needed to improve the consistency of magnetic particle tests and to increase the detection reliability of the method.

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SECTION 15

EQUIPMENT FOR MAGNETIC PARTICLE TESTS

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PART 1
BASIC EQUIPMENT CONSIDERATIONS

Magnetic particle testing equipment can be as small as a handheld yoke or as large as the billet testing units found in steel mills. Magnetic particle systems have evolved dramatically from the relatively small and simple units first produced. The primary improvements parallel developments in other technologies and include faster electronic switching, automatic current control and improved materials for particles, coatings and vehicles.

In its fundamentals, the magnetic particle testing technique has not changed much since its conception in the 1930s. However, significant changes have occurred in three areas: (1) the magnetic particle materials; (2) the configuration of testing systems; and (3) the automated components designed to meet contemporary manufacturing and production needs.

Magnetic particle test systems must fulfill two basic requirements: (1) to accurately perform a nondestructive test based on amperage requirements, test object size, magnetic field levels and suitable testing area; and (2) to perform the test with or without operator intervention at a rate required by the particular production facility.

In turn, these two requirements determine the size, shape, speed and configuration of the magnetic particle testing system.

Effect of Testing Parameters on Equipment Choice

Production Speed

Some magnetic particle testing systems operate at slow production speeds, often as low as a few large components per day. In other instances, the testing equipment is an integral component of a production line, processing and testing hundreds of objects per hour.

If only because of handling considerations, these two applications require completely different types of testing systems, designed and built to accommodate their specific uses.

Test Sensitivity

In some high production applications, the magnetic particle testing system is used as a product screening device: *any* indication of a discontinuity becomes cause for rejection. Once removed from the production line, the rejected object may then be reevaluated or reworked as needed.

In applications such as aerospace or plant maintenance, magnetic particle tests need to be very sensitive. Extremely small discontinuities must be detected and correspondingly small test indications must be produced for evaluation and interpretation.

For some applications, high sensitivity is actually a problem: excess leakage fields produce false indications and dense backgrounds. The magnetic particle test sensitivity must be established in order to indicate discontinuities within a range of severity appropriate to the application.

Configuration of the Test System

The following list is a summary of the choices and considerations that determine the configuration of a magnetic particle testing system for a specific application:

1. particle type (wet or dry);
2. magnetization requirements of the test object;
3. degree of automation required;
4. demagnetization requirements;
5. current requirements;
6. test object size and corresponding test system size;
7. electrical power availability;
8. air supply requirements;
9. accessories needed for the application; and
10. test specifications requiring verification.

Each of these ten considerations is affected by many other testing or manufacturing parameters. Magnetization, for instance, may need to be achieved with alternating current, half-wave rectified alternating current, full-wave rectified alternating current or single-phase rectified alternating current, depending on the nature of the test object and the purpose of the test. As another example, demagnetization requirements are determined by the test object's subsequent use and the magnetization method. In addition, demagnetization procedures may need to be incorporated into the main testing system or performed at a separate station.

Choosing the correct magnetic particle testing equipment is the last of several preliminary decisions. First, there must be a thorough understanding of the magnetic particle technique, especially its capabilities and limitations. This understanding is then applied to the specific requirements of the expected test objects and their anticipated discontinuities. The test object's magnetic characteristics, its geometry and its intended service are all important factors that affect the choice of the magnetic particle system. Finally, the test system must be configured and installed so that it is an integral part of the existing production facility.

The text that follows is a generalized view of magnetic particle testing systems and can serve as a guide for making the more specific decisions required by each testing application.

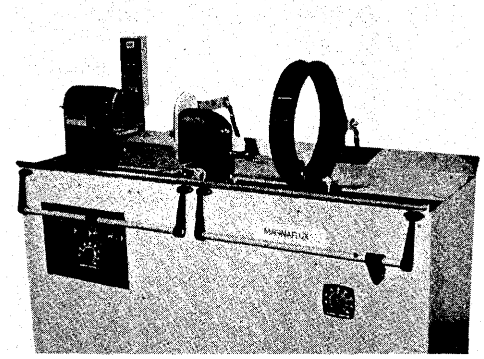
PART 2
WET HORIZONTAL EQUIPMENT

The magnetic particle equipment most commonly used for production testing is the *wet horizontal unit* (see Fig. 1). The name is derived from the unit's use of the wet method test techniques and its horizontal bed for positioning the test object.

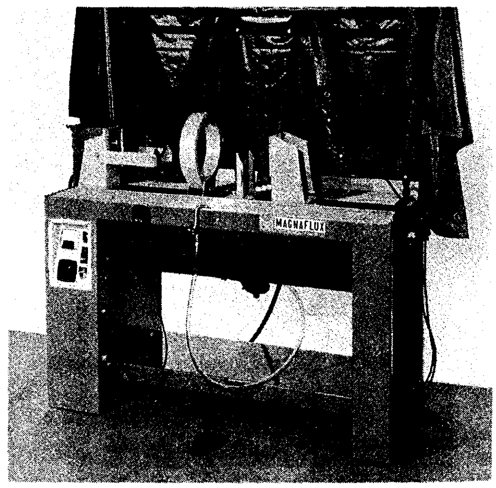
The nominal length of such a unit is determined by the size of the object that can be fixed inside its clamping subsystem. Lengths of 1 to 4 m (3 to 12 ft) are used for most applications. Many other system lengths have been designed, some for objects as small as aerospace bolts a few millimeters in length. On the other end of the scale, very long systems have been built for testing steel billets, gun tubes, oil field pipe or railroad engine crankshafts.

FIGURE 1. Typical horizontal magnetic particle bench testing units: (a) direct current unit with split magnetizing and control functions for two operators; and (b) small alternating current unit with decay magnetizing

(a)



(b)



Positioning the Test Object

Before performing magnetic particle testing, the object is clamped between a headstock and an adjustable tailstock that moves horizontally along rails in the unit's bed.

The headstock holds the test object by means of a compressed air cylinder. An electrically operated switch, often a foot switch, is the common method for controlling the throw of the headstock air cylinder.

The tailstock's position may be controlled by a gear screw and hand crank or, in some smaller units, the tailstock is simply pushed into position along the bed. Some systems use motor driven tailstocks but these are slow and are normally used only in special applications.

Magnetization Procedures

A wet horizontal testing system is usually capable of producing circular magnetization by the direct contact method and longitudinal magnetization with an encircling coil or a yoke configuration.

Once the test object is clamped into position, electrical current is passed through it or through a conductor for setting up an induced field. For longitudinal magnetization, most horizontal systems have a rail-mounted magnetizing coil that may be moved along the horizontal axis of the machine. While the test object is being loaded, the coil is moved clear of the headstock and tailstock opening. After circular magnetization, the coil is moved to encircle the object. On test objects over 450 mm (18 in.) in length, the encircling coil must be repositioned in 350 to 425 mm (14 to 17 in.) increments. With yoke procedures, longitudinal fields are set up along the entire length of the test object, with no need for repositioning. A suitable reference standard with known discontinuities should be used to ensure adequate field strength at the midpoint of the test object.

Following each magnetization procedure, the test object is examined using wet method magnetic particle techniques. Large test objects remain in position on the bed of the unit. Many wet horizontal testing systems are also equipped for demagnetization procedures.

Alternating and Direct Current Systems

Wet horizontal units used for in-service and in-process testing are usually single-phase alternating current systems. Alternating current equipment is less expensive to manufacture because costly rectifying circuitry and associated cooling systems are not required. In addition, a separate demagnetizing unit is not necessary with alternating current units and test objects are demagnetized in position on the unit.

Aerospace codes and many manufacturing standards specify the use of direct current magnetic particle testing equipment. These are usually three-phase full-wave rectified alternating current systems. In the early days of the magnetic particle method, direct current was supplied by a bank of acid storage batteries that were often inefficient and unreliable. In 1941, the rectifier circuit was developed, producing unidirectional current from alternating current and replacing the troublesome battery bank.

Comparison of Alternating and Direct Current Equipment

There are many differences between the basic circuitry in direct and alternating current magnetic particle testing systems.

For example, direct current equipment often has a current timer that is preset for a half second duration so that a low duty cycle can be used. The timer may be bypassed manually and in contemporary units it is adjustable. Test systems using fully rectified alternating current require augmented cooling. Fans help fulfill the cooling requirements of the rectifier circuitry. Such systems may offer demagnetization using reversing direct current with step down procedures or alternating current demagnetizing circuitry with rapid decay.

Because alternating current produces a skin effect (with penetration depth dependent on line frequency), the resulting magnetic field follows the contour of the test object. With direct current magnetization, the current and the resulting field follow the path of least resistance, which is not necessarily the location of discontinuities. Therefore, alternating current equipment is often chosen because of an improved probability of detection. In addition, an equivalent relative field strength in an alternating current system requires only about 50 percent of the current used by a direct current system.

Wet Horizontal System Components

The rated magnetizing output and duty cycle of wet horizontal systems vary with the model and manufacturer. Alternating current equipment usually has a maximum output of 1.5 to 3 kA with some rated as high as 6 kA. Full-wave rectified alternating current equipment usually has a 2, 4 or 6 kA rating. For larger test objects, long systems can be manufactured with 10 kA or more direct current.

Table 1 lists the components of a typical wet horizontal magnetic particle testing system.

Test Systems Used Outside the United States

Magnetic particle testing systems used outside the US differ in several ways. First, because alternating current is in more widespread application, nearly all systems are designed for use with single-phase input. Where applicable, rectified circuitry is generally half-wave rectified alternating current. Single-phase equipment is appreciably less costly to build than the three-phase rectified systems used in the US. Single-phase equipment must have primary current double that of a three-phase system for the same secondary or magnetizing current output.

The main advantage of three-phase rectified alternating current is that the demanded theoretical power usage is lower. However, because most testing applications have a 10 percent duty cycle (0.5 seconds on and 5.0 seconds off), the saving in power is comparatively insignificant. Single-phase magnetizing current provides far greater particle mobility for dry and wet particles.

The second important difference, especially in European systems, is the nearly universal use of yokes rather than coils for developing a longitudinal field in test objects. Many European systems have no magnetizing coil at all mounted on the unit.

A third difference is that most of the electrical or electronic components are separated from the mechanical or handling portions of a system. In many countries, this separation is a code requirement with safety to personnel as justification. Note that since 1950, no instance of electrocution has been traced to a magnetic particle apparatus, mainly because secondary (magnetizing) circuits produce relatively low voltage.

TABLE 1. Components of a typical wet horizontal magnetic particle testing unit

- Hood: encloses the unit for ultraviolet light tests
- Instrument pedestal: holds meters and other controls
- Ammeter: measures amperage of direct current
- Adjustable timer: controls elapsed time of magnetizing current
- Visible light source
- Switches: fan and visible light controls
- Coil: for longitudinal magnetization
- Contact plate: for circuit connection at tailstock
- Tailstock: adjustable to test object length
- Crank: adjusts tailstock position
- Curtain: encloses hood to restrict visible light
- Actuator bar: triggers actuator to operate magnetizing current
- Transfer switch: selects coil or head shot magnetization
- Push button: magnetizing current start control
- Current control: selects current levels
- Foot switch: controls air pressure valve for headstock contact plate
- Actuator: connected to actuator bar to operate magnetizing current
- Power indicator: indicates when power supply to unit is active
- Pump switch: activates pump for magnetic particle suspension
- Shelves: headstock and tailstock contact plates to support test objects
- Hose: delivers magnetic particle suspension
- Nozzle: applies magnetic particle suspension to test object
- Contact plate: for circuit connection at headstock
- Headstock: supports air cylinder that operates contact plate
- Swing arm: allows positioning of ultraviolet light
- Ultraviolet source

Multidirectional Test Systems

Multidirectional testing systems should provide magnetizing current in two or more directions. Fluorescent magnetic particle suspensions are predominantly used with multidirectional magnetization.

Conventional magnetization in one direction is accomplished in a multidirectional unit by energizing a specially designed circuit. In addition, one, two or three circuits can be individually energized in rapid succession. These quickly changing magnetizing currents produce overall magnetization of the test object, allowing complete coverage of potential discontinuity areas.

Multidirectional test systems may be designed for very specific applications: the steel blades in jet engines, for example. For this particular test, the third phase of three-phase alternating current is used to provide a circular field directed through the dovetail of the blade. The circular field adds to a longitudinal field supplied by a coil, giving increased magnetic field strength in the blade's critical dovetail area.

Theoretically, multidirectional magnetization can be applied in a majority of production applications with improvements in resolution and cost. *Suitable reference standards with known discontinuities must be used for set up of multidirectional tests.* When properly applied with assurance of adequate field and directional balance, improvements in discontinuity detection can be as high as 30 percent over typical unidirectional applications. Reduction in labor costs can exceed 60 percent when compared to conventional test procedures on wet horizontal equipment.

Time studies have indicated that forgings weighing 2.25 to 9 kg (5 to 20 lbs) require about 35 percent less time for multidirectional tests because of reductions in handling and testing times. Test objects with multiple apertures are also likely candidates for significant reductions in labor costs when tested with multidirectional methods. Savings in labor up to 90 percent have been reported on tests of plates in shipbuilding through the use of heavy duty multidirectional magnetizing power packs.

PART 3
STATIONARY MAGNETIC PARTICLE EQUIPMENT

Many different stationary bench units are available for specific magnetic particle testing applications. The size of the test system is determined by the size of anticipated test objects. Larger models are commonly used for heavy components such as diesel engine crankshafts, landing gear sections or gun barrels.

Stationary magnetic particle units are generally designed to operate from a 440 V three-phase alternating current source and to deliver alternating or rectified magnetizing current. Current control is often infinitely variable. In older units, the current was manually controlled with a step switch. Because of expanding requirements for close and repetitive control over current density, filtering of the power source may be necessary.

Direct Current Magnetizing Equipment

For magnetic particle testing of large, complex castings, welded structures or plate, overall magnetization with high magnetizing current is usually employed because of cost savings. The rated maximum output values for such applications is usually around 12 kA.

Multidirectional magnetization if often used through two or three magnetizing circuits, making it possible to detect discontinuities in all directions in a setup. This multidirectional magnetization is usually done by electromechanical switching. Better results can be obtained when the switching is done electronically, rather than electromechanically. Electronic switching provides faster rise time and the ability to program switching cycles for more reliable performance.

Automated Magnetic Particle Systems

Automatic or semiautomatic magnetic particle testing in most cases requires magnetization in two directions to detect randomly oriented discontinuities. Since two magnetic fields cannot exist simultaneously in one test object, it is necessary to switch from one direction to the other.

Electronic switching provides advantages in this application, as it does in other system configurations. Current can be switched several times per second and is often triggered by the line frequency. In this way, the test object is both circularly and longitudinally magnetized. Switching triggered by the line frequency allows the field direction to vary at very high speed.

Pulsed or Capacitor Discharge Units

Very high magnetizing currents can be obtained over short periods of time by discharging a capacitor. The main advantage of this procedure is that it can be done with a relatively small unit.

When the capacitor is discharged through the test object or through a coil, a strong magnetic field is set up. The exact magnetizing current may be determined with a peak and duration meter and, with the advances in solid state technology, it is possible to accurately control pulse amplitude and duration. The duration of the magnetizing current is less than 500 ms.

For longitudinal magnetization, the pulse can be applied to a yoke with the test object clamped between a headstock and tailstock. This is an important advantage because it eliminates the possibility of arcing.

Quick Break Magnetization

A quick break magnetization feature is needed in three-phase full-wave rectified systems using coils for direct current magnetization. When an object is placed in a coil and magnetized, the field lines leave the test object in the vicinity of the north pole and reenter near the south pole. The lines of force may be normal to the surface at the ends of the test object. A discontinuity near the end of the object may therefore be in a very unfavorable position for detection by magnetic particle techniques.

In order to overcome this, the direct current applied to the coil is quickly turned off. The rapid collapse of the magnetic field creates low frequency eddy currents within the object in a direction favorable for the detection of transverse discontinuities at the ends of the object.

The use of a yoke or the field flow method makes quick break magnetization unnecessary since the test object is part of the magnetic circuit (see Fig. 2). Periodic checking of the break is critical — on electronically triggered equipment, a malfunctioning firing module could result in evidence of quick break failure.

FIGURE 2. Adjustable electromagnetic yokes for magnetic particle testing

PART 4
MOBILE MAGNETIC PARTICLE EQUIPMENT

Mobile magnetic particle testing systems have outputs up to 20 kA and may be designed to deliver alternating current, direct current, half-wave rectified or pulse current. Table 2 lists the components of a typical mobile magnetic particle test unit. In older systems, the current was adjusted with a thirty-point step switch. Newer units are equipped with infinitely variable current controls. Push button demagnetization is often incorporated into contemporary designs.

In Europe, mobile systems are used as power packs for stationary testing units. This is a safety requirement (installing heavy duty electrical equipment under a kerosene or water suspension tank is prohibited).

TABLE 2. Components of a typical mobile magnetic particle testing unit

- Lifting hooks: For positioning the unit with a crane
- Current control: for adjusting alternating or direct current strength
- Line switch: for power to unit
- Power indicator: indicates power to unit is on
- Remote switch: allows use of remote controls
- Common connector: either-end connector for one side of output current
- Power outlet: 120 V for accessories (powder blower, grinder, light)
- Half-wave connector: with common connector, supplies half-wave alternating current to cables
- Alternating current connector: with common connector, supplies alternating current to cables
- Cables: 4/0 cables for supplying current to prods*
- Connector: either-end slip joint connector for additional cable or accessories
- Remote control: for stopping or starting magnetizing and demagnetizing current
- Casters: two swivel and two fixed casters
- Remote outlet: for remote control
- Current light: indicates current is on for output circuit
- Ammeter: indicates amperage in alternating or half-wave current circuits
- Louvers: ventilation for electrical equipment
- Recess: for cable and accessory storage

*4/0 cable is 12 mm diameter copper equivalent

Mobile equipment is widely used for many types of magnetic particle testing. The advantage of these system configurations is that they can be moved to the test site, whether that is a flight line, a refining tank, large plant machinery or a structural steel weldment. The advantage of a mobile system's high amperage is its ability to inspect large castings, forgings, welds or any other test object requiring strong magnetizing field strengths.

Current and Voltage Parameters

For certain applications, prods or clamps are used with mobile magnetic particle equipment. A solenoid (or a cable wrapped into a coil) may also be used when longitudinal magnetization or demagnetization is desired. A length of cable can serve as an internal conductor for magnetization procedures or, with clamps, a ferromagnetic bar can be used.

Mobile power packs operate on 230 or 460 V single-phase alternating current. Most units manufactured through the 1970s had a maximum output of 2 or 3 kA of half-wave alternating current or single-phase alternating current. Systems are now available with 4 and 6 kA half-wave alternating current and single-phase alternating current outputs or a range of pulse outputs.

In a typical system, selection of alternating or direct current is at the option of the operator using a common terminal on the front panel.

Cabling Parameters

Cable length can be varied and many applications require lengths exceeding 30 m (100 ft). Mobile system cables are usually fitted with slip joint, either-end connectors. Cables are connected to the test system, prods, clamps or to each other (for lengthening the magnetizing circuit). Some high amperage systems use bolted terminals to permit the passage of high currents without overheating.

A 4/0 (12 mm diameter) flexible rubber coated cable is most commonly used for mobile magnetic particle applications. For easier handling, 2/0 (9 mm diameter) cabling is sometimes used for connections to prods. With short cables

5 to 10 m (15 to 30 ft), mobile equipment delivers close to its rated amperage. As the cables (magnetizing circuits) are extended, the amperage available at the test point is considerably decreased. For example, a 4 kA unit with two 30 m (100 ft) cables in the magnetizing circuit delivers about 1 kA at the test point, because of internal resistance of the secondary circuit.

The input power cable to a mobile unit can be almost any convenient length with little or no loss in output. Often the input cable is fitted with a heavy duty contact plug for connection to 230 or 460 V outlets. These outlets are commonly available for welding equipment and other heavy machinery. Mobile magnetic particle equipment may also be operated from alternating current generators.

As the cables and connectors become worn or subject to overheating, their electrical resistance increases. Note that this wear also decreases the available amperage.

Input and Output Current Requirements

Mobile magnetic particle testing units can be operated on 230 or 460 V single-phase alternating current. Changing the operating voltage is easily done through an access port that exposes the terminals. Jumpers are alternately positioned to change the transformer connections and vary the input requirements. With either voltage input, the output rating is the same.

Mobile test systems with 6 kA output are not available with 230 V input and, because of high primary current requirements, must be operated on 440 to 460 V alternating current. Many systems have tap switches to regulate the current by selecting one of eight or one of thirty taps to the transformer. This selection determines the current output for either alternating current or half-wave alternating current.

For demagnetization, mobile magnetic particle testing units use a decaying alternating current or a ramp demagnetizing system.

Operation of Mobile Testing Units

Remote Operation Capabilities

A remote control cable may be connected to a four-point outlet. This allows the operator to control the mobile unit from the actual testing location at the ends of the cables. When using prods, a microswitch for controlling current flow may be located in the prod handle. With clamps, coils or an internal conductor, a special remote switch station is available or the prod switch may be used.

Solid state units have a remote control station that also allows current selection, on-off option and demagnetization procedures. A second 120 V outlet is sometimes provided for remote power to trouble lights, powder blowers, grinders and other accessories.

Demagnetization Procedures

Demagnetizing can be accomplished in several ways with a mobile system. The choice of technique depends on the object being tested and the means of magnetization. Small objects can be demagnetized by selecting alternating current and forming a coil with the cables. The object is drawn through the coil while the coil is energized. The test object must be moved sufficiently far from the coil to outdistance the coil's magnetic field, usually about 1 m (3 ft).

For larger test objects, demagnetization is achieved by touching the surface with the energized coil and then moving the coil away from the test object.

An alternate method of demagnetization uses demagnetizing current flowing through the test object. Cables are connected to the object with clamps. With solid state equipment, the *decay current* or *ramp current* reducing system is used. With older equipment or tap switch units, demagnetization is done with the step down system. An internal conductor can also be used for demagnetization if the test object geometry lends itself to such procedures.

Mobile Capacitor Discharge Systems

Capacitor discharge systems are used for circular magnetization of long hollow test objects and the ends of massive steel components, such as the thread connections of drill pipe and collars. These systems consist of 2 to 4 F boxes charged to a voltage of 50 to 75 V. This low voltage is used because of safety regulations for unshielded conductors.

The capacitor bank, once charged, is discharged either through a 4/0 cable coil or an insulated aluminum rod. The insulation prevents contact with the inside surface of the test object to avoid arc burns. Peak amplitude and pulse duration are recorded for each shot and are then compared with published specifications to ensure that the objects are magnetized to 90 percent of remanence (0.9 B_r). Second and third shots may often be needed to produce this high level of magnetization

Following magnetization, the objects are inspected for discontinuities either by wet or dry particle methods. A typical capacitor discharge system includes the following components: (1) a 2 to 4 F bank charged to 50 to 75 V; (2) current pulse firing control; (3) a 15 m (5 ft) insulated aluminum rod; (4) 4/0 (12 mm diameter) cabling for connection to the rod and for coil wrap; and (5) meters for peak current and pulse duration.

Maintenance of Mobile Testing Systems

Some critical maintenance procedures are required for mobile magnetic particle testing systems. For instance, the cooling intake of the unit must be kept clean to permit the free flow of air, especially if the unit is moved into a dirty testing environment.

Prod tips are another source of concern. They may become corroded or burned, hindering good contact with the test object. Defective prod tips can produce arc burns and these are proven sources of cracking. Similarly, clamps should have good copper mesh gripping points.

Frayed cables and continuous overheating decrease the conductivity of the cable. This produces heat, increases resistance and reduces the amperage available for testing. Connectors and cable joints should be tight and solid to help prevent overheating.

PART 5

PORTABLE MAGNETIC PARTICLE EQUIPMENT

Handheld Equipment

The simplest and perhaps most common magnetic particle test system is a handheld magnetic yoke (see Fig. 3). For small test objects (automotive parts, for example) surface discontinuities can be reliably detected at low production rates with a portable magnetic yoke. Yokes are also used for magnetic particle tests of welds, especially when arc strikes cannot be tolerated. It is difficult to prevent arc strikes when current is applied directly with prods.

Yokes operate on alternating current at standard line voltage, either 120 V or 220 V. For areas where a shock hazard exists, yokes can be made to operate at 42 V. The typical electromagnetic yoke has articulated legs that assist positioning on complex shapes.

Yokes with four poles have been developed in Japan and are in use in several parts of the world, although they are not often used in the US. By switching the poles in pairs at right angles to each other, discontinuity detection in all directions can be performed in a single setup.

Portable System Configurations

Larger equipment is needed when a higher magnetizing current or a higher duty cycle is required. Magnetic particle test systems often require heavy transformers and, excluding the magnetizing cables, can easily weigh 34 kg (75 lb). For that reason, portable units are sometimes mounted on carts and become, by definition, mobile units.

Portable systems may operate from a 115, 230, 460 or 380 V single-phase source. Magnetizing output currents range from 400 to 2,000 A for alternating current or half-wave rectified alternating current applications. Dual prods or clamps are used for direct contact magnetization. Most cables have either-end connectors, allowing the operator to manually form a magnetizing coil from a standard cable.

Portable magnetic particle equipment is most often used for testing welds, but it is not restricted to that application.

Current and Voltage Parameters

Portable systems vary greatly in electrical parameters. Lighter weight units are usually designed to operate on 120 V single-phase alternating current. Output amperage of these units can vary from 400 to 900 A, depending on the model and manufacturer. Because the usual limit on 115 V is 30 A, outputs over 1.0 kA require a 230 or 460 V unit. Most portable magnetic particle testing systems contain half-wave rectified alternating current and alternating current output.

Either two or three connectors are provided for dual output systems: a common connector, one connector for half-wave rectified and a third connector for alternating current. Output is controlled with a tap switch or a potentiometer. A single ammeter serves to measure both the alternating current and the half-wave output.

Accessories and Components

Table 3 and Fig. 3 illustrate the components of a portable magnetic particle test system.

Accessories such as prods, clamps and cables for portable systems are similar to their counterparts for mobile testing units. Cable lengths for portable systems are usually limited to 10 m (30 ft) or two 5 m (15 ft) cables.

With the portable systems, demagnetization is accomplished using (1) manual alternating current step down or (2) a coil formed from cables using alternating current. When step down demagnetization is used, connection to the test object is made using clamps or an internal conductor.

A 120 V coil is a useful accessory for producing longitudinal magnetization. The coil consists of many turns of fine wire; a switch is used to close the circuit when the coil is connected to 120 V alternating current. The coil's primary use is for testing elongated objects such as spindles or axles. The coil can also be used for demagnetizing many kinds of test objects.

A capacitance discharge portable system is also available. Though it operates much like a standard portable unit, it weighs considerably less and can use lighter, smaller magnetizing cables. The input voltage is low in capacitance discharge units, providing the additional benefit of increased operator safety.

FIGURE 3. Portable magnetic particle testing equipment: (a) direct or alternating current model with infinite current control; (b) lightweight pulse portable operating from 120 V outlet; and (c) adjustable yoke, 120 V coil (for magnetizing or demagnetizing) and assorted accessories

(a)

(b)

(c)

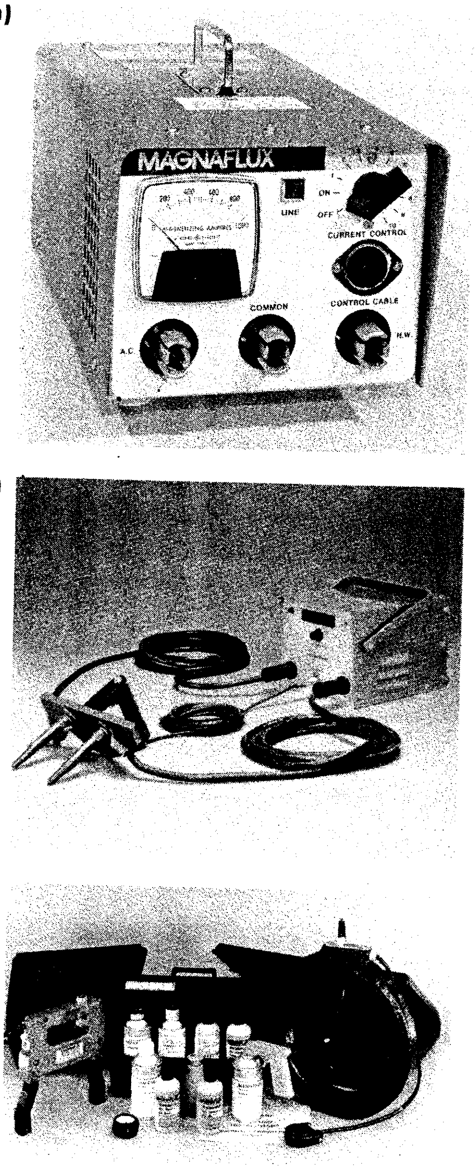


TABLE 3. Components of a typical portable magnetic particle testing unit

- Current control: adjustable or tap switch
- Cables: extra flexibility required for connection to prods
- Prods: in-line components for making electrical contact with test object
- Handle: for positioning and transporting unit
- Half-wave connector: with common connector, supplies half-wave alternating current to cables
- Remote receptacle: for remote cabling hook-up
- Common connector: either-end connector for one side of output current
- Power indicator: indicates when power supply to unit is on
- Alternating current connector: with common connector, supplies alternating current to cables
- Control cable: connects to prod remote switch
- Ammeter: measures alternating and half-wave current output

Yokes

Magnetic particle yokes have a multiturn coil wrapped around an assembly of soft iron laminations. A power cord and switch are part of the typical yoke design. In service, the yoke is placed on the test object and energized. Magnetic particles are applied between and adjacent to the ends of the yoke. A magnetic field is set up between the ends (poles) of the yoke. To find discontinuities in both directions, the yoke is rotated 90 degrees and the operation is repeated.

The original alternating current yokes had a fixed *U* shape. A more recent and useful design has the ends of the *U* jointed so that wider or narrower objects can be tested more efficiently. A rectifier is sometimes used in conjunction with the yoke, providing a direct current field for some penetration below the test object surface.

PART 6
MAGNETIC PARTICLE TESTING POWER PACK SYSTEMS

A power pack is used to set up magnetizing fields when an object is too big for the available stationary testing unit. Most magnetic particle systems used in contemporary production environments have a power pack as part of their design. The electrical components of the magnetizing and demagnetizing circuitry are generally part of the power pack. Timing circuits adapted to the particular production line are also included in the power pack.

Power pack timing circuits are designed for specific applications. This might be hundreds of objects per hour in the automotive industry or an object per minute in the steel industry. In other applications, the power pack could have timers that control the length of the current application in order to meet product specifications. Power pack design is usually dictated by the production requirements of the products being tested.

Power Pack Applications

Steel Industry Uses

In the steel industry, magnetic particle testing is applied to products as diverse as billets, blooms, bars and tubing (see Fig. 4). Magnetic particle technology is used to test semifinished products and is sometimes applied at an intermediate stage of manufacture for process control.

A steel mill testing system typically uses a power pack that supplies magnetizing current to contacting fixtures. Depending on the test object's size, amperage as high as 20 kA full-wave direct current may be used. The test system is like a large bench unit, featuring a means of magnetically contacting the test object after positioning. Steel mill test equipment includes handling systems for positioning steel objects measuring from 12 to 20 m (40 to 60 ft) in length.

After magnetization, the object is rotated and positioned for testing. Magnetic particle test results determine where the test object goes next: a grinding station, a secondary rolling operation or to a shipping point.

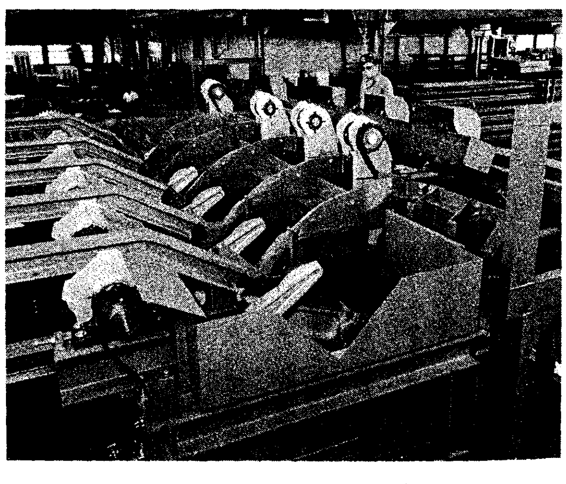
For the majority of their tests, steel mills often use wet fluorescent magnetic particle techniques. In addition to the power pack, circulating pumps, a filtering system and application nozzles are all part of the standard steel mill test system.

Automotive Industry Applications

In the automotive industry, important components such as spindles, connecting rods and crankshafts are routinely tested with magnetic particle techniques. System configuration is based on the use of a power pack to supply the proper magnetizing current. Timing circuits are a vital part of this power pack application: magnetizing current must be applied at a specific time during the test object's conveyance through the system.

Magnetization may be circular or longitudinal and is routinely followed by demagnetization. For small test objects, demagnetization is achieved using an alternating current coil encircling the conveyor. On some systems, the operator drops the test object through a coil after inspection. For large test objects, special contact demagnetizing circuitry is designed as an integral part of the power pack.

FIGURE 4. Magnetic particle system for steel mill product testing: fluorescent test unit showing square billet turner and inspection station



Applications for Large Castings

An important application of the swinging field (see *Multidirectional Power Packs* below) is the nondestructive testing of large, heavy castings. The power pack used in this method can supply up to three separate magnetizing circuits. Contact is made by cables clamped to the test object and the circuits are arranged so that magnetizing current crosses the test object in three different directions. The power pack supplies timing circuitry for shifting current flow from circuit to circuit. In some applications, one of the three magnetizing circuits is used to form a coil, providing longitudinal magnetization in the test object. Demagnetizing circuitry, usually reversing direct current, can be a feature of this power pack unit.

This technique is an overall testing method that uses wet fluorescent magnetic particle suspensions to test the entire surface of large cast objects. In a foundry, for example, this technique can save as much as 90 percent of the labor and time required to inspect an object with prods. In addition, areas can be tested that are inaccessible to the prod method.

Other Power Pack Applications

Full-wave direct current power packs are used for energizing bench units. These systems are usually designed for testing large objects such as landing gear forgings. A full-wave power pack is also useful when large weldments are tested. Instead of prods, the test object is contacted with clamps and magnetizing current is passed along the length of the weld. After this first test, the clamps are repositioned, contacting the object so that current is passed perpendicular to the weldline.

Multidirectional Field Power Packs

In some systems, a power pack is used to supply a circular field to the test object then within milliseconds the field is changed to a longitudinal field. This sequence is continuous and extremely fast since it can be based on the reversals of the 60 Hz power supplied to the unit.

For example, an elapsed time of 0.5 seconds allows fifteen circular field shots *and* fifteen longitudinal field shots. The resulting magnetic field is a swinging field that sweeps across the test object and crosses the plane of a discontinuity regardless of its orientation.

Often, wet fluorescent magnetic particles are used with this magnetization method. The suspension is applied to the test object as the magnetic field swings across the material. The rapidly changing field requires high mobility from the particles and that in turn recommends the free, small particles used in wet fluorescent suspensions.

PART 7
DEMAGNETIZATION EQUIPMENT

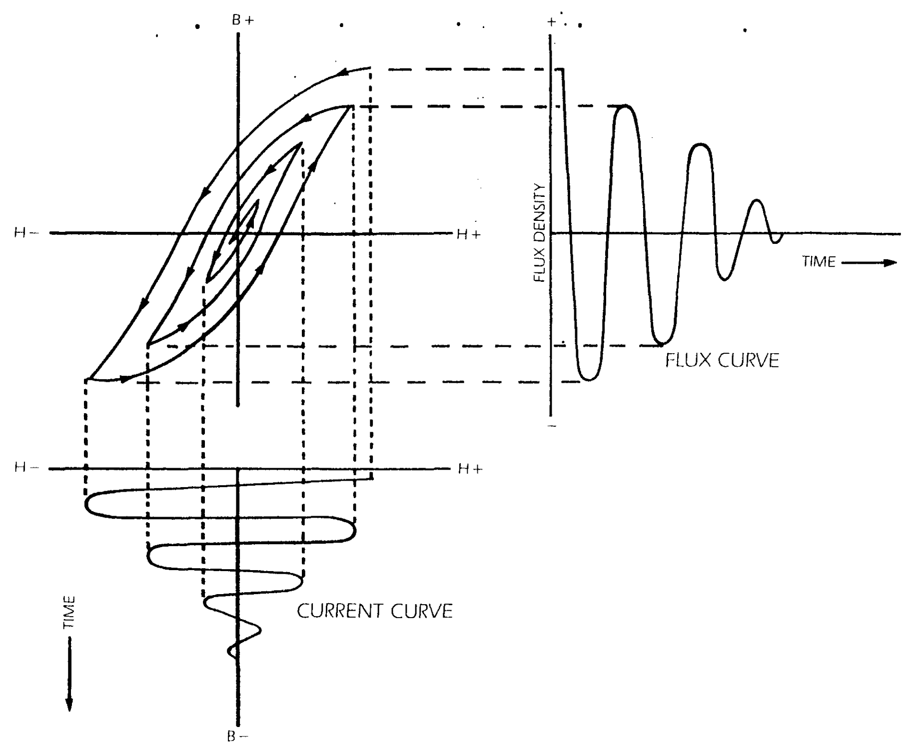
Theory of Demagnetization

Ferrous materials usually retain some residual magnetism after the magnetizing current is removed. The amount of residual magnetism depends on (1) the retentivity of the material; (2) the coercive force of the material; and (3) the strength and direction of the magnetic field. A longitudinal residual field is often simple to detect with a tag wire or a field meter. A circular magnetic field is completely contained in the test object and may not exhibit the leakage fields and poles needed for typical detection methods.

Complete demagnetization is virtually impossible to obtain. Consequently, the demagnetization process is actually a reduction of the residual field to a level that is appropriate for the test object's subsequent service or manufacture.

The demagnetization process exposes the test object to a reversing magnetizing field that gradually diminishes in strength. This causes a corresponding reversal and reduction in the magnetic field strength in the object. Figure 5 shows a typical demagnetization hysteresis curve and a flux curve during reversal and reduction (for more information, see the Section titled *Demagnetization of Test Objects*).

FIGURE 5. Typical flux curve for the demagnetization procedure



Need for Demagnetization

It is sometimes necessary to demagnetize an object before magnetic particle testing. This is particularly true if the test object has a strong residual field from previous operations such as magnetic crane handling or from contact with a magnetic chuck.

It is not always necessary to demagnetize after magnetic particle testing. Below are some of the factors that determine whether demagnetization is needed to reduce the residual magnetic field. These factors focus on the test object's subsequent manufacture and its service life.

When an object is magnetized for magnetic particle testing, the residual field might adversely affect later stages in its production. A residual field interferes with machining operations by causing chips to adhere to the test object and this is detrimental to both tool life and the object's finish. A magnetic field can also interfere with welding operations by actually shifting the arc and producing potentially defective welds. An important reason for demagnetizing is to clean the test object before it moves to any other surface related production step.

Residual fields can also interfere with the function of the test object after it is placed in service. Magnetized milling cutters, for instance, hold ferromagnetic chips and this not only interferes with the cutter's function but damages the surfaces of cut objects. Residual fields can interfere with certain magnetic instruments (compasses, for example) or with any number of sensitive electronic components. A residual magnetic field is particularly destructive to closely fitted moving components such as crankshafts, connecting rods and bearing surfaces.

When Demagnetization Is Not Needed

When test objects have low magnetic retentivity (an automotive block, for example, or low carbon steel used for welded tanks), the residual field dissipates as soon as the magnetizing current is removed. Sometimes, this is also true in large structures and no demagnetization is required after magnetic particle testing.

Demagnetization occurs as a side effect of heat treatment if the test object temperature is taken to the Curie point or above (about 750 °C or 1,400 °F for steel). At the Curie temperature, magnetic domains return to their random orientations and the material is demagnetized when it cools, making further demagnetization unnecessary.

Finally, when an object is remagnetized in a different direction to a level equal to or below its previous magnetization, then demagnetization is not required. Some early specifications required demagnetization between circular and longitudinal magnetization steps of magnetic particle tests. This was unnecessary for the accuracy of the test.

Coil Demagnetization

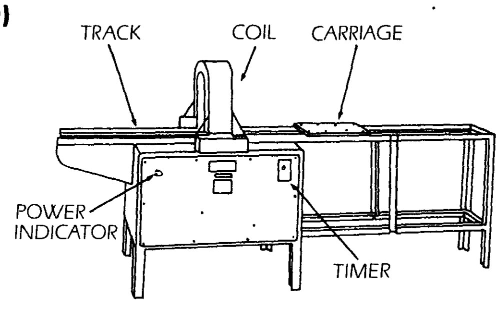
Alternating current demagnetization with a specially built demagnetizing coil is the most convenient and widely used demagnetization method (see Fig. 6). Single-phase alternating current is used to power a multiturn coil. Various voltages (120, 240 or 480 V) are used, depending on availability and the application.

The typical demagnetization procedure comprises three main steps: (1) the test object is positioned within the coil; (2) the coil is energized to a predetermined level; and (3) the test object is removed from the coil and placed outside the coil's magnetic field.

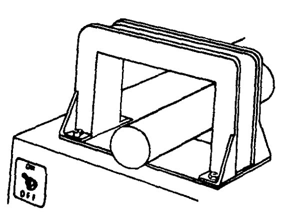
As the single-phase alternating current reverses in the coil, the magnetic field in the test object also reverses. As the object is moved out of the coil's magnetic field, the object's field is weakened as it is reversed. Moving the test object completely away from the coil (usually 1 m away) effectively demagnetizes the part. The current through the coil is maintained until the test object is completely out of the coil's field. If the current is stopped before this, or if the object's movement is stopped within the coil's field, residual magnetism could remain in the test material.

FIGURE 6. Typical alternating current demagnetizing unit: (a) structure of a complete system with track and carriage; and (b) detail of the coil assembly

(a)



(b)



To facilitate handling, a small rolling carriage and track are often furnished with coil demagnetizing systems. The test object is positioned on the carriage next to the coil and pushed through the coil and beyond it to a neutral area.

Circular Field Demagnetization

Alternating current demagnetization may also be achieved with a circular magnetic field. The test object is placed between the contact points (headstock and tailstock) of a magnetizing system. An applied alternating current is gradually reduced to zero and this demagnetizes the object. The procedure is widely used with alternating and direct current systems designed for testing heavy objects.

Reducing alternating current was formerly done with a step down switch connected to a tapped power transformer. The step down was either a motorized switch or the manual current control tap switch of the magnetizing unit. Similar circuitry and procedures were used for mobile equipment, where contact with the object was made with cables and clamps.

A faster system of demagnetizing heavy objects with alternating current is the solid state decaying method. The amperage flowing through the object is rapidly and smoothly reduced by the demagnetizing system's electronics.

Direct Current Demagnetization

Alternating current does not penetrate ferromagnetic materials very deeply. For this reason, large test objects and those magnetized with direct current cannot be demagnetized with alternating current.

Direct current demagnetization requires equipment with (1) a means of reversing the direction of current flow; and (2) a means of gradually reducing the current level. A motorized thirty-point tap switch connected to a tapped transformer is the most common current reduction method. The reducing voltage is fed into rectifiers with each tap setting.

The coil of a magnetic particle testing unit can be used for demagnetization but a more effective method is to put the demagnetizing current directly through the test object with what is called a *head shot*. For heavy objects, this form of demagnetization is the most efficient because it breaks down longitudinal and circular fields. Head shot demagnetization is usually done with large power packs.

On production equipment, demagnetization circuitry can be a part of the test system design. For example, the unit's conveyor can pass through a demagnetizing coil beyond the test station or a circular magnetization shot can be incorporated into the conveyor operation.

PART 8

LIGHT SOURCES AND ACCESSORIES FOR MAGNETIC PARTICLE TESTING

Table 4 lists typical accessories used for magnetic particle testing when the tests are part of a quality control program. Table 5 lists accessories used with a typical production magnetic particle test system.

Visible light and ultraviolet sources are often considered *accessories*, even though they are a vital part of the magnetic particle testing method. An ultraviolet light source is usually incorporated into a hood that darkens the testing area. The hood can be part of the magnetic particle test system or may be located in a separate area designed specifically for the interpretation of test results.

Sources of Visible Light for Magnetic Particle Testing

Magnetic particle testing techniques often rely on an inspector to locate and interpret test indications. The lighting provided for this visual examination is extremely important. It not only affects the sensitivity of the test but is also an important contributing factor to inspector fatigue. Visible light sources for magnetic particle tests are not significantly different from those used for other visual testing applications. Sunlight, incandescent lamps, fluorescent tubes or metal vapor arc lamps are generally quite satisfactory.

Spectral Characteristics of Visible Light Sources

Spectral characteristics are usually not important when using visible light sources. However, it could be better to use a light source that is deficient or rich in particular wavelengths, depending on the color of the particles and the color of the background.

By measuring the spectral quality of light reflected and scattered from typical magnetic particles, it can be seen that red materials reflect highly in the longer wavelengths of the visible spectrum, fall off at about 580 nm and remain comparatively low through the remainder of the spectrum. Yellow powders absorb heavily at the shorter wavelength or blue end of the spectrum up to about 480 nm, absorb less to about 550 nm, above which they reflect strongly. Blacks and grays absorb fairly uniformly throughout the visible spectrum and the spectral distribution of the illuminating light is virtually unaffected.

By knowing the color of the magnetic particles and the color of the background, it is theoretically possible to increase the contrast of a colored particle indication by selecting a particular colored light source.

Because a greater area is made visible, floodlights are often an advantage for inspecting large and relatively flat surfaces. On intricate test objects where areas are accessible with difficulty, handheld spotlights may be more effective.

Illumination Levels for Magnetic Particle Testing

The proper intensity of visible light illumination is determined by the parameters of the test and the physical characteristics of the test object and the particle materials. For large discontinuity indications, a brightness level of 700 to 1,000 lx (70 to 100 ftc) at the surface of the test object is generally sufficient.

TABLE 4. Accessories for magnetic particle tests in quality control

- *Ultraviolet light meter: measures ultraviolet light intensity with digital or analog readout; may also include a sensor for visible light*
- *Test meter: measures amperage output of the magnetic particle unit; selection must be compatible with the unit's current capabilities*
- *Centrifuge tube: used to test the magnetic particle suspension concentration*
- *Tool steel ring standard: used to verify the accuracy of a test set up*
- *Field indicator: provides relative measurement of residual magnetism*
- *Calibrated field indicator: provides actual measurement of residual magnetism*
- *Magnetic field indicator: indicates direction of magnetic field*
- *Hall effect meter: measures magnetic fields in either dynamic or static modes*
- *Reference standard: indicates the direction, penetration and strength of a field*

For extremely critical tests or very small indications, higher visible light intensities are needed. These light levels should be in the 1,500 lx (150 ftc) range. Note that excessive light levels increase inspector fatigue.

Use of Ultraviolet Lamps for Fluorescent Magnetic Particle Tests

Fluorescent magnetic particle indications should be inspected in a darkened area. The lower the level of ambient visible light, the more brilliant fluorescent indications will appear. This is important particularly when testing for very small discontinuities that may attract only a small number of fluorescent particles.

It is also important that the test station be free of random fluorescent materials, whether or not they are directly related to the testing procedure.

Visible Light Interference with Ultraviolet Testing

The visible light intensity in a test area has a dramatic effect on performance and reliability. More visible light makes fluorescent indications harder to see, requiring higher ultraviolet irradiances to permit detection of indications. Table 6 lists several ambient visible light level equivalents. The results of laboratory tests on light levels for fine and coarse cracked panels and a dark adapted inspector are shown in Table 7.

Ultraviolet testing booths cannot typically achieve visible light levels less than 10 to 20 lx (1 to 2 ftc) because ultraviolet lamps (with filters) have some visible light output. In addition, the induced fluorescence from test objects, inspectors' clothing and spills of fluorescent material add to the visible light level

The ultraviolet irradiance at the test surface can be altered by adjusting the distance between the ultraviolet source and the test object. A new, appropriately filtered 100 W ultraviolet bulb can produce up to about 30 $W \cdot m^{-2}$ (3,000 $\mu W \cdot cm^{-2}$) peak intensity at 450 mm (18 in.) from the test surface. Bringing the light source within 50 mm (2 in.) of the surface increases the intensity to over 300 $W \cdot m^{-2}$. Flood bulbs and those lamps provided with fluted filters generally provide substantially lower irradiance levels.

Because test surfaces can be blocked by lamp housings, the shortest practical source-to-object distance is about 50 mm (2 in.). A typical ultraviolet light test can meet most specifications with a distance of 380 mm (15 in.) and a minimum intensity not less than 10 $W \cdot m^{-2}$.

TABLE 5. Accessories for operating a production magnetic particle testing unit

- Hand spray gun: for application of wet method suspension
- Powder spray bulb: for application of dry powder materials
- Contact block: for using cables with a bench unit
- Cables: for portable or bench units; available in 2/0 and 4/0 sizes with lug terminals or slip joint (either-end) connectors*
- Contact clamps: used with cables to make electrical contact with test object
- Prods: used with cables to make electrical contact with test object; commonly used for tests of welds or large test objects
- Split coil: used with mobile units for longitudinal magnetization
- Central conductor set: central conductors in several sizes for use with bench units
- Test object supports: headstock, tailstock and rail mounted supports; various sizes useful for tubing, bars and shaft shapes
- Transport truck: used to carry portable testing units and accessories
- Contact pads: copper mesh pads used to ensure contact with test objects; some models have rubber cushion backing and V blocks
- Connectors: slip joint (either-end) connectors for quick connections to prods, clamps, cables and contact block
- Small part adapters: permits use of standard wet horizontal unit for testing of small objects

*2/0 cable is 9 mm diameter copper equivalent
4/0 cable is 12 mm diameter copper equivalent

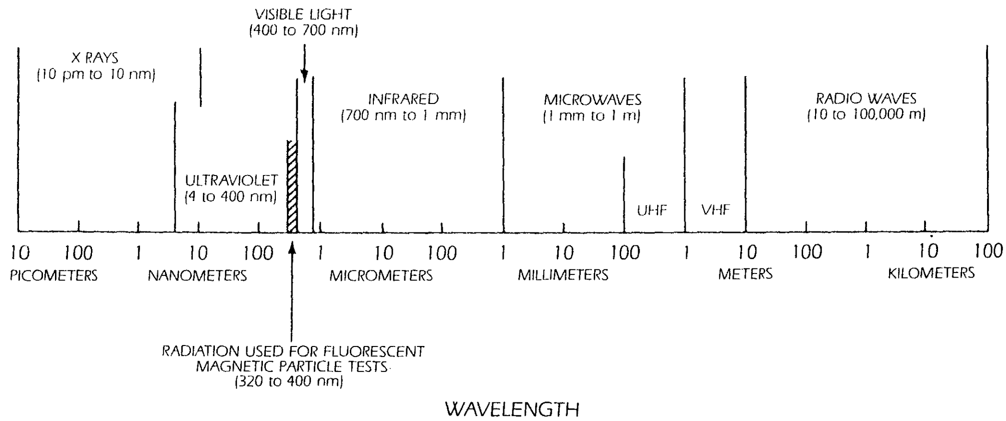
TABLE 6. Ambient visible light level equivalents

Visible Light Intensity lux (footcandles)	Light Level Equivalent
10 (1)	Best ultraviolet testing booth
100 (10)	Dim interior ambient lighting
1,000 (100)	Bright interior; deep shade under sun

TABLE 7. Empirically determined minimum light levels for discontinuity location with fluorescent magnetic particle techniques

Light Intensities for Small Discontinuities		Light Intensities for Large Discontinuities	
$W \cdot m^{-2}$	$\mu W \cdot cm^{-2}$	$W \cdot m^{-2}$	$\mu W \cdot cm^{-2}$
0.3	30	0.1	10
5	500	0.5	50
50	5,000	5	500

FIGURE 7. Electromagnetic spectrum showing the narrow range of ultraviolet radiation used for fluorescent magnetic particle testing



Response of the Human Eye to Light Sources

Response to Ultraviolet Light

The human eye is relatively unresponsive to radiation at wavelengths shorter than 400 nm (see Fig. 7). However, in the absence of longer wavelengths, the sensitivity of the eye to shorter wavelengths greatly increases.

Figure 8 shows the response of the average human eye under various lighting levels. The highest luminance level shown is 340 cd•m^{-2} (100 ftL), a normal, bright light viewing condition.

The second light level at 3.4 cd•m^{-2} (1 ftL) is about the average found in a darkened testing booth. Total darkness is never achieved in a typical testing booth, for the following reasons: (1) near ultraviolet sources also produce some blue and violet visible light; and (2) most testing booths contain some sources of fluorescence, often the inspector's clothing. At the 3.4 cd•m^{-2} ambient light level, the eye becomes sensitive to radiation in the 380 to 400 nm range. This is almost thirty times higher than the sensitivity in bright light conditions. The 380 to 400 nm radiation causes a deep blue visual sensation in the eye, plus greatly increased sensitivity in the blue region to the 405 nm spectral line of mercury vapor lamps. This does have the advantage of allowing the dark adapted inspector to move around the booth safely, accurately locating objects in the testing area.

The top response curve in Fig. 8 is the 0.03 cd•m^{-2} (0.01 ftL) level. This is almost total darkness and is seldom encountered in magnetic particle testing applications. Note that when compared to normal levels, the eye is over 800 times as sensitive under these conditions and can respond to wavelengths down to 350 nm (this causes the cornea and lens of the eye to fluoresce). The eye also detects the presence of longer wavelength visible light more easily at low background levels.

Comparative Eye Response to Visible Light and Colored Light

Visual acuity is the eye's relative ability to resolve detail. As shown in Fig. 9, visual acuity drops as the illumination (brightness level) decreases. Light levels are detected in the retina by structures known as *rods*. Color is detected by the structures called *cones*. As brightness diminishes, the iris of the eye opens wider and the rods become preferential detectors because of their low light sensitivity. At low levels of illumination, the eye is color blind because rods are not color sensitive.

The brightness of the area surrounding the target of vision also affects visual acuity. Reducing the contrast of the background area reduces visual acuity (see Fig. 10). Normally, visual acuity is determined for visible light illumination. Visual acuity for monochromatic light is higher for the yellow and yellow green wavelengths.

Mechanisms of Dark Adaptation

The eye adjusts to changing light intensity by varying the size of the pupil and by changing the retinal sensitivity. This is an autonomic or reflex action in normal vision but full adjustment of low level light does not occur instantaneously. The change from bright, visible light to the darkened environment needed for reliable fluorescent testing normally requires at least five minutes for an average, healthy inspector (see Fig. 9).

FIGURE 8. Relative average response of the human eye to various wavelengths in the visible range of the electromagnetic spectrum at three different levels of ambient light: (a) 340 cd•m^{-2} (100 footlamberts); the maximum response for this curve is set arbitrarily at 1.0 on the vertical scale for relative eye response, corresponding to the photopic eye at maximum sensitivity; (b) 3.4 cd•m^{-2} (1 footlambert); and (c) 0.03 cd•m^{-2} (0.01 footlambert)

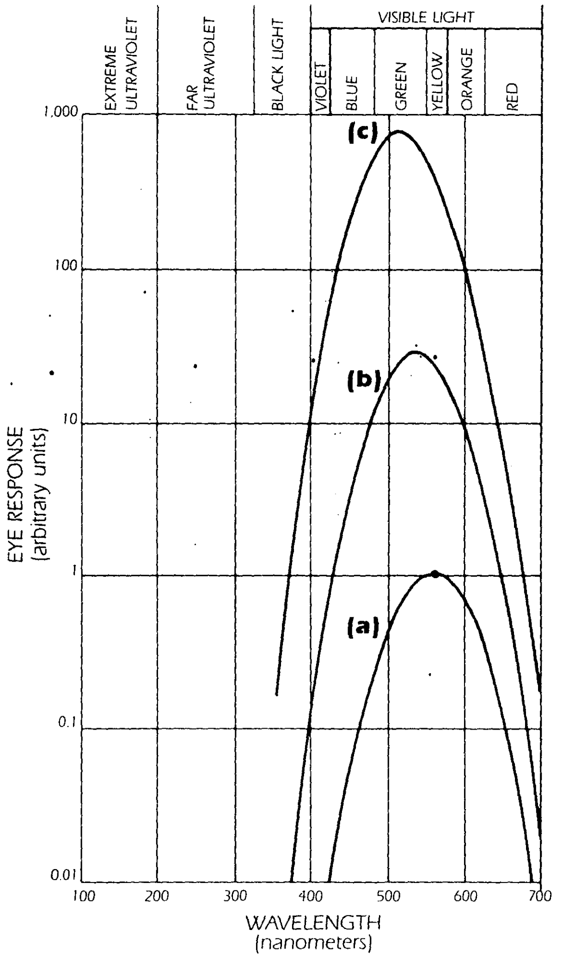


FIGURE 9. Human vision threshold: upper and lower dashed curves show the effect of high and low illumination levels before dark adaptation begins; for areas subtending more than five degrees, the threshold is almost constant but rises rapidly as target size decreases; curves are for a target subtending about two degrees

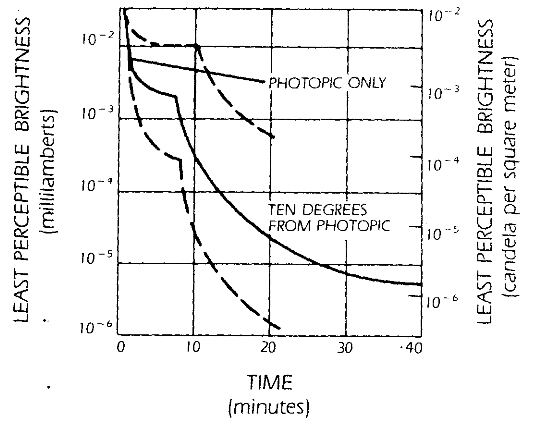


FIGURE 10. Contrast sensitivity of the eye as a function of field brightness; the dashed curve indicates contrast sensitivity for a dark surrounded field

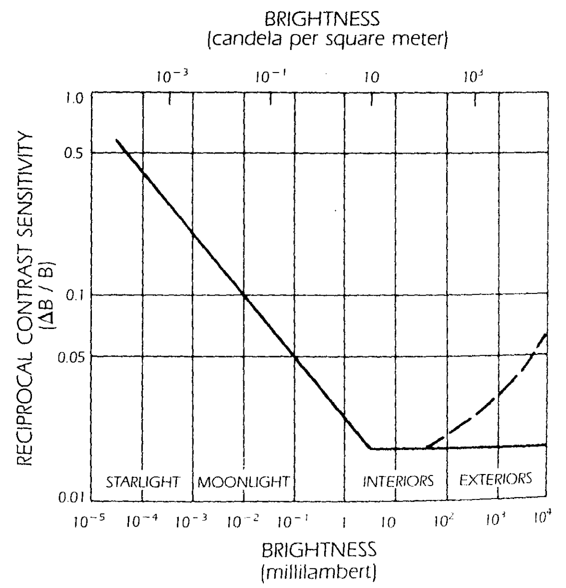


FIGURE 11. Dark adaptation curves measured with a 25 mm (1 in.) test stimulus: (a) subject preadapted to 6,760 trolands (a unit of retinal illuminance) for five minutes; and (b) subject preadapted to 389 trolands for five minutes

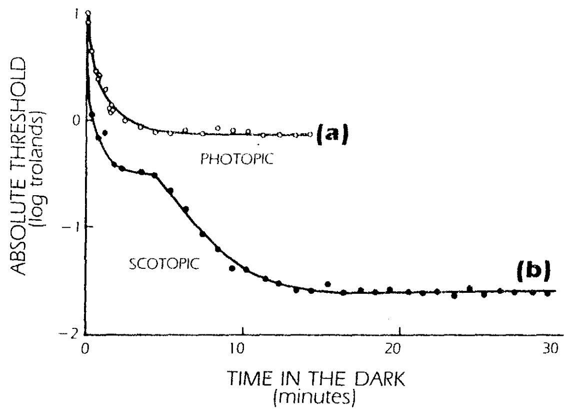


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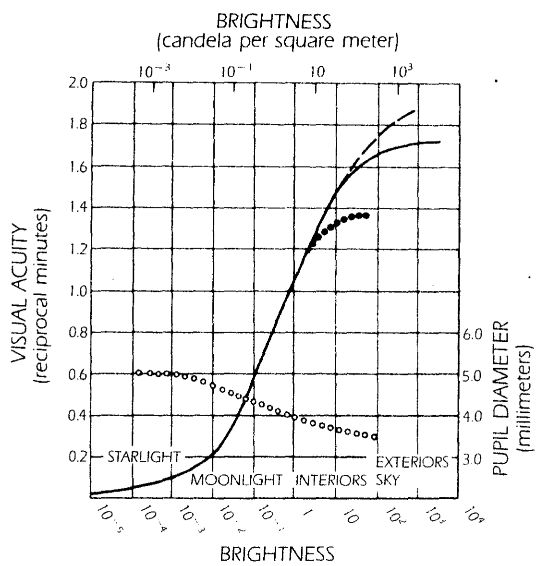
FIGURE 12. Visual acuity as a function of object brightness: the dashed and dotted curves show the effect of increased and decreased background brightness; the open circles indicate the diameter of the pupil



The time required for dark adaptation generally increases with increasing age of the inspector. Dark adaptation is not easily retained — there is a decided physiological safety advantage to having pupils that quickly adjust to bright light. Even very brief visible light exposure requires complete subsequent dark adaptation.

When light levels are reduced, the pupil of the eye expands in diameter to allow more light to enter and the retina of the eye becomes more sensitive. Further dark adaptation occurs below 2×10^{-3} cd•m^{-2} as the eye switches from cone vision to rod vision. Figure 11 shows the variation in brightness discrimination that occurs as a function of dark adaptation time.

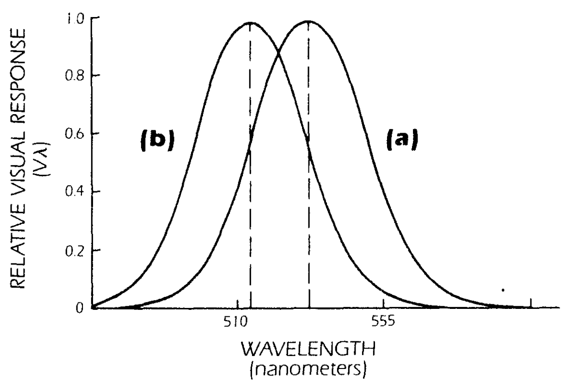
Photopic vision refers to vision under high level lighting conditions (73 cd•m^{-2}). *Scotopic vision* is a term used to describe vision under conditions of total dark adaptation (3×10^{-5} cd•m^{-2}). The change in perception by the human eye for varying conditions of illumination is shown schematically in Fig. 12. The *dark adaptation gap* is that period of time during which the eye is changing and is not capable of performing at maximum sensitivity in either vision condition. The time required for dark adaptation before testing varies with the individual and depends on the overall health and age of the inspector. A dark adaptation time of five minutes is typically required for fluorescent magnetic particle testing with ultraviolet irradiation. Complete dark adaptation may take as long as twenty minutes. Note that some specifications (MIL-STD-1949, for example), require only one minute of dark adaptation before performing fluorescent magnetic particle tests.

The maximum sensitivity of the eye shifts in wavelength during dark adaptation. Figure 13 shows the sensitivity of the eye as a function of light wavelength for normal levels of illumination and also for the dark adapted eye. As dark adaptation progresses, the peak sensitivity of the eye shifts toward the blue end of the visible spectrum with reduced sensitivity in the red. This so-called *Purkinje shift* is a result of the different chromatic sensitivities of the rods and cones of the retina.

Eyeglasses and Fluorescent Particle Tests

At present, there are no official federal regulations covering the permissible amount of ultraviolet exposure an inspector can receive during a work day. However, both the National Institute for Occupational Safety and Health (NIOSH) and the American Conference of Governmental Industrial Hygienists (ACGIH) have recommended the following limits: (1) for the ultraviolet spectral region from 315 to 400 nm, total irradiance incident on unprotected skin or eyes, based on either measurement or output data, shall not exceed 1.0 mW•cm^{-2} (1,000 μW•cm^{-2}) for periods greater than 1,000 s; or (2) for exposure times of

FIGURE 13. Relative luminous efficiency curves for the human eye showing response as a function of incident light wavelength: (a) photopic vision with adequate illumination levels; and (b) scotopic vision with dark adapted eye and low levels of illumination



1,000 s or less, the total radiant energy shall not exceed 1,000 mW s•cm^{-2} (1.0 J•cm^{-2}).

Photosensitive (photochromic) eyeglasses darken in the presence of ultraviolet radiation. The darkening is proportional to the amount of incident radiation. While this type of lens has advantages under sunlight conditions, such glasses decrease the ability to perform fluorescent magnetic particle tests and are not permitted for use in the test area.

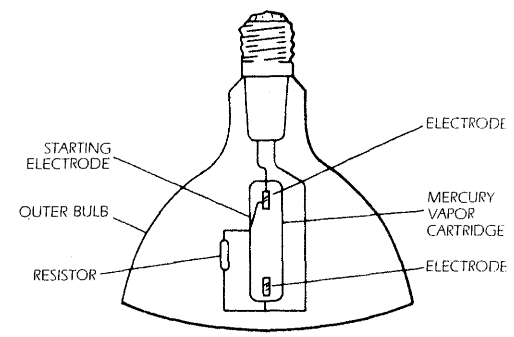
Wearing red lensed eyeglasses when exposed to visible light may aid subsequent dark adaptation. These glasses must be removed after entering the darkened testing booth before viewing fluorescent test indications.

Some commercial eyeglass frames fluoresce and can cause glare or unnecessary fluorescent background illumination. As with any object in the testing booth, glasses should be examined and care should be taken to eliminate extraneous sources of light.

It is possible that an inspector may experience a temporary clouding of vision if black light is permitted to shine into the eye or if it is reflected into the eye from test object surfaces. This clouding occurs because the cornea, lens and the liquid in the eye (the vitreous humor) are also fluorescent materials. *Under no circumstances should shorter wavelength ultraviolet light be allowed to shine or reflect into the eye.*

Because of the eye's own fluorescence, ultraviolet sources in the testing area should be positioned so that neither direct nor reflected light shines into the operator's eyes. Ultraviolet absorbing eyeglasses should be worn if this fluorescence becomes a serious problem and are recommended to prevent unnecessary exposure of the eye to

FIGURE 14. Mercury arc lamp construction



ultraviolet radiation. They are also helpful when viewing critical small particle indications. Such visors or glasses should block all ultraviolet, most violet and blue light, without diminishing the yellow green test indication.

Mercury Arc Ultraviolet Lamps

The most common light source for fluorescent magnetic particle testing is a mercury arc bulb rated at 100 W. Ultraviolet lamps require the use of an autotransformer to regulate current and step up voltage. The ultraviolet light source for fluorescent magnetic particle tests emits light with an average wavelength around 365 nm (3,650 Å). The output was formerly and incorrectly measured in footcandles with a visible light meter. Ultraviolet light meters are now available to measure the ultraviolet intensity directly at the testing point as watts per square meter or as microwatts per square centimeter.

A filter is placed over an ultraviolet light source for two reasons: (1) to block visible light, exposing the test object only to ultraviolet wavelengths; and (2) to restrict the emission of ultraviolet wavelengths harmful to the human body. No magnetic particle test should be attempted without the filter in position. Damaged filters must be replaced immediately. Dirty filters seriously impede the emission of ultraviolet radiation — cleanliness is essential for accurate magnetic particle test results.

The 100 W mercury arc lamp requires about ten minutes to reach full intensity. To lengthen service life, the lamp should remain energized after warm up. It is good practice to keep ultraviolet lamps energized for the entire working day.

Ultraviolet lamps are sensitive to low voltage and voltage fluctuations. For this reason, they must be connected to voltage sources that have little fluctuation (within 5 percent of the voltage rated for the transformer). A tap switch in the transformer allows adjustment to several voltages.

Construction of a Mercury Arc Lamp

Mercury arc lamps are gaseous discharge devices in which an electric arc takes place in a controlled atmosphere and emits light whose characteristics depend on the nature of the atmosphere.

The construction of a typical mercury arc bulb is shown in Fig. 14. The mercury is confined in a quartz or hard glass cartridge and two main electrodes carry current to the arc stream (along the length of the cartridge). An auxiliary starting electrode and a current limiting resistor are also included in the electrical design. The entire assembly is sealed in an outer protective bulb that may either be evacuated, filled with air or filled with an inert gas, depending on the design of the bulb. The lamp is fed from a current regulating ballast reactance or transformer. This is required because the arc tube shows negative resistance characteristics and would quickly destroy itself if not throttled by an external device.

Energizing a Mercury Arc Lamp

When the lamp is first turned on, the mercury in the cartridge is not in vaporous form but is condensed in droplets on the inside of the tube. Under this condition, it would be difficult or impossible to strike the arc. To facilitate starting, a small amount of neon gas is incorporated into the cartridge and a starting electrode is sealed through an end of the tube near one of the main electrodes.

When voltage is first applied, a discharge from the starting electrode moves through the neon. This so-called *glow discharge* carries a small current limited by the protective resistor but is sufficient to vaporize and ionize the mercury and eventually cause an arc to strike between the main electrodes. The heating and ionization process takes five to fifteen minutes after the lamp is first energized.

Spectral Characteristics of Mercury Arc Sources

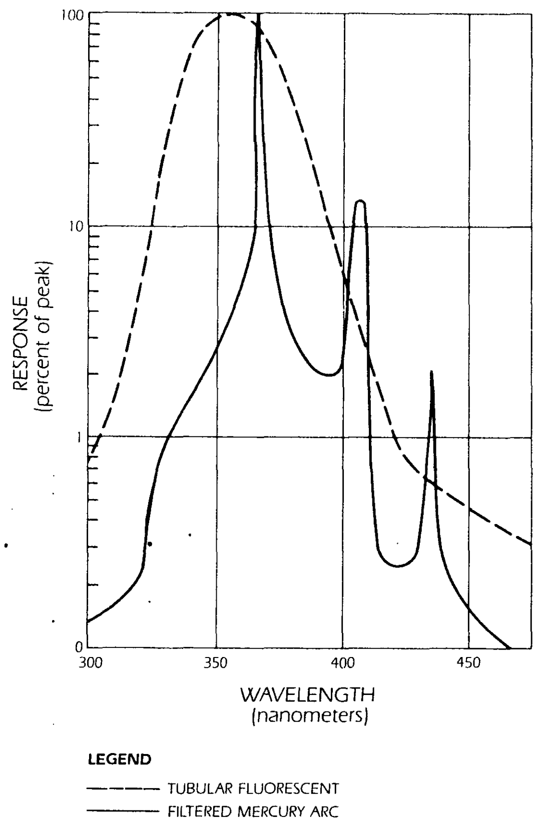
One of the advantages of the mercury arc lamp is that its output can be controlled by design and manufacture. By proper choice of vapor pressure, spectral output can be varied from a few intense but widely scattered lines (when the pressures are near 1 mPa) to an almost continuous spectrum at about 10 MPa (100 atm).

At medium pressures from 100 to 1,000 kPa (1 to 10 atm), the light output is about evenly distributed between the visible, black light and hard ultraviolet ranges. These medium pressure lamps have been used for magnetic particle testing. Figure 15 shows the spectral emission of two kinds of ultraviolet light sources.

Transmission Characteristics of Ultraviolet Filters

Because a limited portion of the ultraviolet spectrum is needed for testing, the output radiation from a light source must be filtered. A commonly used and effective filter is made of heat resistant purple glass. A typical transmission curve for an ultraviolet filter peaks rather sharply near 360 nm and starts to rise again in the neighborhood of 700 nm.

FIGURE 15. Spectral emission of mercury arc and tubular ultraviolet sources



Fixtures for Ultraviolet Sources

For several reasons, ultraviolet sources require a housing and fixturing: (1) to support the filter; (2) to prevent leakage of unwanted visible light; and (3) to permit positioning of the beam onto the test surface.

Various ultraviolet fixtures are commercially available. Some are small and portable. Others are mounted permanently inside a testing booth or on a production testing system. Figures 16 and 17 show portable 100 W mercury arc ultraviolet sources and tubular fluorescent ultraviolet lamps.

FIGURE 16. Portable ultraviolet sources

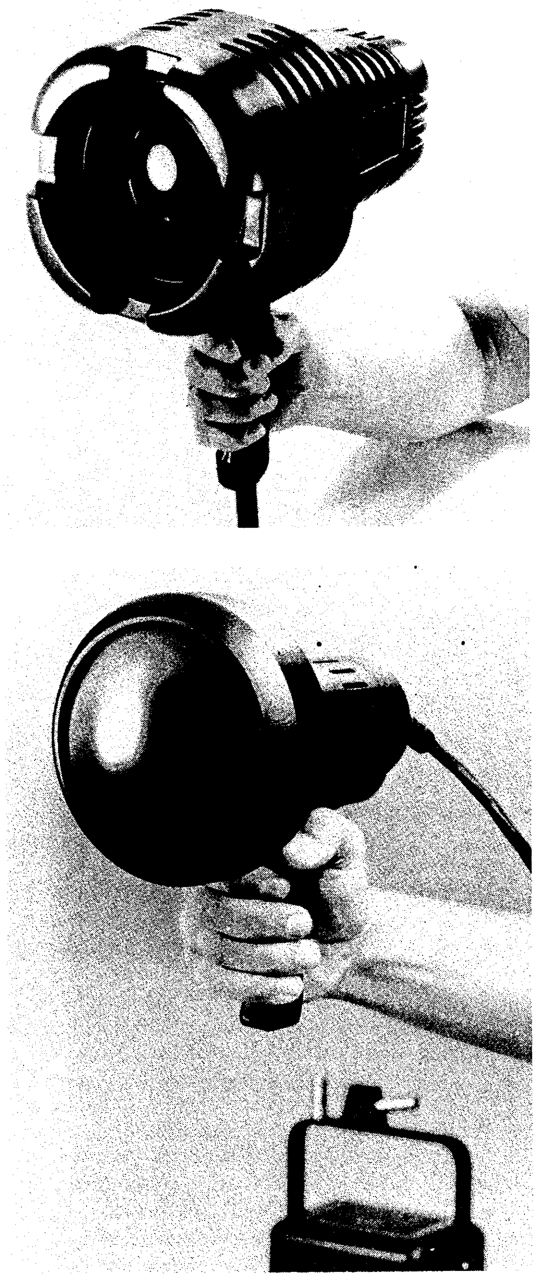


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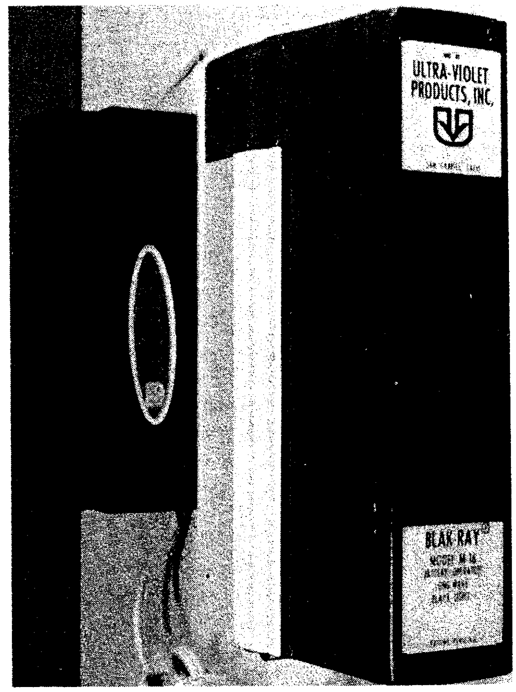
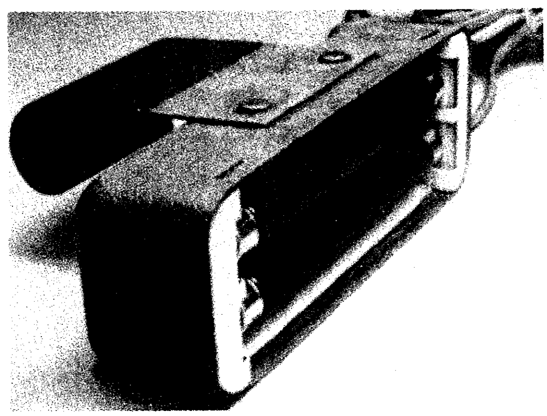
FIGURE 17. Low intensity ultraviolet lamps: (a) portable, battery powered source; and (b) tubular source powered by alternating current

(a)



(b)



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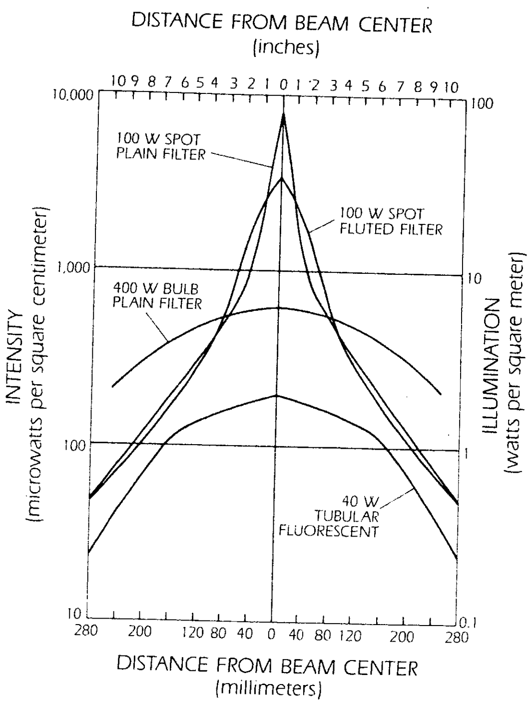
The 100 W lamp is small enough to be portable, although it is often mounted more or less permanently in a testing unit. These lamps come in a variety of configurations from various manufacturers, in *spot* and *flood lamp* types. Spot lamps are used almost exclusively to attain high intensities for localized use. As shown in Fig. 18, spot lamps produce a very intense but narrow beam.

Output Varieties for Ultraviolet Sources

There are many mercury arc ultraviolet sources ranging down to a 2 W size. These have found certain very specialized uses in magnetic particle testing. They usually do not have built in reflectors so their lower power is widely dispersed.

A 400 W ultraviolet source is also available. It is large and typically limited to a stationary mounting. The 400 W source produces a large amount of ultraviolet over a large area and is well adapted to illuminating a large area for quick location of large or medium sized indications. This source does not produce as high a maximum irradiance in any one area as the 100 W bulb.

FIGURE 18. Intensity variations as a function of distance from the beam center for several ultraviolet sources



A 125 W mercury vapor lamp is also regularly used in nondestuctive testing, however several aerospace companies do not permit use of the 125 W source. The bulb has a filter built into its exterior glass shell. Because this is a pear shaped bulb, it has an exterior reflector. The bulb socket and handle are mounted on the reflector. Though the 125 W bulb is bulkier that the 100 W model, it has a number of advantages. The 125 W lamps have less of a warm up period and come up to brilliance much faster. In addition, the 125 W bulb is much less susceptible to voltage variations.

There is still another ultraviolet source available, but it is not suitable for magnetic particle testing applications. It is an incandescent ultraviolet bulb in 75 and 150 W sizes. These are standard incandescent bulbs with a filter glass envelope. Measured on a standard ultraviolet meter, these sources produce ultraviolet irradiance similar to that of a 4 W fluorescent tubular source. In addition, the incandescent bulb produces nearly 30 times as much visible light as the fluorescent tubular sources. Experiments show that small discontinuity indications detected with other sources cannot be detected with incandescent ultraviolet sources. Large indications might be detectable but the high risk of missing indications makes the use of incandescent ultraviolet bulbs unwise.

Fluorescent Tubular Cold Discharge Ultraviolet Sources

Another type of ultraviolet light source for magnetic particle testing is the fluorescent tubular ultraviolet source. Electrically and mechanically, these are standard fluorescent bulbs that come in sizes from 2 to 60 input watts. They are cold discharge tubular lamps containing low pressure mercury vapor glow discharges. The primary radiation generated within the glass envelope is *hard ultraviolet* of 254 nm (2,537 Å) wavelength. The primary radiation is used to excite a special cerium activated calcium phosphate phosphor coated on the inside of the tube. This phosphor, when activated by ultraviolet radiation, emits ultraviolet light with a range of 320 to 440 nm, peaking at 360 nm.

Because a significant amount of visible light is emitted along with the ultraviolet, these bulbs are often made with a purple filter glass similar to that used over high pressure arc lamps. This greatly reduces the emitted ultraviolet but often still leaves an excessive amount of visible blue light, considering the relatively low intensity of its ultraviolet output. Figure 15 shows the spectral emission of the fluorescent tubular source compared to the high pressure mercury arc.

Advantages and Limitations of Fluorescent Tubular Ultraviolet Sources

Fluorescent tubular sources produce sufficient amounts of ultraviolet light but because of their configuration they cannot be easily focused. The irradiance is much lower than that provided by the high pressure mercury arc lamps. Accordingly, fluorescent tubular sources are not often considered adequate for critical fluorescent magnetic particle tests.

Fluorescent tubular sources offer the significant advantages of instant starting, cool operation and low cost. Used in typical four-lamp fixtures, the 40 W tubular sources add up to 160 W and produce near ultraviolet radiation intensities of 1 to 5 $W{\bullet}m^{-2}$ at normal operating distances. Although fluorescent tubular sources may not meet certain specifications (MIL-STD-1949, for example), they are commonly used in industrial applications where stringent performance limits are not required.

Fluorescent tubular sources, especially in the smaller sizes, are the most practical for battery powered portable ultraviolet sources. They are more efficient in their use of electricity when compared to high pressure mercury arc sources. Even more important, they start and reach full output in a few seconds rather than the fifteen minutes required by the high pressure arc.

Care of Ultraviolet Sources

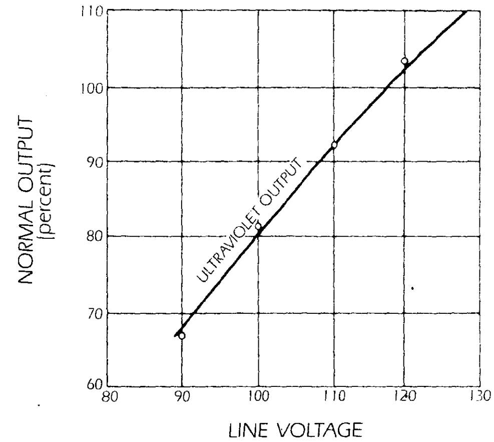
Note: care should be taken to avoid breaking mercury vapor arc lamps. Mercury constitutes a significant health hazard. It may also lead to cracking of aluminum and other metallic components that it contacts. Broken filters can permit exposure to dangerous hard radiation.

The output level of an ultraviolet source depends on the cleanliness of the filter, the applied voltage and the age of the bulb. To keep the output high, the filter should be periodically removed and cleaned, the voltage should be held constant and the bulb should be replaced when its output drops.

Low voltage can extinguish a mercury arc and over time decrease the life of the bulb. Where line voltage is subject to wide fluctuations, with low points at 90 V or less, ultraviolet sources cannot be expected to operate properly (see Fig. 19). High voltage surges also decrease bulb life. Line voltages above 130 V can cause very early burnouts.

On fluctuating power lines, specially designed constant voltage transformers are recommended to control the effects of high and low voltage and extend the source's service life. An additional advantage is obtained by using such a transformer. Certain power lines are subject to sharp drops when heavy machinery is started and the regulating transformer helps eliminate the nuisance of extinguished ultraviolet sources that must cool before re-ignition.

FIGURE 19. Variation in ultraviolet output of 100 W mercury arc lamp (normal power factor ballast and 117 V tap) as line voltage varies



Aging and Life Expectancies of Mercury Arc Ultraviolet Bulbs

The ultraviolet output level of any bulb decreases with age. As a bulb nears the end of its service life, output may drop as much as 75 percent. The service life of these bulbs may vary widely, depending on their care and the original manufacturer. Nominal life expectancy is typically provided by the manufacturer (1,000 hours for a 100 W spot). For various reasons, the actual service life is less for a bulb used in magnetic particle testing. The manufacturer's service life is an estimate based on a standard operating cycle in a fixed and ventilated position. Ultraviolet lamps used in magnetic particle testing are subject to numerous starts and shut offs and to rough handling. In addition, because of filtering and portable housings, ultraviolet lights for fluorescent tests often operate at higher than optimum temperatures.

Extending the Service Life of Ultraviolet Sources

The magnetic particle inspector can contribute to lamp life in two ways. One of these is to avoid operating ultraviolet sources above their rated voltage. Slight increases in voltage decrease lamp life substantially. In some tests, increasing supply voltage to between 125 and 130 V resulted in burned out lamps in as little as 48 hours.

A second way to prolong the life of an ultraviolet source is to keep the number of starts as low as possible. Each time a lamp is started, a small amount of active material is removed from the electrodes. A single start is equivalent to several hours of continuous burning. It is generally more economical to leave lamps burning over rest periods and lunch hours that to turn them off and on again.

Ultraviolet Measurement Instrumentation

It is often difficult to determine the precise amount of ultraviolet radiation required to carry out a particular test. A suitable level can generally be determined by trials on reference standards with known discontinuities.

Fluorescent magnetic particle test interpretation may be considered a visual test and most of the rules applicable to visible light testing apply. Since different amounts of ultraviolet are necessary for different types of testing, some method of evaluating and specifying irradiance level is needed. Experience indicates that ultraviolet irradiance levels of 10 $W \cdot m^{-2}$ are generally adequate.

Selenium Cell Measurement of Ultraviolet Light Intensity

Beginning around 1942, selenium cell photoelectric meters were used to measure ultraviolet levels. The most common, easily used portable footcandle meters were designed for illumination engineers. It was discovered that if the filters were removed from these meters, they became sensitive to ultraviolet radiation.

The *lux* or *footcandle* is a unit of visible light *illuminance*. It is defined in terms of the human eye's response under bright light (photopic) conditions. There is no such thing as a footcandle of ultraviolet radiation. Ultraviolet radiation was incorrectly measured in footcandles for many years with unfiltered footcandle meters. Even though these readings did *not* make logical sense, they did give reproducible relative quantities.

In addition, such metering was always dependent on an uncontrolled portion of the spectral sensitivity of selenium. This part of the selenium response was of no concern to the manufacturer of the visible light meter and could have been changed at any time without notice and without effect on the visible light measurements. The effect on ultraviolet measurement could have been significant. Despite these disadvantages, no portable meter was then available to give true measurements in the near ultraviolet wavelength range.

Ultraviolet Meters

Ultraviolet energy is invisible electromagnetic radiation similar in nature to radio and infrared waves. These radiations are measured in energy per unit time or watts and frequently, as in the case of broadcast radio waves, in kilowatts. Ultraviolet power output can also be measured in watts but is more often stated in milliwatts (mW) or microwatts (μW). Although ultraviolet sources are commonly rated by their wattage, these figures are actually electrical energy input rather than optically radiated output. Because of conversion losses, the radiated output is much less than the input.

Measurement of ultraviolet irradiance requires equipment sensitive in that spectral region calibrated in watts per square meter ($W \cdot m^{-2}$), milliwatts per square centimeter ($mW \cdot cm^{-2}$) or microwatts per square centimeter ($\mu W \cdot cm^{-2}$). Such meters are typically filtered so that they respond only to the appropriate ultraviolet wavelengths (see Fig. 20).

The ideal responsivity function for such a measurement in magnetic particle testing is a constant sensitivity from 320 to 400 nm (the so-called *black light* range) and zero sensitivity elsewhere. With such a responsivity, measurements could be made accurately and simply. Unfortunately, large departures from this ideal responsivity are commonplace in ultraviolet meters. Detectors or filters needed for realizing the ideal are not available.

When the spectral distribution of a calibration lamp and the lamp to be measured are significantly different, the measured irradiance may be substantially in error. Some manufacturers sell calibration equipment (based on black light) to calibrate radiometers primarily used with the 100 W parabolic ultraviolet source. Without a correction factor, such calibrated meters provide erroneous metering values.

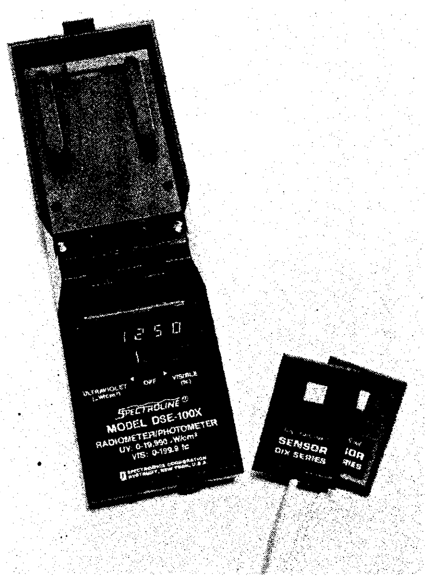
All common industrial ultraviolet radiometers use a bandpass filter. Such filters have variable high transmission from 320 to 400 nm and much lower transmission elsewhere. An ultraviolet meter's ability to measure with minimal interference from other radiations is based on two characteristics: (1) its spectral flatness, the upper limit and constancy of its transmission in the ultraviolet region of interest; and (2) its blocking ability, the lower transmission limit that can be maintained at all other wavelengths. Interfering radiations, usually UV-B (280 to 320 nm), visible (400 to 760 nm) and infrared (760 to 10^6 nm), can be particularly troublesome in magnetic particle testing applications.

Unfortunately, filters with sharp cut-on and sharp cut-off slopes are very costly and they have never been included in magnetic particle testing meters. In addition, errors and confusion can be caused by using radiometers with the wrong spectral response for the application. Military standards and other industry specifications clearly state that the spectral region of interest is 320 to 400 nm for magnetic particle tests. Typical spectra of lamps used in nondestructive testing are shown in Fig. 15.

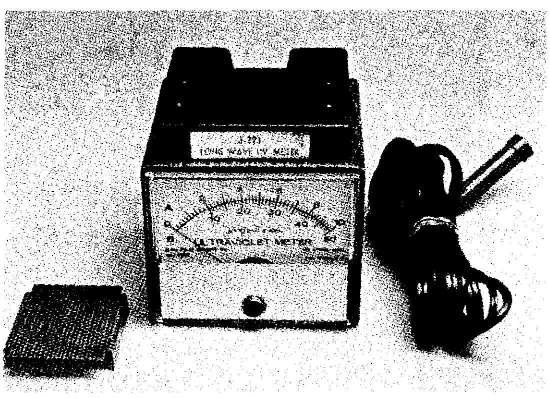
The excitation spectrum is such that some fluorescent magnetic particles increase in fluorescence efficiency beyond 380 nm. Also, the output of commonly used ultraviolet

FIGURE 20. Meters used to measure ultraviolet irradiance: (a) combination radiometer and photometer; and (b) long wave ultraviolet meter

(a)



(b)



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sources does not fall to zero at this wavelength. For these reasons, a meter whose sensitivity falls to zero at 380 nm may fail to explain why one type of lamp causes greater fluorescence than another type. The meter may also differ in relative readings from a radiometer with a spectral bandwidth extending to 400 nm. Using broader bandwidth radiometers generally gives a better indication of the quantity of usable ultraviolet.

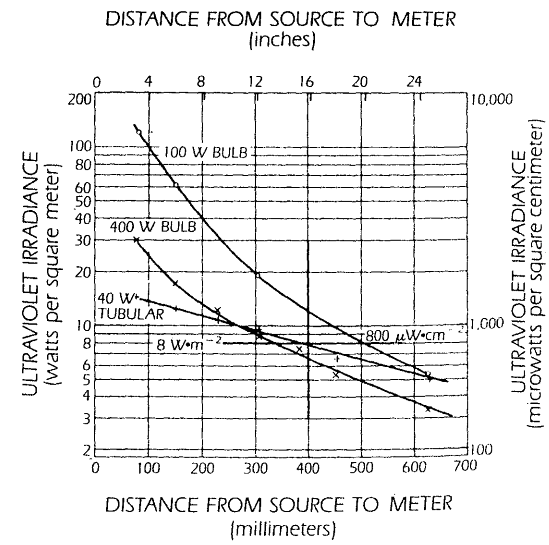
Units of Measure for Ultraviolet Sources

The US Military Standard MIL-STD-1949, *Magnetic Particle Inspection,* calls for a minimum ultraviolet light intensity of 1,000 microwatts per square centimeter (10 watts per square meter) at the test surface, with a maximum of 20 lx (2 ftc) of visible light in the testing area. Some industry specifications vary from these limits.

As shown in Fig. 21, ultraviolet irradiances vary greatly with the distance between the light source and the radiometer and with the type and wattage of the source. Note that, under normal conditions, the irradiance does not vary as the inverse square of the distance. Ultraviolet sources are typically broad beam and the inverse square law strictly applies only to point sources.

Irradiance is an average over the area of the sensor and most radiometers used in nondestructive testing have different sized apertures. For this reason, there may be some

FIGURE 21. Variations in ultraviolet irradiance with distance from the source face for 400 W and 100 W tubular lamps



reading variations even if all sensors were similarly calibrated. The 100 W spot lamp used as a portable ultraviolet source produces a narrow beam of high intensity radiation and some manufacturers' 125 W lamps can be even narrower. Such beams may not cover the entire area of meters with relatively large sensors and this can produce measurements differing considerably from meters with smaller sensing areas.

Using Ultraviolet Radiometers

Ideally, the irradiance of a surface could be measured directly by placing a calibrated detector at that surface at any time, but this is usually not possible with radiometers. To avoid additional sources of error, it is essential that the complete area of the calibrated detector be irradiated. If at all possible, the detector should be oriented normally to the incident radiation to avoid modification of the detector's projected area and to minimize reflections from the filters in front of the detector.

If it is not possible to have most of the incident radiation striking the detector perpendicularly, then an angular sensitivity plot for the detector system must be used to avoid large errors. Sensors with interference filters are especially prone to large errors if the irradiating source is off to one side of perpendicular from the sensor face or if measurements are made close to extended sources.

One commercial meter sensor is provided with an uncalibrated, perforated metal plate transmitting 20 to 30 percent of the ultraviolet radiation striking it, depending on the geometry of the measurement. This allows an effective scale extension of three to five times the normal full scale value of 6,000 $\mu W \cdot cm^{-2}$ and about the same overall range (20,000 $\mu W \cdot cm^{-2}$) as the digital radiometers commonly used. The user of this particular meter must determine the multiplication factor of the metal attenuator under normal conditions.

One manufacturer's radiometer indicates that a 50 percent correction factor is needed when using its meter to measure fluorescent ultraviolet sources.

Not all meters are designed for the same range of conditions or for the particular conditions found in magnetic particle testing applications. Some meters are used in applications such as ultraviolet curing, photolithography or medical phototherapy where the spectral output of the source is considerably different from the sources used in magnetic particle testing.

Service Life of Ultraviolet Meters

Periodic recalibration is absolutely essential if the reliability and accuracy of the ultraviolet meter is to be maintained. Apart from catastrophic events such as thermal or mechanical impact, the components of most radiometric sensors are subject to deterioration, even with careful use. Ultraviolet filters are subject to aging effects, particularly those provided with the interference filters. Humidity and heat that builds up within the multilayer filter can have irreversibly damaging effects on its transmission characteristics.

A plastic wavelength converter is used in most sensors to change the ultraviolet radiation to visible light that is closer to the peak sensitivity of the meter's photodiode. These converters undergo irreversible photochemical damage with use and must be replaced at regular intervals. Most manufacturers recommend a recalibration period of six months. If the meter is heavily used and under extreme environmental conditions, the recalibration period should be shortened.

SECTION 16

SPECIAL APPLICATIONS OF MAGNETIC PARTICLE TESTING

John Brunk, Sandra T. Brunk and Associates, Overland Park, Kansas (Parts 4, 5, 6, 7 and 8)

William Burkle, Precision Tubular Inspection, Lone Star, Texas (Parts 2 and 3)
William Chedister, Circle Chemical Company, Hinckley, Illinois (Part 6)
Brandon Fraser, William Burkle Associates, Bartlesville, Oklahoma (Parts 2 and 3)
Lawrence Goldberg, Sea Test Services, Merritt Island, Florida (Part 1)
Daniel Hafley, General Testing Laboratories, Kansas City, Missouri (Part 8)
Donald Hagemaier, Douglas Aircraft Company, Long Beach, California (Part 5)
John Mittleman, Marine Inspection Technology, Panama City, Florida (Part 1)
Roderic Stanley, International Pipe Inspectors Association, Houston, Texas (Part 9)

PART 1
UNDERWATER MAGNETIC PARTICLE TESTS

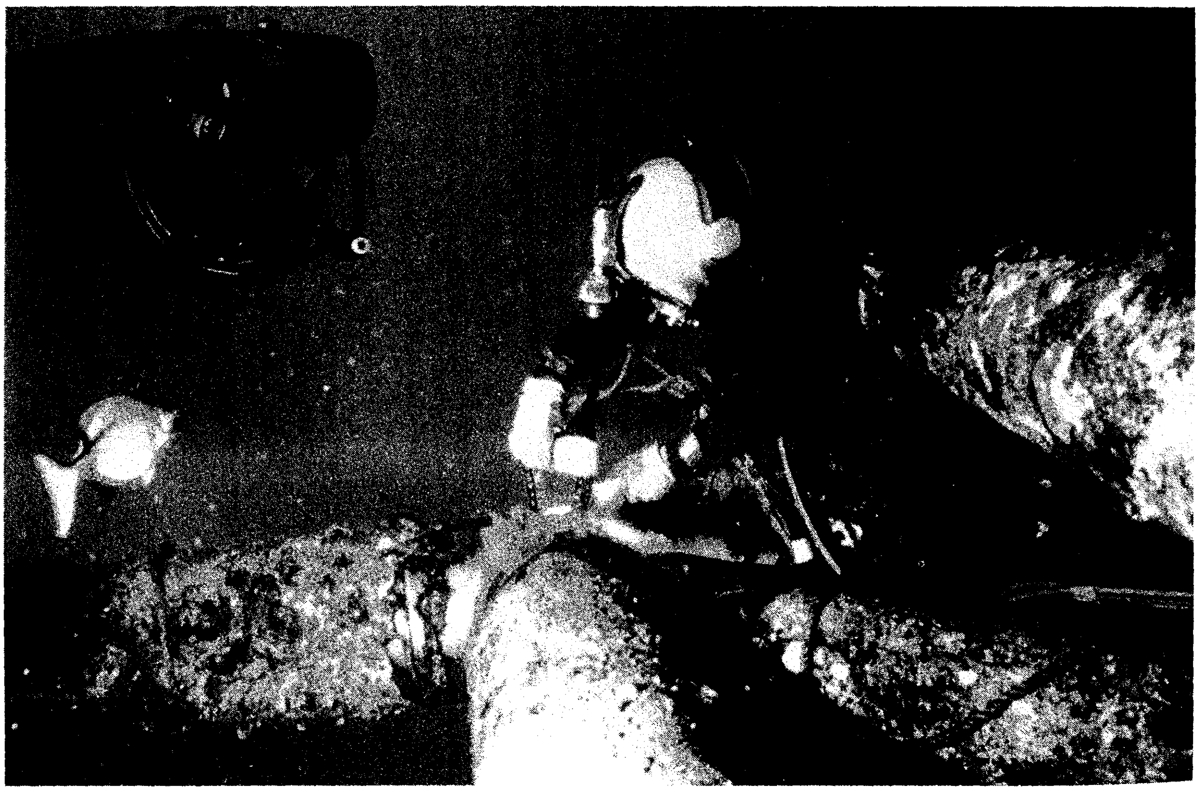
Innovative technology has been developed in the American offshore underwater nondestructive testing industry. These developments provide significant cost reductions, without reducing sensitivity, for standard magnetic particle techniques as well as underwater tests.

Underwater magnetic particle weld testing is different from typical dry and wet magnetic particle testing. In practice, it resembles a hybrid form of both the dry and wet methods, more closely resembling dry fabrication and in-service testing. The main differences are that the particles are delivered in a wet slurry and the inspector is a diver. Figure 1 shows underwater magnetic particle testing being performed as part of a damage survey.

Magnetic Particle Testing through Coatings

Performing any type of underwater testing is costly because of the required peripheral diving support. The cost is increased by the need to remove marine growth prior to visual and magnetic particle testing. Traditionally, most oil and gas companies have required welded joints to be cleaned to bare metal, especially for magnetic particle testing. Most industrial codes have limited magnetic particle testing to surfaces having less than 50 μm (2 milli-in.) of thin nonconductive coating. However, research has shown

FIGURE 1. Diver performing underwater magnetic particle test during a damage survey; remote operated vehicle provides additional surveillance



that it is possible to test through thin coatings with reliable results.[1,2]

This is important because high pressure water guns operating at 138 MPa (20 ksi) can efficiently clean underwater structures to a thin, tightly adhering layer of black oxide having a coating thickness in the range of 75 to 125 μm (3 to 5 milli-in.). Compared to black oxide surface finishes, the cost of cleaning to a bare metal surface finish conservatively doubles the testing cost. It has been determined that magnetic particle testing on black oxide coatings has the same required sensitivity as testing performed on bare metal for detection of incipient fatigue cracks at joint intersections on welded offshore structures.

Underwater Applications of Testing through Coatings

A magnetic particle system sensitivity test was demonstrated to the American Bureau of Shipping (ABS) to obtain certification for using magnetic particle techniques in the field.[3] The demonstration, performed at the Paramus, New Jersey laboratory of ABS, used painted objects having discontinuities of the type that must be located offshore. The technique was certified and subsequently found to produce the required sensitivity without costly cleaning to bare metal. The benefits to the customer are significant reduction in cost (typically fifty percent) without sacrificing reliability.

FIGURE 2. Magnetic particle indication produced on black oxide using an alternating current electromagnetic yoke

Magnetic particle testing through coatings is performed using an alternating current yoke. The sensitivity of the system is based on the detection of fine in-service fatigue cracks with minimum dimensions of 13 mm (0.5 in.) length, 0.025 mm (0.001 in.) width and 0.75 mm (0.03 in.) depth. This sensitivity is within the range of fatigue crack sizes most oil and gas companies require for detection. Figure 2 shows a magnetic particle indication formed on a black oxide surface finish.

Field Tests through Coatings

After magnetic particle techniques were performed successfully underwater for several documented case studies, research was initiated to look at similar tests through coatings in air.[4,5] Research focused on defining threshold coating limits for certain discontinuity sizes. Reliable results were achieved using an alternating current yoke with dry powder on hairline indications through as much as 300 to 400 μm (12 to 16 milli-in.) of paint.

There were two significant findings of these studies. The most important variable for performing magnetic particle testing is not the ability to get sufficient flux density to the discontinuity site, but rather to get sufficient flux leakage out from a discontinuity to form a detectable magnetic particle indication.

Secondly, when using the alternating current yoke (indirect magnetization), it is not always necessary to clean in the area of yoke leg contact. The alternating current provides high surface flux density because of the skin effect. The same test results can be achieved when the area of interest is cleaned, with or without cleaning the base metal at the points of yoke contact.

For example, a crack-like indication detected on a coated weld can be verified by magnetic particle testing through as much as 750 μm (30 milli-in.) of coatings because the break or crack in the coating provides a flux leakage path. Conversely, cracks that occur only in the paint do not produce magnetic particle indications.

Cracks occurring in offshore structural welds are almost always found in the toe of the weld. If the paint coating thickness is 750 μm (20 milli-in.), one way to reduce cost is to clean the weld and 13 mm (0.5 in.) on each side of the weld and then perform the magnetic particle test. Figure 3 shows an example of a tight fatigue crack detected with only the suspect area cleaned to bare metal.

As a result of these studies,[4,5] the American Society for Mechanical Engineers amended its Section V, *Nondestructive Examination Code* (T-724d, *Surface Preparation*) as follows:

If coatings are left on the part in the area being examined, it must be demonstrated that indications can be detected through the maximum coating thickness applied.[6]

Single Leg Electromagnet Technique

When testing *T*, *X*, *K* and *Y* tubular connections in areas of acute angle, it is often impossible to access the geometry with a typical yoke configuration. A technique that can be used successfully under these circumstances is the *single leg technique*. The single leg electromagnet produces a magnetization pattern called a *radial field* that is essentially one half of the longitudinal field produced by the yoke. Because structural steel has a higher magnetic permeability than the surrounding water,[7] the magnetic field can be localized where it is needed. Figure 4 shows testing with the flux leakage field produced by a single leg electromagnet.

FIGURE 3. Magnetic particle indication produced when only the suspect area is cleaned to bare metal and the yoke legs contact 0.5 mm (0.02 in.)

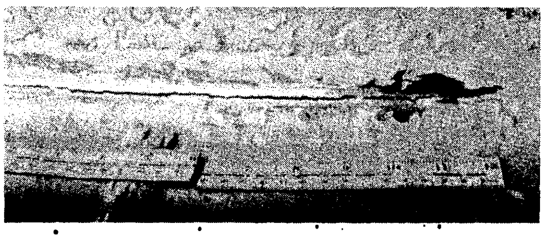


FIGURE 4. Diver performs a magnetic particle test using a single leg electromagnet to access tight areas of interest

In some cases, the single leg technique can provide better sensitivity than small conventional yokes. The main factors affecting test sensitivity for both yokes and single leg electromagnets are: (1) the size of the coil producing the leakage field; and (2) the flux density at the area of interest.

Although no industrial specification references the single leg technique, the method can meet all the necessary specification requirements by (1) picking up a 4.5 kg (10 lb) weight; (2) producing clearly defined indications on magnetic field indicators; (3) producing greater than 240 A•m^{-1} (30 Oe) in the tested area; and (4) detecting discontinuities in production applications or in reference standards with known discontinuities.

Alternating current is always used with the single leg technique because fatigue cracks typically initiate as external surface discontinuities and then fracture through the thickness of the test object. Direct current magnetization and permanent magnets are not recommended for detection of in-service weld cracks. Figure 4 shows an example of the single leg technique used in an area of tight access. Figure 5 shows a magnetic particle indication produced on black oxide with single leg magnetization.

Single leg technology also offers some unique advantages for robotic test systems. Its geometry is universal and it is a low profile package. Since robotic arms can maneuver heavy components, coil size is not a restriction. Layering alternating current with pulsed direct current by stacking or winding one coil over the other can provide the skin effect and particle mobility of alternating current with the field penetration of direct current.[8]

FIGURE 5. Magnetic particle indication produced on black oxide surface finish using single leg alternating current electromagnet

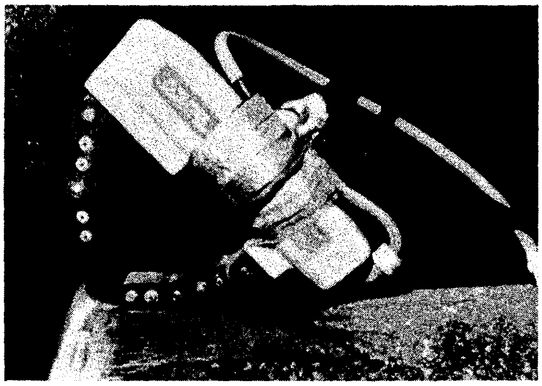
Discontinuity Data Bases

Underwater magnetic particle testing can also be used to define the types of discontinuities that occur, their frequency and the probability of detection. A discontinuity data base for fixed offshore platforms[2] found that, of all the discontinuities detected, the majority was confined to the toe of the weld. This trend applies to fixed offshore platforms (*T*, *K* and *Y* connections, built primarily of mild strength steels) and may not apply to other marine structures, such as mobile offshore drilling units made of high strength steels.

The significance of the trend is that both fracture mechanics models and documented empirical data for fixed offshore structures indicate a low probability of occurrence for transverse discontinuities. Yoke manipulation and scanning efficiency can be maximized by restricting testing procedures to those that detect longitudinal discontinuities.

The yoke should straddle the welded joint so that the lines of flux cross discontinuities at the most nearly perpendicular angle. Techniques that use criss-cross (45 degree) pole placement are less sensitive for detecting longitudinal cracks and should not be used. Figure 6 shows the proper yoke setup for testing in the longitudinal direction.

FIGURE 6. Optimum orientation of an electromagnetic yoke for the detection of weld toe cracks on offshore structures



PART 2

DRY POWDER MAGNETIC PARTICLE TESTS OF PAINTED WELDS

A literature search produces little information about the technical feasibility of alternating current yoke magnetic particle tests of painted welds. Empirical data and practical opinion are somewhat mixed concerning this procedure and there are reports of both successful and unsuccessful magnetic particle tests of welds through paint.

Such a wide variation in reported feasibility is not entirely surprising. Thousands of different paints exist and are applied in a wide range of thicknesses and in a nearly infinite number of primer and topcoat combinations. Each paint or coating system has a characteristic magnetic permeability that influences the degree to which magnetic flux may be introduced to a ferromagnetic substrate.

Yoke Break Test

A *yoke break test* was devised to help evaluate the effect of coating type and thickness on the introduction of flux to a ferromagnetic substrate. This simple test relies on the contention that the flux strength produced in a ferromagnetic material may be gaged by the amount of pull produced by the yoke on that material. The test uses a dynamometer to pull an energized yoke from a bare test plate. The plate is then coated with progressively increasing thicknesses of paint. After the application of each paint layer, the force required to pull (or break) the yoke from the plate is measured along with the coating thickness. During this test, the poles of the yoke are maintained at a constant spacing.

Such a test was performed using ASTM A-36 steel plates as a substrate. Four separate coating types were evaluated, including inorganic zinc, zinc chromate, enamel and phenolic epoxy. Yoke break test data obtained for each coating are presented graphically by Fig. 7, where pull is plotted against applied coating thickness.

Weld Bead Crack Reference Standards

In an attempt to quantify the thickness of the coating at which sensitivity is diminished, four ASTM A-36 plates were prepared, each containing a single shielded metal arc weld bead in which copper ferrite dilution cracking had been induced. Copper ferrite cracks are very fine and barely visible to the unaided eye. Each plate was tested with yoke magnetization and a record of the particle indications was made for each direction of magnetization.

Each plate was then coated with inorganic zinc, zinc chromate, enamel or phenolic epoxy. Coating thicknesses were measured and recorded and the plates were then retested with a yoke technique. Particle indications were recorded and the indications were compared to those obtained during magnetic particle tests of the bare metal. This process was repeated until each plate reached the point at which coating thickness diminished the indication detectability. Table 1 summarizes the results of this study and lists the critical thickness of each coating.

Reference Standards for Weld Cracking

To confirm that bead crack test data would be valid when applied to actual welds, three additional plates were prepared to contain multipass groove butt welds with multiple bead weld caps. Each weld cap was approximately 25 mm (1 in.) wide. These welds contained undercuts of varying severity as well as copper ferrite dilution cracks. Except for the cracking, the welds were typical of those commonly encountered during industrial magnetic particle tests.

An initial test was performed and records of particle indications were made. Each plate was then coated with

TABLE 1. Copper ferrite dilution cracking detectability for various applied coating thicknesses

Coating Type	Critical Thickness* micrometer (milli-inch)
Enamel	300 (12)
Inorganic zinc	225 (9)
Zinc chromate	200 (8)
Phenolic epoxy	175 (7)

*MAXIMUM THICKNESS OF APPLIED COATING AT WHICH NO LOSS OF INDICATION DETECTABILITY WAS OBSERVED inorganic zinc, zinc chromate or enamel. The paints were allowed to dry, coating thicknesses were measured and recorded and each plate was retested with yoke magnetization.

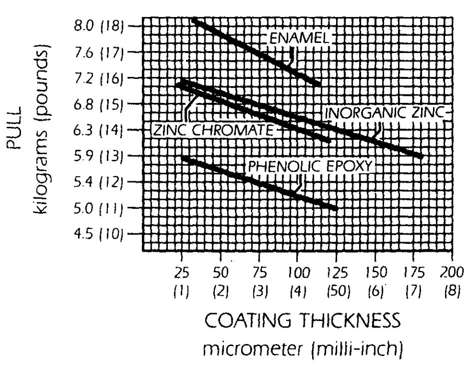
Records of the particle indications were made and test results were compared to those obtained from the unpainted plates. Even though each of the applied coating thicknesses was less than 80 μm (3 milli-in.), all of the test objects revealed a dramatic loss of indication detectability.

Effect of Coating Thickness on Test Results

The data in Fig. 7 show that the introduction of magnetic flux to a ferromagnetic substrate with an alternating current yoke is affected by interposing thicknesses of paint. The extent of this effect may be significant, depending on the type of paint and its thickness.

There is a surprisingly large difference in the data obtained from single bead test welds and from multiple bead test welds, especially as it relates to the coating thicknesses that permit yoke magnetization. It is believed that this difference may be the result of concurrent leakage fields (Fig. 8) that existed in the multiple bead weld cap but not in the single bead weld. This could have produced decreased flux density in leakage fields at the crack sites and in turn could have reduced the ability to attract and hold particles through the coatings.

FIGURE 7. Decrease in pull with increase in coating thickness; yoke produces a pull of 8.7 kg (19.3 lb) on a bare test plate; yoke center-to-center pole spacing maintained at 110 mm (4.25 in.) during all tests



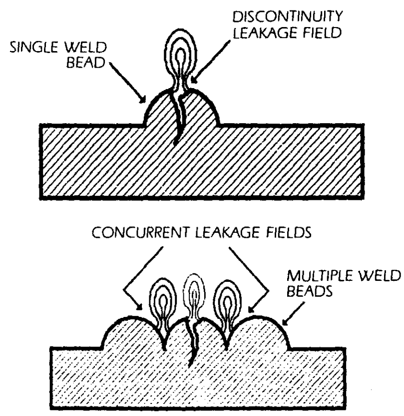
Concurrent Leakage

The concept of concurrent leakage was investigated further. A single shielded metal arc weld bead containing copper ferrite dilution cracking was deposited on a carbon steel plate. The bead was tested with magnetic particle yoke techniques and the discontinuity indications were recorded.

An additional bead was then deposited on each side of the original weld and the new weld was retested. After seven beads had been deposited (three on each side of the original weld bead), a distinct decrease in indication detectability was observed.

This indicates that magnetic particle testing of painted welds is dependent not only on coating type and thickness, but also on the weld profile.

FIGURE 8. Concurrent leakage fields produced in a multibead weld cap as the result of abrupt cross-sectional change at the weld toes; redistribution of the magnetic flux caused by these fields reduces the leakage field in an adjacent discontinuity



PART 3

MECHANICAL PAINT REMOVAL AND ITS EFFECT ON CRACK DETECTABILITY

To assess the effect that mechanical paint removal might have on weld discontinuity detection, a comparison was made of the detectability of copper ferrite dilution cracking in welded test plates before and after a paint removal procedure. Copper ferrite dilution cracking is characteristically very fine and difficult to detect visually. Its small size makes it representative of the sort of weld discontinuity that could be affected by surface working during paint removal.

Test Object Preparation

Five ASTM A-36 steel plates were prepared, each about 300 mm (12 in.) long by 150 mm (6 in.) wide by 13 mm (0.5 in.) thick. A single *V* groove butt weld was produced in the center of each plate by the shielded metal arc welding (SMAW) process, using E-7018 electrodes. Each weld was divided into segments 50 mm (2 in.) long and two of these segments in each weld were selected for crack implantation.

Copper ferrite dilution cracking was induced in each of the two selected segments. Each plate was assigned a sample identification number and each was tested using an alternating current yoke and dry magnetic particles.

A transparent tape transfer record was made of all discontinuity indications for each direction of magnetization. Because liquid dye penetrant materials are difficult to remove from capillary voids such as the cracks produced in the sample plates and because these materials could interfere with subsequent coating application, an initial liquid dye penetrant examination was not performed.

Visual Test Results

Copper ferrite dilution cracks tend to form fine, branched indications that vary significantly in length and width. Depending on orientation and their reflective characteristics, many such cracks are not consistently detectable during visual testing. To ensure that crack detection comparisons were based on a reliable and consistent frame of reference, an effort was made to determine which of the sample weld crack indications could be repeatedly and consistently detected.

Fifteen welding inspectors certified by the American Welding Society visually inspected each of the five test plates and produced a detailed sketch of crack locations and orientations. Each inspector's sketch was compared to the previously obtained magnetic particle tape transfer record for the appropriate sample segment.

Those cracks that were most consistently reported by all fifteen inspectors were selected for use as reference cracks in comparing detectability before and after paint removal.

Coating Application

The five plates were sandblasted in preparation for coating application. Five commonly used paint systems were applied by brushing or spraying in strict accordance with the manufacturers' recommendations. The applied paint systems and the average applied coating thicknesses are detailed in Table 2.

TABLE 2. Coatings and thicknesses for paint removal study

Sample	Primer	Thickness micrometer (milli-inch)	Topcoat	Thickness micrometer (milli-inch)
B1	Zinc chromate	35 (1.4)	enamel	98 (3.9)
B2	TNEMEC™	48 (1.9)	enamel	88 (3.5)
B3	TNEMEC™	45 (1.8)	Carboline™ 305	130 (5.2)
B4	Carbozinc™ 11	110 (4.4)	Carboline™ 305	275 (11.0)
B5	Carbozinc™ 11	85 (3.4)	none	

Each plate was given fourteen days to dry and cure. After curing, the welds were visually inspected to determine if cracking was visible through the paint and none was detected.

Visual Retesting

The coatings were removed by applying surface conditioners (solvents) in combination with manual and power wire brushing. Five certified welding inspectors then performed visual examinations of the plates. Each inspector produced a detailed sketch of the location and orientation of detected cracks.

A redetection frequency was determined for each of the reference cracks by comparing the sketches to the original magnetic particle transfer record and to the sketches of crack locations before coating. In all cases, the reference cracks were redetected and recorded without significant change. A reduction in the cracks' reflective characteristics was noted.

Magnetic Particle Test Results

An alternating current yoke, dry powder magnetic particle test was performed on each sample segment. Transparent tape transfers of all discontinuity indications were obtained for each direction of magnetization. Comparisons were made of tape transfers taken before and after coating removal and the discontinuity indications were found to be identical.

A liquid dye penetrant test was then applied to each test plate using a solvent removable visible dye penetrant and nonaqueous wet developer. A dwell time of twenty minutes was observed before penetrant removal and developer application. Eighty percent of the reference cracks were *not* revealed by this method.

Cross Sections

The welds were then cross sectioned through various crack locations. Cross sectioning was used to determine physical characteristics such as crack width; to determine if smearing or working of the metal surrounding the crack openings had occurred; and to determine the extent to which the coating may have entered and occluded the reference cracks.

On the basis of laboratory reports and a subsequent test of the samples, crack widths were determined to be in the range of 25 μm to 0.25 mm (0.001 to 0.01 in.) at the plate surface. After paint removal, a layer of disturbed metal was observed to partially seal the crack openings. Laboratory tests indicate that this layer was on the order of one or two metal grains in thickness. No paint was detected in any of the crack voids.

Conclusions

Magnetic particle tests of welds produce reliable results after coating removal operations. No significant degradation in crack detectability was noted (all reference cracks detected by magnetic particle methods were also detected by visual examinations).

Test results suggest that, compared to magnetic particle techniques, the liquid dye penetrant testing method is not reliable for detecting discontinuities after paint removal. It is suspected that this is primarily the result of a partial smearing of the weld surface metal across discontinuity openings.

In a further investigation, a test weld containing copper ferrite dilution cracking was liquid penetrant tested both before and after sandblasting. Before sandblasting, the cracks were readily detected. After sandblasting, crack detectability was significantly reduced. This suggests that surface preparation also contributes to smearing and again points to the advantages of magnetic particle test methods.

PART 4

MAGNETIC PARTICLE TESTING USING REMOTE VISUAL EQUIPMENT

Magnetic particle methods are sometimes required for testing surfaces that are not accessible for direct viewing. The problem may be inherent in the test object (the inside surfaces of hollow forgings or castings, for example) or in the design of the testing facility.

Television systems are sometimes used to solve accessibility problems, such as the need to inspect both sides of an object without actually moving it. Television systems can also be considered if it is necessary to increase the speed or to automate a testing process. High production quantities for cost justification, adequate lighting and sufficient space are all necessary to support a television system.

When it is impossible or impractical to use standard television cameras, other types of remote visual testing instruments may be effective.

Types of Instruments

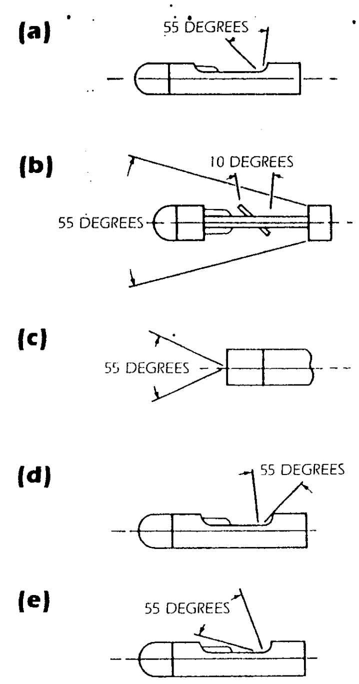
When access to the area of interest is restricted, remote visual equipment may be used to achieve inspectability. The following text details such equipment for use with visible (color contrast) and fluorescent magnetic particle testing techniques. Four primary types of remote visual testing instruments should be considered.

Lamp Illuminated Rigid Borescope

Rigid borescopes are available with insertion tube diameters from 9 to 70 mm (0.4 to 2.8 in.). Extendable borescopes may have lengths up to 30 m (100 ft) or more. There are several types of viewing heads available to give the desired direction or angle of view (see Fig. 9).

The rigid borescope can provide very bright visible light illumination. For ultraviolet applications, large borescopes can be equipped with the same 125 W ultraviolet sources used in portable lamps, although bulb size can then restrict access. Much smaller ultraviolet tubes (Fig. 10) may also be used to increase accessibility but these typically do not meet certain intensity requirements, such as those specifications that call for measurement at a distance of 380 mm (15 in.) from the source surface. This ultraviolet illumination problem is common to all four types of remote visual instruments.

FIGURE 9. Borescope viewing heads for various applications: (a) bends the cone of view at right angles to the borescope axis, providing a lateral view; (b) circumference or panoramic head projects forward to view at slanting incidence a 360 degree band; (c) bottoming head provides cone of view directly forward with uniform circumference illumination; (d) bends cone of view at a retrospective angle to borescope axis, providing a view of the area just passed by an advancing borescope; and (e) bends cone of view to a forward oblique angle to borescope axis



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The rigid borescope has the advantage of superior image quality. Resolution in excess of 75 line pairs per millimeter is available with some instruments when viewing directly through the eyepiece. When a video adapter is added, some loss of detail results, and the amount of image degradation depends on the video components. This can be a critical consideration, depending on the resolution needed to detect the smallest significant magnetic particle indication.

Fiberoptic Illuminated Rigid Borescopes

The fiberoptic borescope uses a separate light source and fiberoptic filaments to transmit light through the insertion tube to illuminate the area of interest. Such borescopes are available with insertion tube diameters from 1 mm (0.04 in.) to 20 mm (0.8 in.) or more. A few have been produced with diameters as small as 0.5 mm (0.02 in.). Like the lamp illuminated borescopes, fiberoptic instruments are available with several kinds of directional viewing heads.

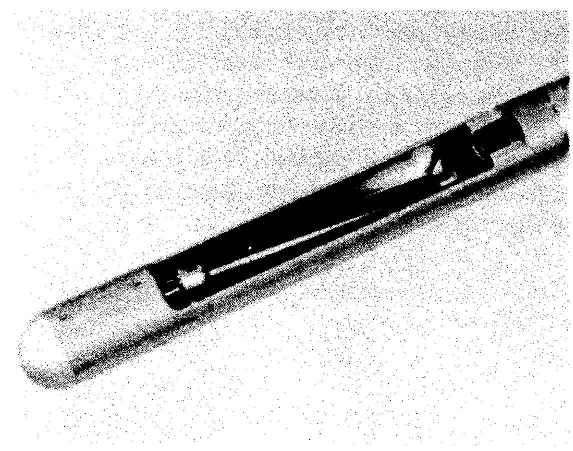
In addition to increased accessibility because of their small size, fiberoptic borescopes may also be used in places where electrical wiring or heat from a lamp is hazardous.

The intensity of fiberoptic illumination is determined by the type of light source used and the size, number and length of the illumination fibers. Visible light sources are available up to 300 W. In general, meeting visible light intensity requirements is not a problem with insertion tube diameters of 3 mm (0.12 in.) or more and lengths at least 1 m (3 ft).

Very high ultraviolet intensity is produced by sources with 200 to 300 W xenon lamps. The intensity available at the scope tip is limited by absorption of ultraviolet in the fiberoptic illumination guide. Subject illumination can be improved by using high purity quartz illumination fibers in the scope itself and a quartz or liquid filled guide to conduct light from the lamp to the borescope. Borescopes of this type can produce ultraviolet light intensities above 1,000 $\mu W \cdot cm^{-2}$ at typical scope-to-surface distances of 50 mm (2 in.).

The fiberoptic illuminated borescope typically uses the same type of rigid optical lens imaging system as the lamp illuminated borescopes and gives comparable detail resolution. The effects of adapting video equipment are similar for both types of viewing apparatus.

FIGURE 10. Borescope head with a miniature ultraviolet source



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Fiberscopes

Fiberscopes are used when a flexible insertion tube is needed to reach the test surface. Some fiberscopes are available with two-way or four-way articulating tips for changing the direction of view. Fiberoptics are used to conduct light to the probe tip and to conduct the image back to the eyepiece.

Compared to a rigid borescope of the same length, a fiberscope has much greater loss of initial light intensity reaching the eyepiece. For lengths beyond about 1 m (3 ft), there is often insufficient visible light intensity for color contrast magnetic particle detection and interpretation.

Light transmission depends on the size and number of both the illumination and imaging fibers. All else being equal, larger diameter instruments can be made in longer lengths to achieve the same image brightness. For fluorescent magnetic particle testing, it is generally necessary to use a high purity quartz fiberscope. A 10 m (30 ft) quartz fiberscope has about the same ultraviolet light transmission efficiency as an otherwise similar 1 m (3 ft) conventional fiberscope.

Compared to conventional fiberscopes of the same diameter and length, quartz instruments are more expensive and often less flexible (larger minimum safe bending radius). Their advantage is that they can be used for ultraviolet light tests, an application not possible with conventional fiberscopes.

Some quartz fiberscopes produce light intensities up to 1,000 $\mu W \cdot cm^{-2}$ at tip-to-surface working distances of 25 to 50 mm (1 to 2 in.). They are available with insertion tube diameters as small as 0.5 mm (0.02 in.). The minimum diameter needed for ultraviolet light testing is about 3 mm (0.12 in.).

Image resolution with fiberscopes is not as good as with rigid borescopes. Thirty-four line pairs per millimeter is an expected value for an 8 mm (0.3 in.) diameter fiberscope. This resolution depends on the number and size of imaging fibers and the size of the field of view. In general, smaller diameters and more flexibility necessitate fewer fibers and less resolution. With adaptation to video systems, fiberscopes tend to suffer more image degradation than rigid borescopes.

Flexible Video Borescopes

Instead of imaging fibers or a rigid lens system, a flexible video borescope uses a very small charge-coupled television camera in the tip of a flexible insertion tube. There is no eyepiece and the image is viewed on a video monitor.

Optical fibers are used to transmit light from an external source to the probe tip. Transmission loss problems occur with ultraviolet sources. As with the other types of remote viewing instruments, there is enough light intensity on the test surface at normal working distances but not at 380 mm (15 in.) from the probe tip.

These probes generally give better detail resolution than fiberscopes used with television but not as good as the resolution from rigid borescopes. Unlike other flexible instruments, video borescopes do not develop black spots in the image from fiber breakage and they can safely negotiate tighter bends than fiberscopes of the same diameter.

Flexible video borescopes are available with insertion tube diameters from 6 mm (0.25 in.) to 13 mm (0.5 in.) and with lengths up to 31 m (100 ft). For ultraviolet light applications, miniature camera probes are limited to lengths less than 2 m (6 ft). Because of the high sensitivity of the imaging chip, much longer lengths can be used for visible light testing. Like fiberscopes, video borescopes are available with two-way and four-way articulating tips and removable adapters to change the direction of view.

Comparison of Remote Viewing Instruments

Light Intensity

Except where there is access for an instrument with a standard ultraviolet source, it is not now possible to obtain 800 $\mu W \cdot cm^{-2}$ at a distance of 380 mm (15 in.) from the distal tip of the insertion tube. It may well be possible to obtain 1,000 $\mu W \cdot cm^{-2}$ or more at the test surface under normal tip-to-surface operating distances. The subject of ultraviolet light intensity requirements and appropriate measurements techniques is regularly under review. Military and industrial specifications do not currently address the use of remote viewing instruments for magnetic particle tests. Present specifications typically cover the light needed for direct viewing of discontinuity indications by an inspector.

Consideration must be given to the loss of intensity between the distal tip of the instrument and the eyepiece or the video monitor. These losses vary between different types of instruments. For ultraviolet or visible light tests, a quartz fiberscope gives a satisfactory image with less light intensity on the test surface than a comparable conventional fiberscope. For rigid borescopes, the important factor is the light transmission efficiency of the optical system. For flexible video borescopes, it is the sensitivity of the camera chip.

The recommended approach to demonstrating the adequacy of a testing technique with any type of remote viewing instrument is to prove the ability to image an appropriate discontinuity indication. This image might also be compared with the same indication viewed directly under acceptable conventional lighting conditions. The demonstration of the adequacy, documentation and control of a nonstandard testing technique is allowed by many codes and specifications.

Image Resolution

Differences in resolution capabilities of remote viewing instruments may be very important when it is necessary to detect fine cracks. It may be of little consequence for locating larger discontinuities. The adequacy of a specific technique can *only* be determined by practical application of the test.

It is advisable to use a rigid borescope when flexibility is not needed because they are less expensive, easier to use and less susceptible to damage than typical fiberscopes.

Measurement of Test Indications

It is often necessary to measure the size of a discontinuity indication to determine whether it is acceptable. When using a remote viewing device, it is not possible to measure in the usual ways. Most test setups produce some image magnification, depending on several factors: (1) the wider the field of view, the lower the magnification at a given distance (instruments are available with fields of view from about 10 to 90 degrees); (2) the greater the distance from the lens tip to the test object, the lower the magnification. Magnifying eyepieces, zoom lenses or video monitor screen size can also affect magnification.

For an individual system, the relationship of magnification to distance can be determined experimentally and it may then be possible to maintain a constant distance with fixturing, such as when testing the inside of a straight cylinder with a rigid scope. Some borescopes are also available with measuring eyepieces. In addition, accessory video components are available to provide a direct digital readout of the indication size when adjustable lines on the screen are positioned at the edges of the indication.

In some situations, object distance may be variable and uncontrollable. For example, when flexible borescopes are used, it may be difficult to precisely control the distance from the lens tip to the test object. One type of instrument solves this problem by using a small depth of field — the discontinuity indication appears very fuzzy unless the object distance is within a specific, narrow range. When the image is in focus, then the nominal distance is known.

Some flexible video borescopes and fiberscopes have working channels that allow wires to be passed through the insertion tubes. This permits attachment of devices that are visible through the scope and can serve as reference objects for comparative measurements. Small scales, wires of known length or diameter, or spheres can be compared with the nearby images of discontinuity indications. The probe is manipulated so that the comparator is resting on the test surface beside the indication.

The reference device can also be an extension of known length beyond the probe tip, brought into contact with the test surface to define object distance and thereby magnification. This technique is best used with a video monitor. It is not reliable when the probe is not perpendicular to the test surface. Lasers have also been used to project a reference spot of known size on the test surface.

Recording Test Results

Video tape is an obvious choice when television systems are used, but it should first be determined that the recorded image has adequate resolution (home-type recorders may not be good enough).

Video hard copy machines show considerably more fine detail. Thirty-five millimeter cameras are a good choice for use with eyepiece viewing systems.

Remote Viewing Applications

It is possible to use a remote viewing instrument to inspect any area where it is possible to spray a magnetic particle suspension. The corners of inside diameter surface grooves, the far sides of inside diameter weld reinforcements and blind holes or cavities may often be inspected more completely and reliably with a borescope than with a mirror.

There are also exposed surface situations, such as weld root passes and discontinuity grind-outs, where the inspector does not have the space to properly position the light source for direct viewing.

Figure 11 shows two magnetic particle indications on the inside surface of a 75 mm (3 in.) diameter pipe weld. Figure 12 shows fluorescent magnetic particle indications of cracks in a steel forging. Both figures were made with a video hard print machine.

FIGURE 11. Black magnetic particle indications on the inside diameter surface of a pipe weld, viewed with a video borescope system and a rigid borescope adapter

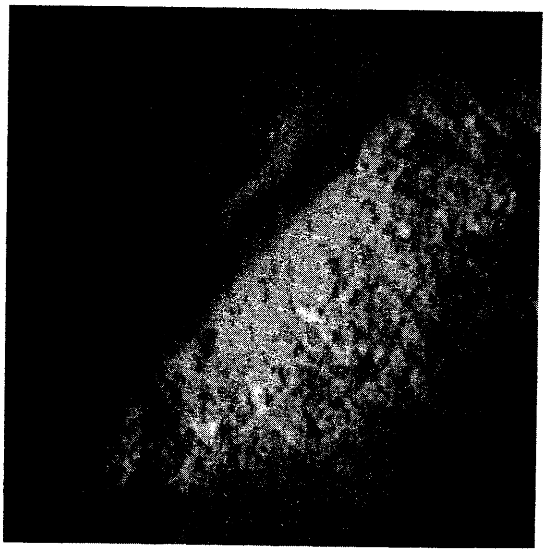

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FIGURE 12. Fluorescent magnetic particle indications on a forging, viewed with a video borescope system and a rigid borescope adapter

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PART 5
TYPICAL FALSE INDICATIONS IN MAGNETIC PARTICLE TESTS

Whenever a testing technique produces a localized, characteristic nonrelevant indication, there is some danger of inspectors getting a false sense that *any* indication in this area is nonrelevant. The following application is typical of many examples of in-service failures due to unfortunate combinations of manufacturing processes and testing techniques that led inspectors to disregard indications of real discontinuities.[9]

False Indications in a Bellcrank Assembly

An initial, single case of failure occurred in a slat drive bellcrank, resulting in complete fracture (Fig. 13). Subsequently, inspectors found other cracks in or near weld areas of the bellcranks. Complete failure of one bellcrank had occurred circumferentially through the forging adjacent to weld 4 (Figs. 13 and 14).

The second (unfailed) component contained two circumferential cracks in the forging between welds 2 and 3 (Figs. 14, 15 and 16). The two cracks were diametrically opposite each other. One crack had occurred through approximately 180 degrees of the forging circumference, while the other encompassed 70 degrees of the circumference.

Discontinuity Characteristics

The weld bead geometry and quality in the two bellcranks did not meet the dimensional requirements of the engineering drawing or the weld quality specification. All welds in the two bellcranks exhibited undercuts, overlaps, splatter and evidence of arcing.

Fatigue cracking of the failed bellcrank (Figs. 13 and 15) appeared to emanate from a prior crack that was typical of a weld or heat treat quench crack, as evidenced by a featureless topography, high temperature oxidation and an elliptical crack geometry. The quench crack extended approximately 115 degrees around the forging circumference and had occurred through 75 percent of the thickness at its maximum depth. This crack grew by fatigue and final failure occurred by ductile overload (Fig. 15).

Magnetic Particle Test Results

Examination of the fracture face on the unfailed bellcrank revealed that the two cracks were also typical of weld or quench cracks. Both fractures had occurred through 50 percent of the forging cross section and there was no evidence of in-service propagation (Fig. 15). Laboratory magnetic particle tests of the failed bellcrank revealed numerous indications in the remaining three weld beads. Metallographic examination through a number of sections revealed these indications to be false because no cracks

FIGURE 13. Failed bellcrank assemblies

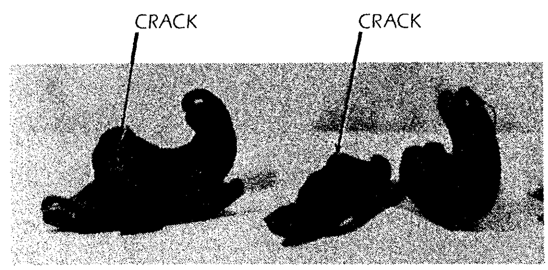
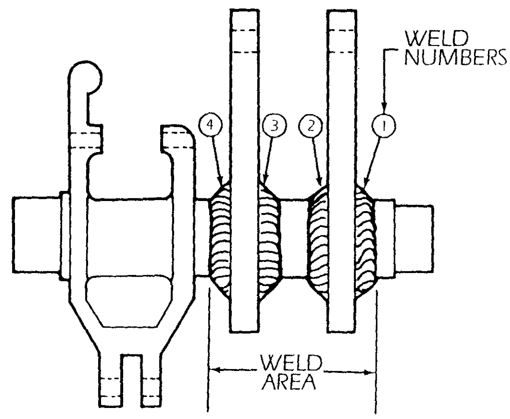


FIGURE 14. Slat drive actuator bellcrank weld identifications



were observed. Therefore, a low concentration oxide solution in conjunction with residual magnetization was developed to retest the bellcrank. This procedure eliminated false indications and indicated numerous cracks along the toes of welds 2 and 3 (Figs. 14 and 16) that were subsequently verified by sectioning. The topography of these cracks was typical of quench cracks.

A laboratory search revealed three cracked bellcranks previously rejected due to weld discrepancies. These three and the previous two cracked bellcranks prompted a review of the manufacturing and quality assurance standards applicable to the components. The investigation disclosed that there were two basic problems: (1) the weld bead was of poor quality; and (2) the magnetic particle testing procedure did not accurately represent the discontinuities.

The engineering drawing was changed to specify component serialization and to allow tungsten inert gas (TIG) welding repairs of the initial arc welds. These changes were necessary because it was physically impossible to arc weld the bellcrank to drawing requirements. Tungsten inert gas welding was necessary to build up and repair weld discrepancies and serialization was added for tracing the components through the manufacturing cycle.

The magnetic particle testing specifications were revised to clarify in-process testing requirements and the detailed methods to be followed. These methods were worked out in the laboratory on cracked components, prior to release. The laboratory investigation revealed that thermal cracks, induced by welding or quenching, were located at the weld-to-parent metal interface, in the forged parent metal adjacent to the weld and in the weld itself.

Characterizing Nonrelevant Indications

In attempting to determine why the cracks were missed, it was found that false indications of background magnetic particles were intermittently generated at the toe of the weld (intersection of the weld and parent metal). These indications appeared when the test objects were inspected using the wet continuous method and standard concentrations of black or fluorescent oxides.

A cracked bellcrank was taken to the five testing laboratories responsible for the testing of these components and the inspectors were asked to evaluate them. In all cases, the inspectors claimed that the indications were typical and false due to weld geometry or permeability changes in the heat-affected zone.

Other experience indicated that permeability changes are not intermittent and produce strong indications of magnetic particles on both sides of the weld for its full length.

FIGURE 15. Cross section through cracked bellcranks: (a) weld 2 and weld 3 of the unfailed bellcrank; and (b) weld 4 of the failed component

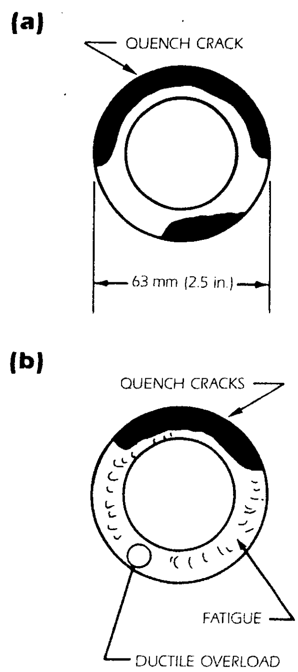


FIGURE 16. Enlargement of magnetic particle crack indication in unfailed bellcrank

Metallurgical evaluation revealed that the magnetic particle indications were caused by a combination of unacceptable conditions — cracks, cold laps and sharp geometrical transitions between the weld and parent metal.

The assembly is fabricated from a 4140 steel forging to which are welded two links also fabricated from 4140 hand forgings. The links are heliarc welded to the forging using mild steel. The assembly is subsequently heat treated to the 1,240 to 1,380 MPa (180 to 200 ksi) strength range, then cadmium plated and primer coated. In the course of fabrication, the bellcrank is magnetic particle tested four times — after machining, after welding, after heat treating and after cadmium plating. The cracks initiated during welding or heat treatment should be detected by the magnetic particle procedures.

Resolution of the Misinterpretation

All bellcranks in stock and in manufacturing were then tested using a low concentration of oxides and residual magnetization. Numerous test objects were reworked by tungsten inert gas welding or were scrapped. All testing personnel were instructed in the use of the new testing technique.

Because of the problems associated with manufacturing the welded bellcrank, a one-piece forging was designed for future production. These components show a marked improvement in quality. Finally, an in-service magnetic particle test procedure was developed for use by airline personnel.

False Indications in Threaded Fasteners

Threaded fasteners, especially those with thread diameters less than 8 mm (0.3 in.), are often difficult to test properly. When they are inspected for circumferential discontinuities in accordance with coil magnetization current formulas such as in MIL-STD-1949, nonrelevant indications in thread roots, sharp fillets and minor surface irregularities due to magnetic saturation are commonly observed.

Simply reducing the magnetizing current creates an uncontrolled risk that real discontinuities will not be detected. Sometimes, low power magnification is used to distinguish discontinuities from nonrelevant indications. With a binocular microscope and a standard 125 W ultraviolet light source, it is extremely difficult to position the lamp so that thread roots can be viewed with sufficient illumination.

One effort to solve these problems led to the use of reduced magnetizing current levels and a black oxide water bath, replacing the original fluorescent oil suspension.[10] Small screws and bolts provided no appropriate location for magnetic field meters that could quantitatively indicate accurate or consistent magnetization from one size screw to another.

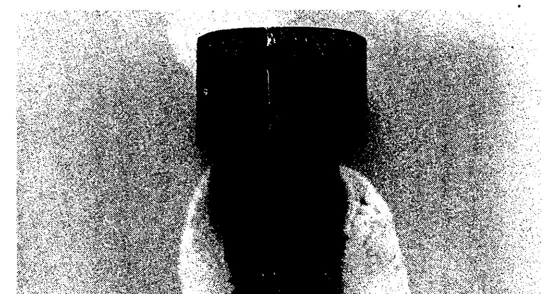
Magnetic Particle Test Parameters

To produce reference standards with known discontinuities, a variety of screws were pulled with a tensile testing machine to initiate cracks. Previously accumulated rejects were also used. Some cracks were produced in unthreaded lengths of screw stock, allowing the use of a magnetic field meter in intimate contact with the test object surface.

A field strength of about 1.2 kA•m^{-1} (15 Oe) was registered with the meter probe resting on the thread crests and ensured detection of cracks open to the surface. Depending on the thread size, nonrelevant indications in the roots caused significant interference with proper evaluation of cracks when the field strength reached 3.2 to 4.8 kA•m^{-1} (40 to 60 Oe).

These two readings provided a practical range for suitable magnetizing current levels. When the test objects were magnetized in accordance with MIL-STD-1949, field strength readings ranged from 2.7 kA•m^{-1} to 17.8 MA•m^{-1}

FIGURE 17. Fluorescent magnetic particle indication of a longitudinal seam extending from a bolt head across several thread crests



(34 to 223 Oe). For a given length-to-diameter ratio, the reading varied with material composition (permeability) and overall size.

It was found that reducing the magnetizing current to eliminate nonrelevant indications greatly reduced the need for a microscope. However, changing to a black oxide suspension and visible light illumination made it much easier to confirm findings with 5× or 10× magnification. With either fluorescent or black oxide magnetic particles, a water suspension was found to give less background interference from particles held by gravity in the thread roots, possibly because of faster runoff with the water suspension.

Although circumferential or transverse discontinuities are the most serious in threaded fasteners, some specifications require inspection for discontinuities of any direction. Seams in the wire used to produce screws and bolts often become longitudinal discontinuities in finished test objects (see Fig. 17).

It is very awkward to use the headstock and tailstock of a horizontal magnetic particle system to test for longitudinal discontinuities in small fasteners. It is also extremely slow, a critical consideration if large numbers of components are tested.

One semiautomatic system tests screws and bolts up to 9.5 mm (0.38 in.) in diameter. This allows detection of both circumferential and longitudinal discontinuities in one operation. The test object is sequentially magnetized by three mutually perpendicular coils wrapped around cores.

The component is held in a vertical position in one of four stations around an indexing turntable. The test sequence is: load the test object, apply suspension, magnetize, magnetize, magnetize, remove the test object, inspect. The current through each of the coils is individually adjustable. Proper current values must be determined for each configuration and material to allow for the residual effects of one magnetization on the next magnetization stage.

PART 6

MAGNETIC PARTICLE TESTS OF MAINTENANCE INDUCED CRACKING

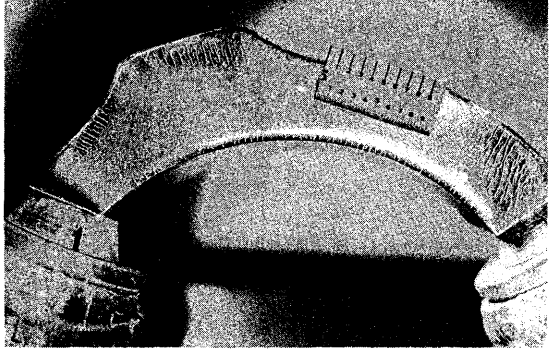
Grinding Cracks

There are many operations designed or intended to repair material discontinuities in manufactured components. Magnetic particle tests often reveal the *need* for such operations by providing visible indications of the discontinuities. Because repair procedures typically introduce thermal or mechanical stresses, attempts to restore a component or remove discontinuities can often create new problems.

Grinding is an operation used to remove surface or near surface discontinuities or to provide a specified surface finish. Grinding operations can also produce thermal cracks from localized overheating. These cracks are typically perpendicular to the grinding direction. Figure 18 shows the grinding cracks present in a section removed from a steel landing gear. Also visible in the photograph are the legs of an electromagnetic yoke used to magnetize the component for magnetic particle tests. Figure 19 shows grinding cracks around the flanges of two steel fittings.

Figure 20 shows cracks in a twist drill bit caused by straightening the bit with a peening hammer. Figure 21 shows cracks in a steel test fixture caused by using a rivet gun to loosen fasteners.

FIGURE 18. Fluorescent magnetic particle indications of cracks in a section removed from a steel landing gear component



These illustrations represent an important application of magnetic particle testing. The technique may be used to locate discontinuities in an object, but it must also be used after operations intended to repair the original problem. Such retesting is especially important subsequent to control operations such as sharpening cutting wheels and straightening drill bits.

Repair of Hydroplane Blades

Unlimited class hydroplanes use aircraft engines developing 3,000 or more horsepower and may reach speeds over 90 $m{\cdot}s^{-1}$ (200 mph). Highly stressed components that require magnetic particle tests include propellers, propeller shafts, gears and turbocharger components.

FIGURE 19. Fluorescent magnetic particle indications of grinding cracks

FIGURE 20. Fluorescent magnetic particle indications of cracks caused by straightening a drill bit with a peening hammer

FIGURE 21. Fluorescent magnetic particle indications of cracks caused by using a rivet gun to loosen fasteners from a steel fixture

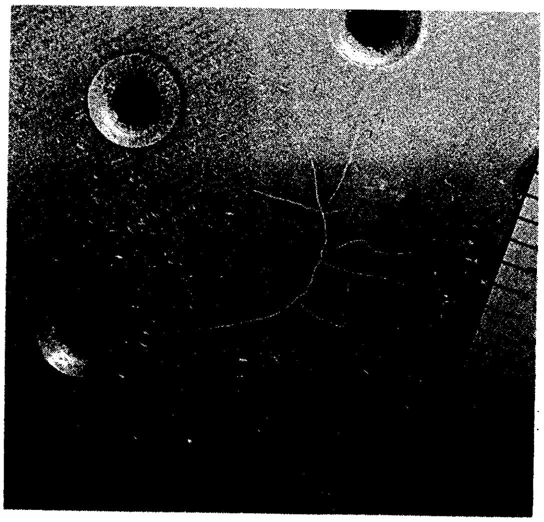
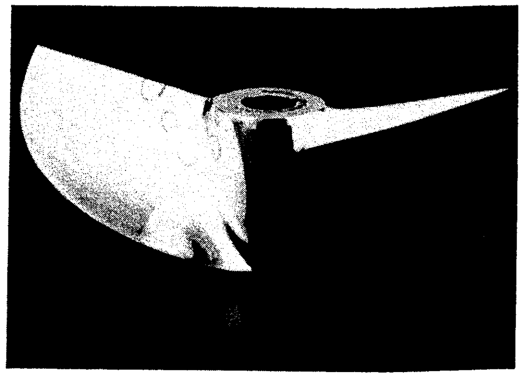


FIGURE 22. Magnetic particle indications of cracks in a racing hydroplane propeller blade

(a)



(b)

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Hydroplane propellers rotate at more than 10,000 rpm. In service, such rotation rates alone can cause stress cracking. In addition, under racing conditions, propellers can leave and return to the water very quickly. This causes rapid and dramatic changes in the density of the blades' operating medium, which in turn produces sudden flexing and very high stresses.

A propeller blade is originally shaped for thrust by machining, grinding and polishing. For purposes of operating efficiency, the blade tip is very thin, sometimes tapering to a sharp edge that serves as a stress riser during use.

After magnetic particle or visual tests locate damaged areas, propeller blades are often repair welded. This may initiate new problems in the heat affected zone and can introduce any of the discontinuities associated with welding procedures. Retesting after weld repair is a critical magnetic particle application.

Figure 22 shows three magnetic particle indications of cracks in a propeller blade. These cracks were found using coil magnetization and a fluorescent magnetic particle water suspension.

PART 7

CONTROL OF WET MAGNETIC PARTICLES FOR YOKE MAGNETIZATION

Suspension Quality

One of the important factors that determine the effectiveness and reliability of wet method magnetic particle testing is the efficacy of the magnetic particle suspension.

The commonly required settling test has some important limitations that become very evident during field tests using the wet method with an electromagnetic yoke. The settling test is appropriate for a suspension that is mechanically agitated in a large stationary magnetic particle system, but the test is less appropriate for suspensions applied manually from pump spray bottles or for suspensions purchased in sealed pressurized cans. When spray bottles are used, the inspector is responsible for mixing the suspension properly and agitating it sufficiently during use. Pressurized cans, on the other hand, are labeled to show the particle concentration when filled, but this concentration level may not be maintained from the first use to the last.

The time and amount of material required for settling tests to monitor each container (and each inspector's agitation technique) make this method much slower and more expensive than inspecting with dry magnetic powder techniques. For example, if inspection continues while waiting for the results of a settling test, then a reading outside acceptable limits make it necessary to retest every area inspected since the last acceptable settling test. This is avoided by stopping all inspections while waiting for the results of a settling test. Neither alternative is efficient enough for production applications.

Important Suspension Properties

There are three properties of a magnetic particle suspension that are important to the inspector.

Relative sensitivity: all else being equal, how does the smallest discontinuity indicated with one suspension compare to that indicated with another?

Consistency: are detectable discontinuity size minimums the same every time a suspension is used?

Signal-to-noise ratio: does background fluorescence interfere with detecting and evaluating discontinuity indications? Excessive background could result from using an overly sensitive suspension on a rough surface or from excessive loose fluorescent material in the suspension.

Use of the Settling Test

The settling test is intended to evaluate these characteristics based on the assumption that they are directly related to the concentration of magnetic particles in the suspension. The availability of magnetic materials with different particle size distributions — to produce suspensions of low, medium or high efficacy — is another reason for adopting alternative means of evaluating the suspension. Tests to measure the overall sensitivity of a testing procedure (for example, the tool steel ring standard for wet horizontal machines) are not specified for yoke techniques. Reference standards can help evaluate the end product of several independent variables and how they work in the overall test system, but they not do specifically address the quality of the magnetic particle suspension.

One way to evaluate the quality of a suspension is to use a block of permanently magnetized material with a network of many natural cracks of various sizes. This block standard is similar to the aluminum crack blocks used to compare penetrant procedures. Because the crack pattern is very complex, it is difficult to rely on visual observation and memory for evaluation. A better way to compare magnetic particle suspensions with this block is to compare photographs made under identical lighting and exposure conditions. The block standard described below is a better choice for routine use because it gives a numerical reading of relative sensitivity.

Use of Prism Block Standards

A prism block standard consists of a steel block with an artificial linear discontinuity and a calibrated scale. The zero end of the scale is adjacent to a permanent magnet. The strength of the leakage field across the crack is inversely proportional to the distance from the magnet. The better the quality of the suspension, the lower the magnetic field strength required for it to produce an indication. Therefore, the length of an indication measured from the scale is directly proportional to suspension sensitivity.

To make a measurement, the block is held with the artificial discontinuity on top, tilted enough to allow excess suspension to run off. Suspension is applied (sprayed, in this case) and the length of the indication is read from the scale under ultraviolet light. After making the reading, the indication can be removed by wiping the block with a lint free cloth. Magnetic particles remaining in the discontinuity can be removed with a soft bristle brush.

To develop a working procedure for using a block standard, freshly prepared suspensions were evaluated by the settling test and the block standard. These tests gave a range of acceptable values for periodic field checks of suspensions applied from a pump bottle. Because the block standard field checks are almost instantaneous and use only a small amount of suspension, it is practical to repeat them frequently.

For pressurized spray cans, the prism block standard may also be used to verify concentration levels as the can is used or to check variations between different cans of particles.

Significance of the Block Standard Measurements

It is important to understand what the block standard test does and does not do. It evaluates the magnetic particle suspension as an independent variable. It gives no information about the functioning of the yoke (or any other magnetizing apparatus that might be used for the test) or about the effectiveness of any specific test setup for detecting discontinuities. Its use can replace some settling tests but not any required test of field strength, field direction or equipment function for overall test sensitivity.

It does *not* provide a *traceable* calibration procedure because there are slight variations between blocks. For example, a test of the same suspension with several different blocks might give a range of readings from 17 mm (0.7 in.) to 19 mm (0.8 in.). This variation is not critical to an inspector using a single block. However, it must be considered in any applications where different blocks are used.

There is no predetermined minimum reading for a *good suspension*. Appropriate suspension concentrations must be determined for a specific application (with reference standards) and these concentrations may then be verified with the block standard. Tests made by preparing suspensions of low, medium and high sensitivity magnetic powders according to their manufacturers' recommendations gave block readings from 6 mm (0.25 in.) to 27 mm (1.1 in.).

TABLE 3. Comparative discontinuity indications on a block standard

Particle Material	Block Standard Reading	Length of Indication millimeters (inches)
A	9	22 (0.9)
A	12	28 (1.1)
A	15	29 (1.2)
B	15	30 (1.2)
B	17	33 (1.3)
B	21	33 (1.3)

One example of the significance of the numerical readings was obtained by inspecting a natural crack visible to the unaided eye at one end and tapered to a sharp edge at the other. Two particle materials and three suspension concentrations of each material were compared (see Table 3).

When the suspension concentration is repeatedly increased, a point is reached where block standard readings no longer increase proportionally and background fluorescence does increase. Although the block does give a qualitative indication of background fluorescence, this is better judged on the actual test surface. It appears that an optimum combination of high sensitivity and low background is typically reached at concentrations well below the maximum allowable settling volume reading.

Conclusion

The use of a block standard with a permanent magnet and a scaled artificial discontinuity is a simple and practical way to monitor two of the three important characteristics (sensitivity and repeatability) of wet magnetic particle suspensions used in the field with yokes.

The third important characteristic, background fluorescence (signal-to-noise ratio) is a function of the test surface as well as the suspension. The block standard can be used to find the concentration above which sensitivity shows little or no increase and background fluorescence is expected to increase.

The use of the block standard with understanding of its functions and limitations can greatly improve the effectiveness and control of wet magnetic particle tests performed in the field with yoke magnetization.

PART 8

MAGNETIC PARTICLE FIELD TESTING OF STRUCTURAL WELDS

Magnetic particle testing is performed on a variety of welds used in bridges, buildings and other structures. The American Welding Society *Structural Welding Code* with its nondestructive testing requirements is often incorporated into construction contracts.

Inspectors typically must work under less than ideal conditions, particularly when existing structures are tested. Field welds made to connect fabricated subassemblies can also present significant problems.

Effect of Weld Surface

Most weld surfaces are left in the as-welded condition for service or for testing. It is up to the inspector to decide whether a particular surface is good enough for magnetic particle testing. Dry magnetic particles, half-wave rectified current or alternating current are typically used with electromagnetic yokes.

The mobility of dry powder with the pulsed magnetic fields produced by yokes is essential for effective testing of irregular surfaces. Testing with yokes and fluorescent suspensions is increasingly required for welds that are ground smooth, such as those in vessels fabricated to American Society of Mechanical Engineers *Boiler and Pressure Vessel Code* Section VIII.

On rough surfaces, particle suspension can be trapped in depressions, creating unwanted background fluorescence. The geometry of the test surface, particularly where fillet welds are used, often requires a yoke with articulating legs. The distance between the yoke poles may have to be changed frequently to fit the available contact areas. Some yokes have adjustable magnetizing current when used in the half-wave rectified mode.

Field Strength Adjustments for Tests of Welds

The magnetic field strength is adjusted to correspond to the required pole spacing and the test material. This is done by observing the test surface for nonrelevant indications and excessive buildup of particles around the poles. With rectified current electromagnetic yokes, the current is usually increased to the point where these things occur and is then reduced slightly for the actual test. A magnetic field pie gage can be used conveniently if the test is being performed on a horizontal surface with sufficient space for positioning the gage.

Alternating current and switchable yokes do not have a means for adjusting the magnetizing current. However, some alternating current yokes do have removable pole extensions to compensate for variations in pole spacing on the surface. These are available as more than one length and are sometimes articulating. Depending on their length and design, the addition of pole pieces can reduce the tangential magnetic field strength midway between the poles by a factor of 25 to 50 percent. It is possible to determine the reduction of field strength caused by incomplete contact of the poles with rough surfaces using a Hall element gaussmeter.

Partial penetration in structural welds is common, as are welds joining sections with substantial differences in thickness. These conditions are common causes of nonrelevant indications with half-wave rectified magnetization. This problem may be eliminated by changing to alternating current — because of its skin effect, variations in magnetic field strength with section thickness are minimized.

Although rectified current is sometimes specified because of its deeper penetration and its increased ability to detect subsurface discontinuities, alternating current is becoming more widely accepted in the United States. Empirical data have shown that alternating current yokes are capable of detecting discontinuities that are not open to the surface, to a depth of at least 1 or 2 mm (0.04 to 0.08 in.). With any type of yoke, it is difficult to predict the maximum depth at which a subsurface discontinuity will be detected.

Effect of Coating on Tests of Welds

When welds in existing structures are being tested, they are often coated with paint or rust. One study had shown that the maximum thickness of paint that does not significantly reduce the detectability of a particular size discontinuity depends on the types of coating materials and also on the weld surface profile.[11] Because the type and thickness of coating on an existing structure are generally unknown, the safe thing to do is to remove it in the areas of interest. Although it is possible to make measurements of paint thickness with a portable magnetic induction coating gage, this does not provide information about the relative magnetic effects of different coatings.

Studies have also shown that mechanical removal of paint, such as by power wire brushing in conjunction with applying solvents, does not significantly reduce the reliability of magnetic particle testing.[12]

Effect of Other Tests Parameters

Lighting for Weld Inspection

It is important to have adequate illumination of the test surface. Even when working outdoors in bright daylight, some welds are covered by shadows. Some specifications leave determination of adequate visible light intensity to the discretion of the inspector,[13] while others specify a minimum intensity (for example 2,200 lx) at the test surface.[14] The common practice of using a standard flashlight is very often inadequate.

Electric power is required at the test site for the electromagnetic yoke and it can also be used with a portable high intensity lamp. Instruments such as borescopes and fiberscopes can be used to inspect areas where direct visual access is limited.

When dry fluorescent powders are used outdoors, it is important to have shielding for minimizing visible light. This is at least as critical as providing sufficient ultraviolet light intensity.

Relationship with the Welder

The magnetic particle inspector often works closely with the welder, who is called on to clean surfaces that are too rough and to chase discontinuity indications. The welder is often the best source of information about what types of discontinuities are probable and where they are likely to be.

Developing good communication with the welding contractor can result in more effective and reliable testing. A good start is to explain the magnetic particle procedure and the need for particular surface conditions. It is equally helpful if the inspector is informed of the welding process used.

Figure 23 shows a fillet weld presented as ready for testing. The inspector has marked three deep crater pits to be reworked before magnetic particle testing. In Fig. 24, a short overhead fillet weld is tested for transverse discontinuities. Figure 25 shows an indication of a longitudinal discontinuity going around the corner of a weld.

FIGURE 23. A fillet weld with three deep crater pits to be reworked before magnetic particle testing

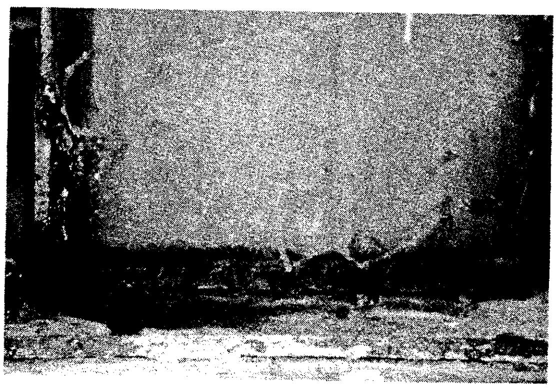

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FIGURE 24. A short, overhead fillet weld tested for transverse discontinuities

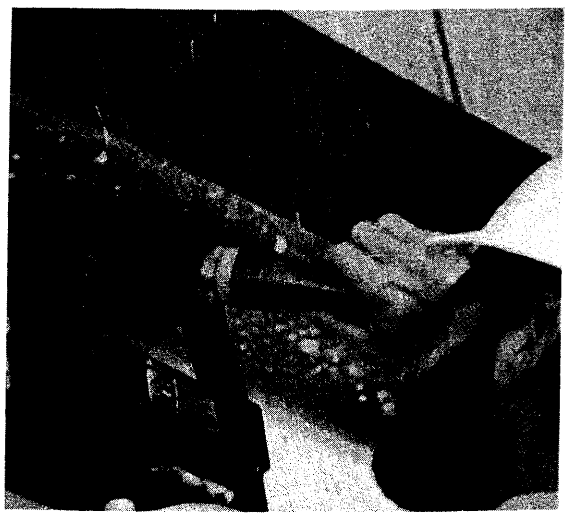

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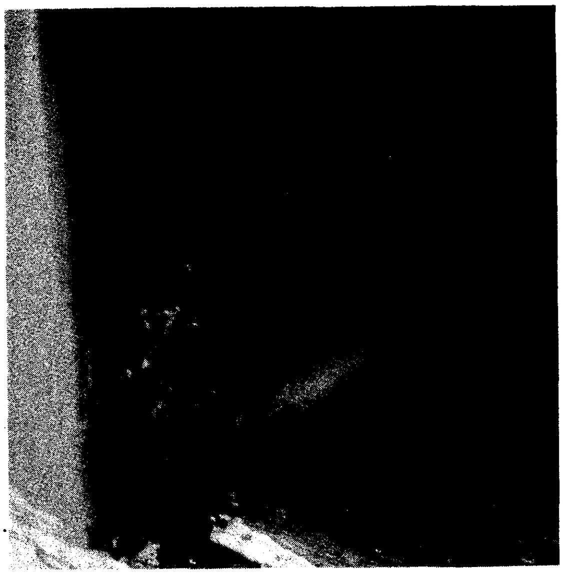
FIGURE 25. Magnetic particle indication of a longitudinal weld discontinuity



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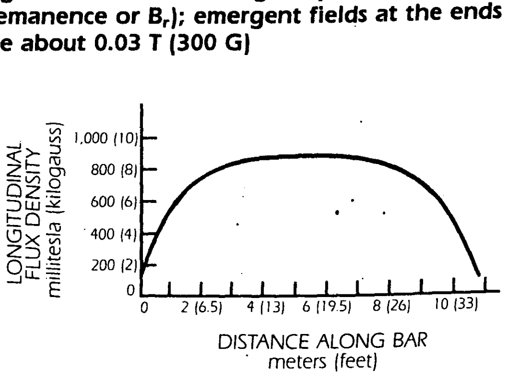
PART 9

OIL FIELD APPLICATIONS OF MAGNETIC PARTICLE TESTING

In the United States, there are more than 660,000 oil and gas wells containing an enormous amount of steel tubular material down the wells, in wellhead fittings and in cross country flowlines. The text below outlines some of the magnetic particle testing applications routinely performed in oil fields, including: (1) aspects of magnetization from the oil field inspector's viewpoint; (2) specifications used for oil field tests; and (3) some of the misconceptions about oil field applications of magnetic particle tests.

Magnetic particle testing is applicable only to ferromagnetic materials and should be studied as a specialized branch of electromagnetic testing. It is impossible to test all tubes for imperfections, both inside and out, using magnetic particle tests alone. Other magnetic flux leakage techniques are more cost effective and have been used on oil field tubes for many years. These tests often make use of Hall element, magnetodiode and coil pickup methods for sensing the magnetic flux leakage from material discontinuities.

FIGURE 26. Axial component of flux density in an 11 m (36 ft) steel bar; the value in the central region is close to the ring sample value (remanence or B_r); emergent fields at the ends are about 0.03 T (300 G)



Longitudinal Magnetization

When a tube 10 to 15 m (33 to 50 ft) in length is longitudinally magnetized, discontinuities transverse to the tube axis can be detected by their magnetic flux leakage. In this circumstance, two distinct test object geometries must be considered: (1) the ends of the tube; and (2) the larger region away from the ends. The axial component of the magnetic flux density (after the material has passed through a magnetizing coil) is shown in Fig. 26. In the central region and for much of the tube, the steel is magnetically saturated and holds a flux density close to the remanent value for the material. At the ends, the flux lines begin to emerge and the axial magnetic component falls as the normal component rises.

When testing tubes for longitudinally and transversely oriented discontinuities in the end regions, magnetic particle testing is the technique preferred from among the flux leakage methods. This is mainly because the high normal component of the emergent magnetic field strength can obscure discontinuity indications when using other flux leakage methods.

Because of bearding effects, wet particles are preferred, just as they are when any short object is being tested for transversely oriented discontinuities. Wet particles do not fur along external field lines because of the surface tension of the liquid vehicle (the surface tension effect greatly predominates over the magnetic field strength).

Using wet particles at the ends of tubes and bars, despite the emergent normal fields, also allows the applied coil field to be raised to levels in excess of those normally used for body wall testing.

Coil Field Criteria

When magnetizing the end of an elongated object, it is critical to ensure that the magnetization levels produce flux leakage from surface discontinuities sufficient to hold particles and give a discontinuity indication. With solid bars, this may be one magnetization level and with tubes it may be another. Sometimes the appropriate magnetization level is determined by the ease with which indications can be seen.

For the magnetization of tube ends, two very different types of coil are used. One is the traditional wound wire magnetization coil, excited by alternating current or direct current. The other is a coil made of a few turns of 0000 cable (over 100 mm^2 of copper) pulsed from a capacitor discharge system.

Direct Current Coil (Residual Induction Tests)

One method for magnetizing the ends of long test objects is to apply the magnetizing field from a direct current coil. In view of the high field strengths used, such coils should be supported either from the floor or the roof of the testing facility so that the test object can be centered in the bore of the coil. Under such conditions, a simple test may be performed to ensure the required magnetization of the ends.

The test object is saturated in one direction then the coil is turned and placed with roughly 300 mm (12 in.) protruding beyond the coil. A Hall element gaussmeter is positioned to detect the field strength that emerges from the end of the material.[15] The current in the coil is raised and turned off in increments until the gaussmeter reading saturates. Figure 27 illustrates typical data for just such a test, although it must be realized that coil sizes, material diameters and material wall thicknesses all contribute to the applied field strength at which the material saturates.

Using this technique, the ends of tubes are shown to be adequately magnetized if the following equation is applied. The equation is written for tubes with outside diameters less than 200 mm (8 in.). For tube diameter D_1 measured in millimeters and field strength measured in millitesla:

$$B = 20 + 0.12D_1 \qquad \text{(Eq. 1)}$$

or

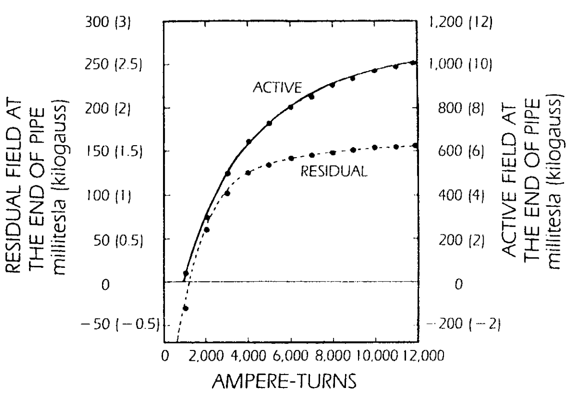
$$B = 200 + 30D_2$$

for outer diameter D_2 in inches and field strength in gauss.

The field strength is over 40 mT (400 G) when the tube's outside diameter is greater than 200 mm (8 in.).

This equation covers the worst situations and explains the general increase in tube wall thickness with increased outside diameter found in American Petroleum Institute (API) tubular materials. It is a relatively simple matter to determine the field strength at the center of such a coil using a gaussmeter. This eliminates the misuse of older equations that state only the number of ampere-turns on coils.

FIGURE 27. Hall element data taken at the end of a tube to ensure saturation prior to particle application; coil positioned 300 mm (12 in.) from the end of a pipe with 90 mm (3.5 in.) outside diameter



Alternating Current Coil

When testing with alternating current coils, two points are important to remember. The first is that the magnetic field roughly obeys the typical eddy current skin depth relation, so that at 50/60 Hz, the skin depth in steels is on the order of 1 mm (0.04 in.). A peak surface field of 2,400 $A{\bullet}m^{-1}$ (30 Oe) gives good discontinuity indications from outside diameter surface breaking discontinuities.

The second point is that there is little penetration through to the inside diameter for tube wall thicknesses in excess of 4 mm unless a direct current field is also applied to lower the effective relative permeability of the material. Such fields can easily be measured with a gaussmeter.

Capacitor Discharge Coil Field

A common method for the magnetization of tube ends is to wrap a 0000 (over 100 mm^2) welding cable around the end of the test object and to apply several shots from a capacitor discharge system.

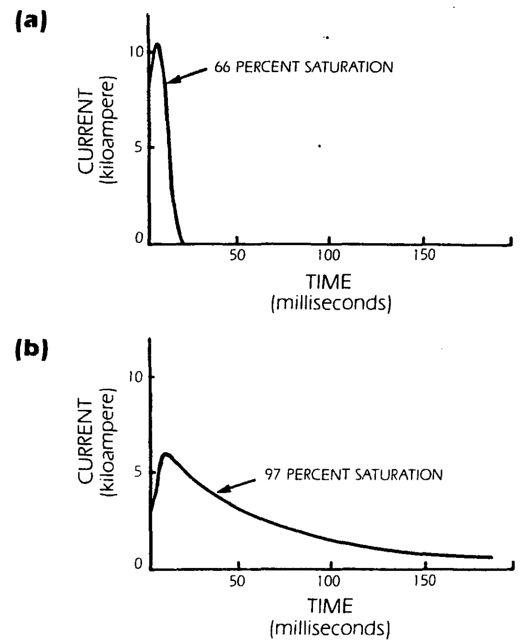
This is typically a bank of capacitors charged to a voltage limited by safety requirements (limit may differ depending on local regulations). The bank is designed to produce a single spike of unidirectional current. Ideally, the current pulse has a long decay time so that its field strength can penetrate the material despite eddy current effects created during the initial rapid rise of the current.

The theory of capacitor discharge magnetization includes considerations of the inductance L, capacitance C and resistance R of the entire system, including the object being magnetized. Because many different types of capacitor discharge systems exist, it is not possible to make sufficiently general statements about the measurable parameters of a pulse and the resulting flux density in the test object.

Magnetization of the material can be ascertained by any one of three methods. The first is simply to hold a gaussmeter near the end of the material and require that it is close to saturation. The second method is to use a portable surface discontinuity. The third is to use a fluxmeter.[16] The shape of the current pulse is shown in Fig. 28. Shorter pulses that are not effective for magnetizing deeper portions of an object are shown in Fig. 28a. More elongated and effective pulses[17] are shown in Fig. 28b.

As the number of coil turns increases around the test object, the inductance in the *LCR* circuit increases as the square of the number of turns. This elongates the pulse and can easily cause a capacitor discharge box (normally operating in the curve of Fig. 28a) to begin operating in the curve of Fig. 28b. The problem is that pulse systems generally operate with a rectifier that shuts down the current at the instant the pulse reaches its negative-going portion (Fig. 28a). Should the pulse be similar to Fig. 28b, then the rectifier never closes and circuitry must be included to close off the pulse from the capacitor charging circuitry.

FIGURE 28. Typical pulses from capacitor discharge systems: (a) short pulse effective for deeper magnetization; and (b) long pulse more effective for magnetizing a tube



Magnetization Requirements

In many cases, the number of ampere-turns supplied by coils can be specified. This in turn provides a flux density in the material that produces residual induction indications from surface breaking discontinuities. When a coil field is applied as shown in Fig. 29 the magnetization field at the outer layers of the material is caused by coil turns very close to the test object. This is different from the situation described in residual induction with direct current. When the tube's outer diameter is less than 200 mm (8 in.) and measured in millimeters:

$$NI_m = (50 + 0.33D_1)D_1 \qquad \text{(Eq. 2)}$$

or

$$NI_m = (1{,}300 + 200D_2)D_2$$

when measured in inches. When the diameter is greater than 200 mm (8 in.) and measured in millimeters:

$$NI_m = 115D_1 \qquad \text{(Eq. 3)}$$

or

$$NI_m = 2{,}900D_2$$

when measured in inches. For drill collars and tool joints measured in millimeters:

$$NI_m = 230D_1 \qquad \text{(Eq. 4)}$$

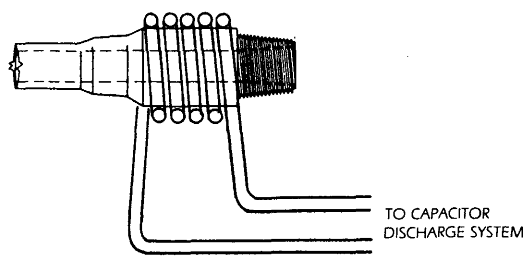
or

$$NI_m = 5{,}800D_2$$

Where:

N = number of coil turns;
D_1 = outside diameter of the coil (millimeters);
D_2 = outside diameter of the coil (inches); and
I_m = maximum current from the capacitor discharge system (amperes).

FIGURE 29. Longitudinal magnetization of drill pipe tool joint with a capacitor discharge system and several turns of 0000 (100 mm²) cable



For magnetizing the end of a 200 mm (8 in.) outside diameter drill collar, the diameter of the coil is about 225 mm (9 in.). The number of ampere-turns is 230 × 225 or 5,800 × 9 or about 52,000. Should the capacitor discharge system produce a peak current of 9,000 A, then six turns are required. Alternatively, two or three pulses should be fired and the resulting residual induction checked with a field indicator.

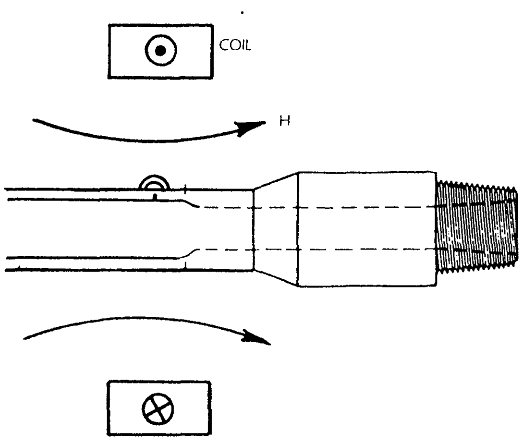
Oil Field Applications for Longitudinal Magnetization

The ends of drill pipe and drill collars are magnetized longitudinally so that cracks may be detected in their threaded regions. If the connections are not made tight enough (torque values are listed in API Recommended Practice RP 7G),[18] the threaded regions may first elongate and then cracks may form at the roots of the threads. The most common place for such cracking is in the last engaged thread.

In order to perform good magnetic particle testing, threads must be cleaned and burrs removed. The particle suspension should be more dilute than normal (1 to 3 mL per liter of solution), to reduce the number of false indications. Surface ultraviolet illumination should be around 20 $\mu W \bullet mm^{-2}$.

For internal fatigue cracking in drill pipe, the leakage field must be strong enough at the outside diameter of the tube to hold dry particles (Fig. 30) or the inside must be inspected with a borescope. The presence of one fatigue crack is sufficient for rejecting the tube. The field strength used for the test in Fig. 30 is around 40 mT (400 G). The coil is passed back and forth over the suspect region to obtain a crack indication in the presence of furring. When a borescope is used, appropriate crack indications can generally be produced with longitudinal residual induction techniques.

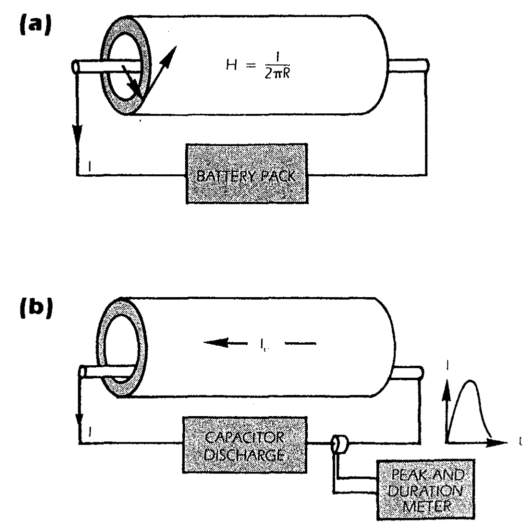
FIGURE 30. Direct current magnetization of drill pipe for internal fatigue crack detection; the coil field must produce sufficient flux leakage at the outer surface for dry particles to bridge the discontinuity



Circumferential Magnetization

Two distinct methods[16] are used for circumferential magnetization of tubes up to 14 m (45 ft) long (see Fig. 31). Both methods employ an insulated rod typically made from aluminum and designed to pass through the bore of the tube. In Fig. 31a, the rod is reasonably well centered in the bore and carries some form of direct current. In mill installations, this might be full-wave or half-wave rectified alternating current for wet fluorescent magnetic particle testing. In field operations, banks of batteries have been extensively used to provide magnetizing current.

FIGURE 31. Two methods for establishing circumferential magnetization in elongated tubes: (a) central conductor method with battery pack to provide high current; and (b) internal conductor method with capacitor discharge system; a peak and duration meter is often used to measure pulse amplitude and time



Central Conductor Magnetization

When the magnetizing current is pure direct current and the conductor is centered within the bore, the magnetic field strength H at the outer surface of the tube is given by:

$$H = \frac{I}{2\pi R_o} \qquad \text{(Eq. 5)}$$

Where:

I = magnetizing current (amperes); and
R_o = the outer radius of the tube (meters).

In Eq. 5, the field strength is given in amperes per meter since R_o is expressed in meters (see Fig. 32). Field strength can also be measured with a Hall element gaussmeter and, because 1 G is equal to 1 Oe in air, conversion to gaussian units gives:

$$H = \frac{2I}{10R_o} \qquad \text{(Eq. 6)}$$

Where:

I = magnetizing current (amperes); and
R_o = the outer radius of the tube (centimeters).

This equation should be used with Hall element meters that have scales or digital readouts in gauss.

Full-Wave and Half-Wave Rectified Alternating Current

Rectified alternating current is often used with central conductor magnetization. It is important to remember that such current waveforms induce eddy currents in the test object. The field strength waveform at the outer surface can be seen by positioning a Hall element to detect the field and then feeding the output of the meter to an oscilloscope.

Capacitor Discharge Magnetization

In another circumferential magnetization method (shown in Fig. 31b), the motive force is provided by a capacitor discharge unit.[17] There is no need for precise rod centering with this magnetization method, providing a distinct advantage for field testing. Unfortunately, magnetization by capacitor discharge obeys no simple rules. The rapid rise of the rod current causes the induction of an eddy current in the tube and this detrimentally affects penetration of the magnetizing field strength into the material.

The direction of the induced eddy current I_e with respect to the rod current I is shown in Fig. 31 for a centered rod. By Lenz's law, the eddy current induced on the inner surface of the tube must create within the material a magnetic field that opposes the field produced by the rod current I. The field strength at radius r (in meters), at some instant while the rod and eddy current fields are finite, is given by:

$$H = \frac{I}{2\pi r} + H_e \qquad \text{(Eq. 7)}$$

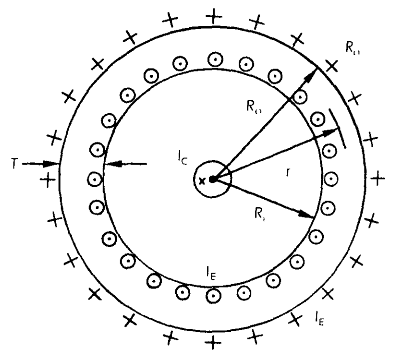
where H_e is the magnetic field strength created by the eddy current itself.

Eddy Current Effect

Ampere's law indicates that the magnetic field at the radius r is caused by the currents inside that radius, the rod current and the inner wall eddy current (see Fig. 32). The outer wall eddy current is the return loop for the inner wall eddy current and plays no role in the theory as outlined so far.

However, since the outer wall eddy current does represent an unwanted current flowing in the tube, its presence leads to the very practical consideration that pipes being magnetized before testing should be insulated from each other by an air gap. If this insulation does not occur, then the outer surface eddy current can jump from protrusions in the pipe being magnetized to the next pipe in the string. The resulting arc can cause burns on both tubes and this can in turn cause hardening and locations where corrosion preferentially occurs. It is particularly important to avoid arc

FIGURE 32. The eddy current I_E created in a steel tube at the beginning of a pulse I in a rod centered within the bore of a tube; the direction of I_E on the inner surface opposes that of I; the outer surface forms the return path



burns on API 5CT Group 2 materials,[19] some of which require a hardness less than 22 on the Rockwell C scale for longevity in sour environments.

Magnetized material should also be insulated from the metal racks that carry it. If pipe racks are not insulated with a layer of electrically nonconductive material (rubber or wood), then the outer wall eddy current can flow to ground through the rack and there is a finite possibility of arc burn at the point of contact with the rack.

Use of B-H Curves for Setting Specifications

When test objects are magnetized with the capacitor discharge internal conductor method, a tool steel ring *B-H* curve governs the flux density value in the material. In effect, knowing the *B-H* properties of the material from a ring standard investigation allows field strength levels to be set. Figure 33 shows the *B-H* properties of two typical oil field tubular materials: a 620 MPa (90,000 psi) proprietary material and a 380 MPa (55,000 psi) casing material.[17]

After application of about 3,200 A•m^{-1} (40 Oe), these materials are effectively saturated. It is generally true of oil field tubular materials that 3,200 to 4,000 A•m^{-1} (40 to 50 Oe) are required within the material to provide magnetization sufficient for residual induction testing.

This magnetic field strength level is required at each point in the tube wall, despite the demagnetizing effect of the eddy current. Unfortunately, this requirement does not lead to a current equation that can be simply executed in the field. Experimental specifications discussed later have been found effective for saturating tubes.

Typical Requirements for Direct Current Magnetization

If the central conductor method is used for magnetizing tubes, then the values given in Table 4 reflect the magnetizing field at the outside diameter for typical pipe sizes. The wall thickness, the mass per meter (weight per foot) and the tube grade all affect the magnetic and electrical properties of the material, but because the magnetization method is direct current, these parameters do not affect the magnetic field strength. The actual field strength value is often stated by specifications agreed on by the manufacturer of the material and the user. A typical specification is given by Eq. 8, where D_1 is the diameter of the tube in millimeters:

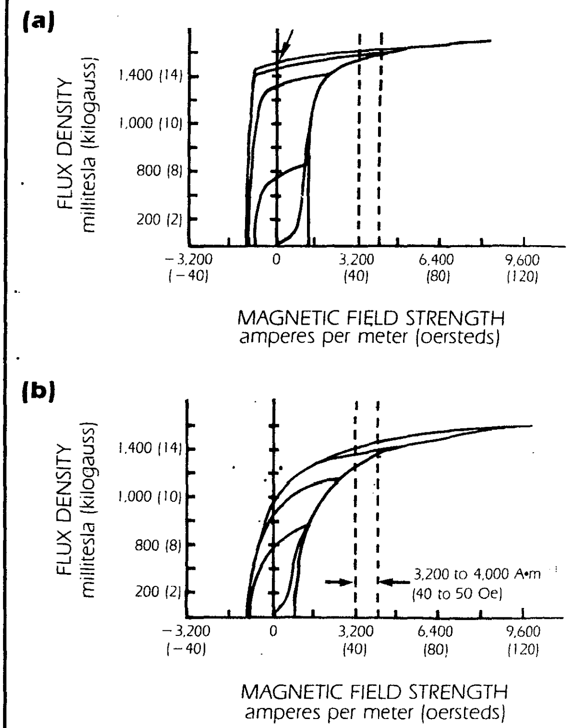
$$I = 12D_1 \quad \text{(Eq. 8)}$$

or

$$I = 300D_2$$

where D_2 is the diameter of the tube in inches.[16] The specified equations give the equivalent of 3,760 A•m^{-1} (47 Oe) at the tube surface. It can be seen from Fig. 33 that such a field strength raises the value of the flux density in the tube to a high level so that, after the field has fallen to zero, the flux density in the material is at a value close to remanence B_r.

FIGURE 33. Magnetization curves for oil field tubular materials; the dashed vertical lines indicate that the materials are magnetized almost to saturation by application of 3,200 to 4,000 A•m^{-1} (40 to 50 Oe) magnetic field strength: (a) high strength tube material; and (b) low strength casing material



Pulsed Current Magnetization

Internal conductor magnetization using single pulses of current differs from direct current (and from continuous magnetization by the central conductor method) because the induced eddy current may not have time to dissipate before the field strength from the conductor current dies away.

TABLE 4. Current requirements for magnetization of tubes: direct current or long pulse (more than 0.5 seconds) only; not valid for capacitor discharge magnetization

Diameter millimeters (inches)	I_1*	I_2**
60 (2.375)	600	910
73 (2.875)	730	1,100
89 (3.50)	890	1,340
102 (4.0)	1,020	1,530
114 (4.50)	1,150	1,720
127 (5.0)	1,280	1,910
140 (5.5)	1,400	2,100
168 (6.625)	1,690	2,530
178 (7.0)	1,790	2,680
194 (7.625)	1,940	2,920
219 (8.625)	2,200	3,300
245 (9.625)	2,450	3,680
273 (10.75)	2,740	4,110
299 (11.75)	3,000	4,500
340 (13.375)	3,410	5,120

*3,200 A·m^{-1} (40 Oe) AT OUTSIDE DIAMETER
**4,800 A·m^{-1} (60 Oe) AT OUTSIDE DIAMETER

Time Variations

Figure 28 shows two variations that are measurable for single current pulses such as those provided by capacitor discharge units. The first variation is that of the magnetizing current versus time (I versus t): a relatively rapid rise of current to its maximum value I_{max} is followed by a much slower fall to zero. The entire pulse length is about 200 ms.

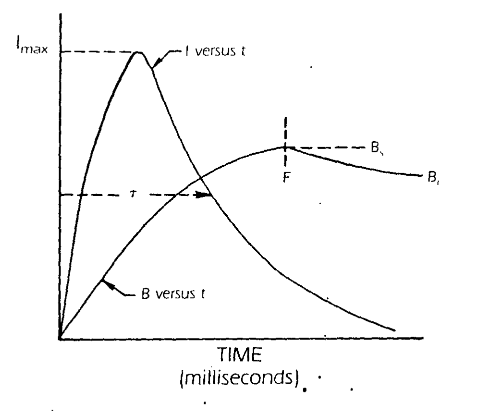
This time variation is a response to the discharge of a capacitor C initially charged to V_o volts through a resistor R in a circuit that contains inductance L.

Flux Density Variations

A second variation is that of the average bulk flux density within the material (B versus t). This quantity rises at a much lower rate than $I(t)$ due to the shielding effect of the eddy current I_e. A high level of magnetization is reached when the flux density at the point F is close to the saturation value B_s for the material. As shown in Fig. 34, deep magnetization of the tube only occurs when the detrimental effect of the eddy current is overcome by elongating the pulse in time. In this way, the magnetizing current is still effective as the eddy current is dissipating.

The fall in induction from F to B_r is expected when the magnetizing field strength falls to zero, as it does after the passage of a pulse. This is determined by the B-H curve for the material undergoing magnetization. Should the point F not represent saturation B_s, then the material reaches some average bulk flux density lower than B_r.

FIGURE 34. Plots of the capacitor discharge internal conductor current (I versus t) and the average flux density (B versus t) induced in a tube; I_{max} and τ are measured with a peak and duration meter; note that the flux density peaks well after the current



While the surfaces are magnetized sufficiently to form indications of longitudinal discontinuities, no information on the interior condition is required. However, when relatively thin elongated tubes can be inspected from the outside diameter surface only, saturation of the material is necessary for inside diameter discontinuities to produce magnetic flux leakage at the outside diameter.

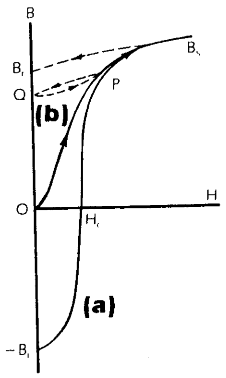
Common Pulsed Current Application

A new material's magnetic condition is often unknown to the inspector who must generally assume the worst possibility: magnetic saturation in a direction directly opposite that of the operator's equipment. Stated another way, the worst possible case is that of taking a material from an unknown value of remanence in one direction to remanence in the other direction. This is shown in the B-H curve in Fig. 35.

The material might arrive with an induction between zero and $-B_r$, with testing to be performed at $+B_r$. During magnetization, the material should take the path $-B_rH_cPB_sB_r$, through saturation B_s to remanence B_r.

For materials at zero induction, the tube is at 0 on the B-H curve in Fig. 35 and takes the path OPB_sB_r during magnetization. Materials not saturated by a pulse may follow a magnetization path such as $-B_rH_cPQ$ or OPQ. It is essential to then fire additional pulses. A possible magnetization path during a second pulse is QB_sB_r. The final net induction is raised as shown.

FIGURE 35. Possible paths taken by circumferentially magnetized material from various initial magnetization conditions to saturation B_s and then remanence B_r in a known direction: (a) material at remanence in the opposite direction; (b) material at zero induction; point P indicates a weak pulse followed by a second pulse



Analysis of Pulse Current Magnetization

Generalized analysis of the pulse current internal conductor method for magnetizing elongated tubes is presented below. Simplified equations are given for the types of current pulses used for magnetization. The theory of current pulse time dependence (I versus t of Fig. 34) is discussed and equations are presented for the inductance experienced by the magnetizing circuit.

The equations illustrate: (1) the dependence of inductances on the average value of the differential permeability (dB/dH) of the test object; and (2) the dependence of the field strength and flux density limits (imposed by the exciting current) and the B-H properties of the test object.

Current Pulse Time Dependence

For LCR circuits, the time variation of the current pulse obeys the equation:

$$\frac{d(LI)}{dt} + IR + \int I \frac{dt}{C} = 0 \qquad \text{(Eq. 9)}$$

The three terms on the left of Eq. 9 represent the instantaneous voltages across the inductance, the resistance and the capacitance in the circuit (Fig. 31b).

The inductance in the circuit is mainly that of the rod and tube system, since by careful design, the presence of additional inductance between cables and ground can be minimized. Because the inductance is time dependent, it is included in the derivative term.

The resistance is the combined resistance of the rod, cables and their connection and resistance within the capacitor discharge box. The internal resistance of the capacitor discharge box could be from the forward resistance of a silicon controlled rectifier included to eliminate the possibility of current oscillation. The capacitance of the system is generally in the region of 2 to 8 F.

There are three solutions for Eq. 9, if the time dependence of L is ignored. These solutions depend on the relative values of L, C and R.

$$I = \frac{2V_o}{\sqrt{\frac{4L}{C} - R^2}} \exp(-\beta t) \sin\sqrt{\frac{4L}{C} - R^2 t} \qquad \text{(Eq. 10)}$$

$$I = V_o C(\beta^2 t) \exp(-\beta t) \qquad \text{(Eq. 11)}$$

$$I = \frac{2V_o}{\sqrt{R^2 - \frac{4L}{C}}} \exp(-\beta t) \sinh\sqrt{R^2 - \frac{4L}{C}}\, t \qquad \text{(Eq. 12)}$$

Where:

V_o = the charged voltage of the capacitor bank; and
β = $R/2L$.

Equation 10 is an oscillatory solution, but the presence of the silicon controlled rectifier limits the pulse to the first positive-going peak (see Fig. 28). In this particular example, the pulse has a length of 17 ms and reaches 10,500 A. Such pulses are ideal for magnetizing objects of low electrical conductivity (ferrite magnets). However, with highly conducting materials such as steel tubes, the initial rapid current rise (may be millions of amperes per second) induces shielding eddy currents I_e that do not permit field penetration into the bulk of the material. The net effect of this is magnetization at the outer layer only.

The exponential Eq. 11 is known in its mechanical analogue as *critical damping*. It is difficult to achieve in this magnetic particle application because it depends on a known value of L that is in turn dependent on the physical and magnetic parameters of the test object.

The sin h solution in Eq. 12 leads to the longest pulses because there is no oscillation. Pulses up to 160 ms are commonly used in oil tube testing.

It has become common to define the length of such pulses as the time taken for the pulse to reach 0.5 I_{max} during decay τ. Both I_{max} and τ are measurable with an inductive ammeter or a peak and duration meter. These pulses are effective for magnetizing tubes because the field strength from the rod current is still high as the eddy current in the test object dissipates (there is penetration of the field into the bulk of the test material).

Because the inductance is a function of time, a full solution for the variation of the pulse current $I(t)$ can only be obtained by modeling the effect that the induced eddy current has on the instantaneous value of L. Experimental evidence indicates that, for elongated tubes, the physics of the magnetization process can be illustrated by a study of the constant-L case.

Typical Values for Inductance, Capacitance and Resistance

When designing a capacitor discharge pulsing system, it is essential to provide a pulse length sufficient for deeply magnetizing the material. There are two reasons for this. First, the tested material may arrive in a longitudinally magnetized condition and it may be necessary to remagnetize it circumferentially before magnetic particle testing. Secondly, some specifications call for relatively low emergent longitudinal field strengths at the ends of elongated test objects and rotation of the bulk flux density into the circumferential direction may be the simplest way to meet the specification.

An additional consideration, unrelated to the physics of test object magnetization, is the safety of the system in permanent and field testing situations (the National Electric Code should be consulted for details). For field use, it is essential to limit the charging voltage of the capacitor bank to 50 V. The tendency of this limit is to add capacitance to the system.

Resistance Values

The resistance of the magnetization system is an important factor in permitting high currents to flow. Resistance is minimized for field tests by using parallel strands of 0000 (100 mm²) copper welding cable for the connections between the rod and the capacitor discharge box.

The rod is made of aluminum, mainly for its handling advantages, but any highly conductive material works equally well. The requirement of elongating the pulse length to ensure the presence of its field after eddy currents have dissipated far outweighs the requirement of minimizing the overall resistance of the magnetizing circuit. Typical resistance values for 50 m (165 ft) of cable and 15 m (50 ft) of rod are 1 to 5 mΩ.

Capacitance Values

The capacitance in a capacitor discharge supply is generally between 2 and 8 F. This relatively large value is provided for two reasons: (1) because of the need to maintain relatively low voltages around the circuit; and (2) to elongate the pulse.

While the values of resistance R and capacitance C can be controlled by the capacitor manufacturer, the value of inductance L cannot.

Inductance Values

Inductance is dependent on characteristics of the test object. In the case of a tube, inductance is given by:

$$L = \frac{\ell}{2\pi}\left(\frac{dB}{dH}\right)\ln\frac{R_o}{R_i} \qquad \text{(Eq. 13)}$$

Where:

ℓ = the length of the tube (meters);
dB/dH = the differential permeability;
R_o = the outer radius of the tube (meters); and
R_i = the inner radius of the tube (meters).

See Fig. 32 for a diagram of these dimensions. Tube wall thickness T is often much smaller than the average radius of the tube. Under such conditions, Eq. 13 may be converted to:

$$L = \frac{\ell}{2\pi}\left(\frac{dB}{dH}\right)\ln\frac{r + \frac{T}{2}}{r - \frac{T}{2}} \qquad \text{(Eq. 14)}$$

or

$$L \cong \left(\ell\,\frac{T}{2\pi r}\right)\frac{dB}{dH} \qquad \text{(Eq. 15)}$$

In gaussian units, Eq. 15 becomes:

$$L \cong 2 \times 10^{-7}\left(\ell\,\frac{T}{r}\right)\frac{dB}{dH} \qquad \text{(Eq. 16)}$$

where r is $1/2(R_o + R_i)$. All lengths are in meters and dB/dH is dimensionless.

The inductance of thin-walled tubes is seen from Eq. 15 to be proportional to the tube length ℓ and wall thickness T and inversely proportional to its radius or diameter. Neither of these physical parameters nor the value of dB/dH can be controlled by the designer of the magnetizing equipment. However, for much of the tubular products used in oil fields, the value of T/R does not vary a great deal (perhaps by a factor of two).

The average magnitude of dB/dH encountered during magnetization can be seen from Fig. 33 to vary widely. The value is dependent on: (1) the point reached by the material on the B-H curve during magnetization; and (2) the starting point for magnetization (anywhere from $-B_r$ to Q on the vertical axis of Fig. 35).

As an example of a typical inductance calculation, consider a pipe magnetized to saturation following the path $-B_rH_cPQ$ and having:

B_r = 1.2 T (12 kG)
P = 1.2 T (12 kG)
ℓ = 10 m (30 ft)
T = 12.6 mm (0.5 in.)
R = 136.5 mm (5.25 in.) and
H = 2,400 A•m^{-1} (30 Oe)

Here dB is 2.3 T (23 kG), so that dB/dH is 0.001 in the SI system (800 in gaussian units) and L in SI units is:

$$L = 10 \text{ m} \frac{12.6 \text{ mm}}{2\pi \cdot 136.5 \text{ mm}} 0.001$$

$$L = 141 \ \mu H$$

or, in gaussian units:

$$L = (2 \times 10^{-7})(10 \text{ m})(12.6 \text{ mm}) \frac{800}{136 \text{ mm}}$$

$$L = 148 \ \mu H$$

Using the same tube as above, a path is taken from Q through P and B_s to B_r by a second pulse, with:

Q = 1.0 T (10 kG)
B_s = 1.5 T (15 kG) and
dH = 4,000 A•m^{-1} (50 Oe)

The average value of dB/dH is then only 1/8,000 (1.25×10^{-4}) in the SI system or 100 in the gaussian system. Dividing the original inductance value by 8 (the ratio of the two dB/dH values exhibited by the steel) yields:

$$L = 18.5 \ \mu H$$

As another example, consider an unmagnetized pipe that follows a path OPB_sB_r with:

B_s = 1.5 T (15 kG)
ℓ = 9.1 m (30 ft)
T = 4.8 mm (0.2 in.)
= 28 mm (1.1 in.) and
dH = 3,200 A•m^{-1} (40 Oe)

The inductance value is calculated in the SI system as:

$$L = 9.1 \text{ m} \left(\frac{4.8 \text{ mm}}{2\pi \cdot 28 \text{ mm}}\right) \frac{1.5}{3{,}200}$$

$$L = 116 \ \mu\text{H}$$

or in the gaussian system as:

$$L = (2 \times 10^{-7})(9.1 \text{ m})(4.8 \text{ mm}) \frac{15{,}000 / 40}{28 \text{ mm}}$$

$$L = 119 \ \mu\text{H}$$

The relatively large change in inductance exhibited by the tube in the first two examples affects the shape of the pulse waveform, notably the easily measurable parameters of peak current I_{max} and pulse duration τ (see Fig. 28).

Design Considerations

Good equipment design must consider the material being magnetized. The worst internal and external resistances of the magnetizing system should be known to the manufacturer and corresponding inductance values should be investigated. Under no circumstances should peak currents be stated for the purpose of magnetization without an electrical and magnetic load being used for the system evaluation.

Depending on the use of the equipment, regulations should be consulted with regard to insulation, isolation, explosion proofing, intrinsic safety and purging. Such regulations are available from many sources, depending on the use of the product. Notable among these are the Occupational Safety and Health Administration and the National Institute of Safety and Hygiene. Various foreign standards are considerably more stringent than those in the United States. Equipment designers should particularly note the requirements of the United Kingdom, Norway and West Germany when designing for North Sea applications. The Canadian Standards Administration should be consulted when designing for applications in Canada.

Magnetization Recommendations

Tubular products vary between such wide limits of diameter and wall thickness that it is difficult to provide a universal specification for the measurable parameters of current pulses for high residual induction. However, the values in Table 5 are based on research with a variety of tubes and can serve as broad guidelines to ensure adequate magnetization.[15]

As tabulated, the pulses are classified into long, moderate and short duration. Long duration pulses are those in excess of 100 ms (see Fig. 34). For such pulses, the induced eddy current is assumed to have dissipated while the magnetizing field strength is still high enough to cause saturation.

Moderate pulses are those with durations between 40 and 100 ms (Fig. 34). For magnetization, the longevity of the induced eddy current is acknowledged by its effect on the tube, shown in calculations by the use of the tube's lineal mass rather than its outer diameter.

Short pulses are defined as those with durations below 40 ms. By comparing the requirement for the single short pulse with that for the single moderate pulse, it can be seen that the maximum current requirement is higher for the same lineal tube mass. In effect, higher current causes a larger magnetizing field strength, in an attempt to overcome the eddy current.

Should it be necessary to use two such pulses, the peak current requirement falls because the material is partially magnetized. If the peak current can only reach an I_{max} value of 180(W), where W is tube weight in lb•ft^{-1}, then two such pulses are required. Finally, should the pulse be too small to magnetize the tube with two pulses, then a third pulse is necessary. The three pulse sequence should be such that I_{max} is equal to 145(W).

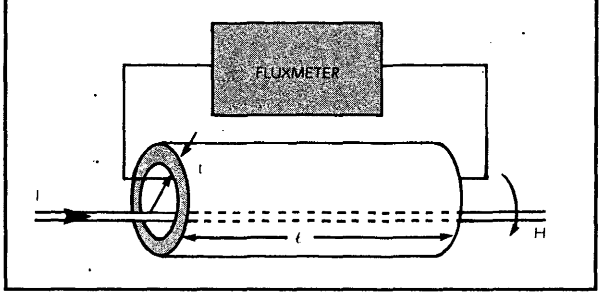
The requirements summarized in Table 5 are designed to ensure that the bulk induction following the magnetization pulse is at least 90 percent of the remanence value. In many cases, it is higher.

TABLE 5. Generalized current duration requirements for adequate magnetization of tubes

Magnetization System	Duration (millisecond)	Current Requirement Equation
Long pulse	>100	$I = 11.8\,(D_1)$ $I = 300\,(D_2)$
Moderate pulse	40 to 100	$I = 74\,(W_1)$ $I = 110\,(W_2)$
Single short pulse	0 to 40	$I = 161\,(W_1)$ $I = 240\,(W_2)$
Double short pulse	0 to 40	$I = 121\,(W_1)$ $I = 180\,(W_2)$
Triple short pulse	0 to 40	$I = 97\,(W_1)$ $I = 145\,(W_2)$

I = CURRENT IN AMPERES
D_1 = OUTER DIAMETER IN MILLIMETERS
D_2 = OUTER DIAMETER IN INCHES
W_1 = TUBE WEIGHT IN KILOGRAMS PER METER
W_2 = TUBE WEIGHT IN POUNDS PER FOOT

FIGURE 36. A technique for measuring flux density induced in the circumferential direction



Evaluating Current Pulse Effectiveness

There are two methods for evaluating the effectiveness of a magnetizing current pulse. The first method is a variation on the ring standard technique for the evaluation of magnetic flux. The second method is an indirect technique that employs an inductive ammeter (peak and duration meter). A third method, using simulated contact discontinuities (field indicators), is a valuable technique for evaluating surface fields only.

Fluxmeter Techniques

Fluxmeters measure the total magnetic flux threading an area defined by a search coil. When circumferentially magnetizing a hollow object by the internal conductor method, the search coil can be considered a one-turn coil through the test object. Flux changes are given by:

$$\Delta\Phi = A\Delta B \qquad \text{(Eq. 17)}$$

Where:

$\Delta\Phi$ = changes in magnetic flux density (tesla);
A = the area of the test object ($A = T\ell$) perpendicular to the search coil (square meter); and
ΔB = the change in the test object's flux density induced during magnetization.

Commercially available fluxmeters often compensate for the area A so that the device reads the average flux density directly. The problem with this approach for measuring the final flux density is that the initial flux density (with respect to the vector direction of the search coil) must be zero. When flux changes are measured, the initial value must be known. However, if the tube shown in Fig. 36 is unmagnetized or if prior magnetization is longitudinal, then the fluxmeter reads the average density of induced circumferential magnetization.

The output of the fluxmeter can be presented on an oscilloscope. Flux values intermediately between the beginning and the end of the magnetization process represent the flux linked by the one-turn coil. These intermediate values contain the effect of the flux in the air between the terminals of the fluxmeter.

During the pulse, the air field (caused by current I in the rod) and eddy currents (I_e in the test object) affect the instantaneous fluxmeter reading. When these currents have died away, only the test object flux perpendicular to the one-turn coil affects the final reading. If the operator has time to wind more than one turn around the test object, the error in final bulk flux density can be reduced. However, this procedure is not necessary for establishing the presence of residual induction in the test object for magnetic flux leakage from discontinuities.

Inductive Ammeter Techniques

As shown in Fig. 31b, the pickup coil of the device is threaded onto a convenient part of the magnetizing circuit. When the pulse is fired, the meter reads the peak current (I_{max} of Fig. 34) and the duration of the pulse (τ of Fig. 34).[20]

Saturation of the material has occurred when successive readings on the ammeter are identical. This can be explained as follows. When the first pulse is fired, the material exhibits its highest dB/dH value (the steep slope of the B-H curve is included in the value of L). The average value of dB/dH is effective for determining the value of the inductance in Eq. 9 through Eq. 13. This value is relatively large in comparison with the value exhibited during a second pulse. Figure 35 indicates high values of dB/dH for a first pulse (about 0.0008 in SI and 800 in gaussian) and much lower values during the second pulse (around 1.25×10^{-4} in SI or 100 in gaussian). In effect, the second pulse experiences a lower inductance than the first pulse.

The second pulse's lowered inductance permits peak current I_{max} to reach a higher value than it reached on the first pulse. In effect, the material is different. The system response is also to lower the duration τ. By monitoring I_{max} and τ, it is possible for inspectors to determine the test object's relative magnetization.

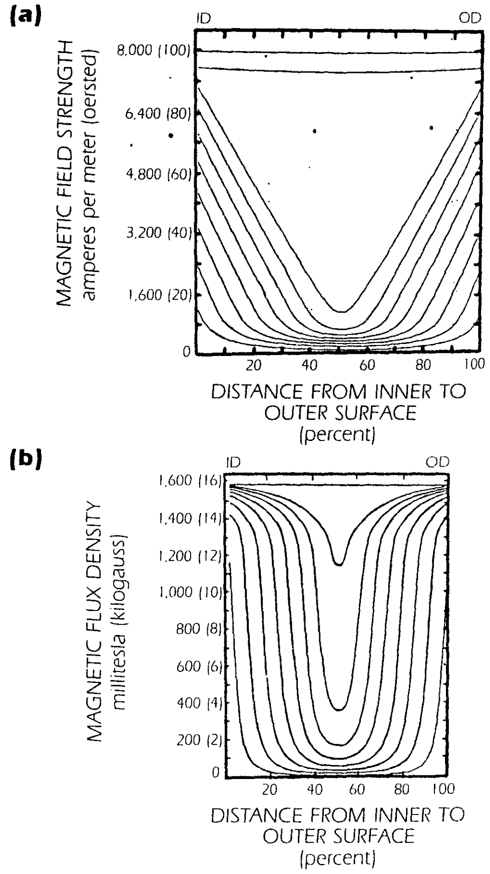
Using Inductive Ammeters

When materials are magnetized with pulse techniques, the values of field strength H and flux density B change with time as shown in Fig. 37. The horizontal axes show the percent distance from the inner surface to the outer surface. The vertical axes show either the fraction of H required to saturate the material or the flux density B. The lowest lines show time from the start of the pulse. The uppermost lines show the field strength and flux density levels at later time increments.

Figure 37 indicates that three phenomena occur during pulse magnetization: (1) inner and outer surfaces are rapidly magnetized; (2) the midwall region is the last part of the material to be magnetized; and (3) the midwall region can be left with a low state of magnetization if the pulse field strength is insufficient to saturate the material.

This last phenomenon contributes to magnetic fields from discontinuities at one surface but produces no leakage field at the other surface when the material is not saturated. The leakage field into the midwall section of the material merely raises the local magnetization level to a higher degree.

FIGURE 37. Plots against elapsed time and wall thickness of a tube for (a) magnetic field strength; and (b) magnetic flux density; lower curves represent magnetic field and induction at the beginning of the pulse; time proceeds from bottom to top; central regions are the last to be magnetized



When sections of the test object are not maintained at field strength levels sufficient for saturation (point P in Fig. 35), then the ensuing bulk residual flux density is low and the material requires additional pulses to saturate it. The magnetization process calls for the highest value of inductance L in Eq. 9 through Eq. 15 during the first pulse and lower values during subsequent pulses. The general effect of a high inductance value is to lower the value of I_{max} and elongate the value of τ.

In order to verify this and to limit the necessary mathematical computation, Eq. 11 was selected and from it the closed form results for I_{max} and τ are found below. First, the time τ at which I_{max} occurs is found by differentiation of Eq. 11 to be:

$$t = \frac{2L}{R} \quad \text{(Eq. 18)}$$

When this value is used in Eq. 11, the result for I_{max} is:

$$I_{max} = V_o \frac{CR}{2L_e} \quad \text{(Eq. 19)}$$

This result indicates that the value of I_{max} is inversely proportional to that of L (greater L gives lower I_{max}). In order to find τ, $I(t)$ is set at 0.5 I_{max}. The result is:

$$\tau = 5.36 \frac{L}{R} \quad \text{(Eq. 20)}$$

In this case, the pulse duration defined by τ is proportional to the value of L. That is, larger values of L, such as those for the initial pulse, lead to larger τ values (the longest pulse durations).

The B-H curve indicates that the lowest value of inductance that can occur under these magnetization conditions is exhibited by saturated material, when the value of dB/dH is at its lowest (see Eq. 15). If two identical readings are obtained from an inductive ammeter, the material must be exhibiting its lowest inductance to the magnetizing circuit and must therefore be at remanence B_r.

Operating Principles of Inductive Ammeters

The inductive ammeter is a microprocessor with an inductive pickup coil. The toroid coil contains a large number of turns wound onto a nonconducting nonmagnetic ring core. The ring is threaded onto cables from a capacitor discharge system or onto a central rod. When a pulse is fired, the flux caused by the current surge links with the windings on the ring and the voltage induced in the coil is given by:

$$E = 2 \times 10^{-7}\, Nd \frac{dI}{dt} \ln \frac{b}{a} \quad \text{(Eq. 21)}$$

Where:

N = the number of turns in the ring;
d = the axial length of the ring;
b = the outer radius of the ring;
a = the inner radius of the ring; and
dI/dt = the rate of change of current.

This equation is derived from Faraday's law of induction. In order to provide a signal related to the current itself, Eq. 21 must be integrated. The result is:

$$e = \int E \cdot dt = \left[(2 \times 10^{-7}) Nd \ln \frac{b}{a}\right] I \quad \text{(Eq. 22)}$$

where e is the output of the integration circuit.

In effect, since all the terms in the brackets are known, the output of the integration of induced voltage is proportional to the instantaneous current and the instrument can be calibrated to read current directly. Electronic circuits are used to measure the peak current I_{max} and the pulse duration τ.

Use of Field Indicators and Simulated Discontinuities

Typical Configurations of Field Indicators

Occasionally, a magnetic particle test operator needs to verify the orientation of induction after tubes have been magnetized by the capacitor discharge internal conductor technique. In the case of perfectly concentric tubes with constant metallurgical properties throughout, there should be no external leakage field. This fact eliminates the use of Berthold reference standards (elevated discontinuities surrounded by high permeability material) in this application.

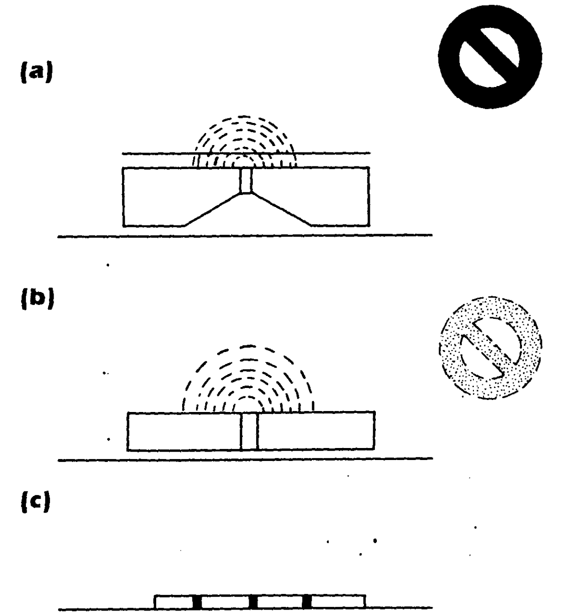
Figure 38 illustrates three common field indicators (erroneously called *penetrameters*) widely used in magnetic particle tests of tubes.

Pie Gage and Raised Cross Devices

Compared to the raised cross device, the pie gage has somewhat wider acceptability for tests of tubes, mainly because it can sit closer to the test object surface than the raised cross configuration.

The raised cross device contains perpendicular slots with a 0.13 mm (0.005 in.) gap. A nonmagnetic shield is sometimes used to cap the device. The pie gage comprises six 60 degree sections of high permeability steel with no cap and gaps up to 0.75 mm (0.03 in.). In both cases, the width of the air gaps determines the sensitivity of the device.

FIGURE 38. Typical portable magnetic field indicators: (a) raised cross with nonmagnetic cap; (b) pie gage; and (c) strip device; widths of the air gaps or slots made from nonmagnetic materials differ between the types



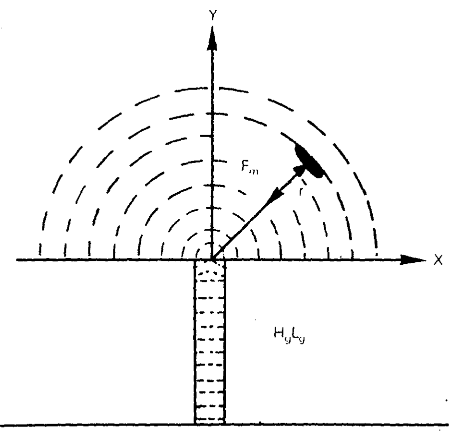
The device's sensitivity may be defined as the ability to produce a particle indication in an ambient magnetic surface field. In simple Foerster leakage field theory,[13] the particle holding ability depends on the product $(H_g L_g)^2$, where H_g is the magnetic field strength in the gap and L_g is the gap width.

Strip Indicators

The field indicator preferred for tube tests are strip indicators (Fig. 38). Such strips typically contain three discontinuities encapsulated for support in high permeability material (often brass). The strip is placed in intimate contact with the test object after magnetization so that the lift-off is limited to the thickness of the brass carrier. Under such circumstances, the magnetized test object shares flux with the strip.

The encapsulation is necessary because strips contain discontinuities that are very small in comparison to the other types of indicators. In effect, the gaps in the high permeability base material are activated by the same surface fields that activate magnetic flux leakage from similarly sized discontinuities in the test object.

FIGURE 39. The magnetic force on an isolated particle in the flux leakage field from a slot; the semicylindrical magnetic flux leakage approximation is according to Foerster (see Equation 26)



Principles of Operation

The principle of operation for all field indicators relies on the ability of the device to turn a relatively constant surface field into a highly curved field (it is well known that magnetic particles are attracted to highly curved fields). The surface field of the test object is converted by a air gap or slot into a curved field. The magnetic force on a particle in such a field is given by:[22]

$$\overline{F}_m \propto \mu_o V(\overline{H} \cdot \nabla)\overline{H} \qquad \text{(Eq. 23)}$$

Where:

α = a demagnetization factor of the particle (dependent on particle shape);
μ_o = the permeability of free space ($4\pi \times 10^{-7}$ H•m^{-1});
V = the particle volume; and
∇ = the vector calculus gradient operator.

For a two-dimensional discontinuity (Fig. 39) placed at right angles to the surface field, the vector operation reduces to:

$$\overline{F}_m \propto \mu_o V\left(H_x \frac{\partial}{\partial_x} + H_y \frac{\partial}{\partial_y}\right)(\hat{i}H_x + \hat{j}H_y) \qquad \text{(Eq. 24)}$$

where H_x and H_y are the leakage field components in the region above the slot. Calculations beyond this point require equations for the leakage field components. The simplest relation for a crack leakage field is given by:

$$H_x = \frac{H_g L_g y}{\pi(x^2 + y^2)} \qquad \text{(Eq. 25)}$$

and

$$H_y = \frac{H_g L_g x}{\pi(x^2 + y^2)}$$

These equations work reasonably well as long as the particle is located at a distance more than L_g from the mouth of the slot, as is the case if the slot has a thin nonmagnetic cover. The result of combining Eq. 25 with Eq. 24 is:

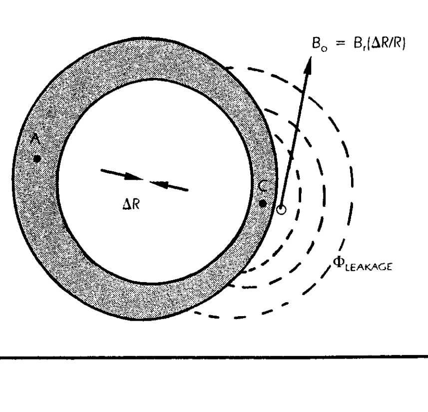
$$F_m \propto \frac{\mu_o V(H_g L_g)^2}{\pi^2 r^3} \qquad \text{(Eq. 26)}$$

where r is the distance of the magnetic particle from the mouth of the slot. In this simple approximation, Eq. 26 indicates that the magnetic force holding a particle is: (1) proportional to the gap parameter $(H_g L_g)^2$ and various particle dimensions; and (2) proportional to the inverse cube of its distance from the mouth of the slot. It is necessary then to determine the cause of H_g.

Fortunately, when seamless tubes are made by the mandrel piercing process, there is generally some eccentricity present (see Fig. 40). If the material is magnetized to remanence by the capacitor discharge internal conductor method, then the conservation of magnetic flux indicates that the flux present in the material at point A must equal the total of that at C plus the leakage flux. Consideration of the tube's cross section areas at A and C yields:

$$\Phi_{\text{leakage}} = (A_A - A_C)B_r \qquad \text{(Eq. 27)}$$

FIGURE 40. Broad magnetic flux leakage field from an eccentric circumferentially magnetized tube with points A and C at remanence B_r; such leakage fields can activate magnetic field indicators (portable discontinuities)



Where:

A_A = the cross section area at A;
A_C = the cross section area at C; and
B_r = the remanence value for the test material.

If the leakage field falls off in an inverse manner with distance, then the strongest surface leakage flux B_o is approximated by:

$$B_o = B_r \frac{\Delta R}{R} \qquad \text{(Eq. 28)}$$

where ΔR is the amount of eccentricity present in a tube of radius R. Equation 28 indicates that:

1. the higher the remanence B_r, the stronger the leakage field;
2. larger eccentricities give larger leakage fields for the same radius and remanence; and
3. for the same B_r and ΔR, the leakage field falls off as the tube diameter is raised (leakage fields are stronger on the smaller tubes).

At low induction values, the flux at A and C can be equal without the presence of a leakage field. Figure 40 shows that the flux density at C (the thin wall) must be the remanence value for the material if there is to be any leakage field. When this occurs, the flux density B_A at A obeys the relation:

$$B_A A_A = B_r A_C \qquad \text{(Eq. 29)}$$

Before this occurs, it may be possible to obtain a magnetic particle indication with a strip indicator. Because there may be no external fields, it is not possible to obtain an indication with the pie gage or other field indicator. It must then be recognized that metallurgical variations within the tube affect B_r and cause some external leakage flux.

Documents for Magnetic Particle Testing of Tubes

Table 6 lists American Petroleum Institute specifications and recommended practices that refer to magnetic particle testing for tubular materials. Of these, RP 5A5 addresses the most commonly used magnetization methods, plus wet and dry magnetic particle testing procedures. Many oil and gas companies now produce their own specifications, including those for magnetic particle tests.

In most documents, particular attention is given to the following parameters: (1) wet particle concentration; (2) dry particle bulk permeability; (3) dry particle visual contrast with the inspected surface; (4) dry particle filler content;

(5) verification of saturation for circular magnetism; (6) intensity of ultraviolet light at the test surface; (7) time intervals between ultraviolet intensity checks; (8) relation between field strength at the center of a coil and the current through the coil; and (9) time intervals between magnetizing coil current calibration.

Though not always specified, it must be recognized that the test object surface condition plays a critical role in determining which kinds of magnetic particles are acceptable for specific applications.

High contrast is required for visibility and accurate interpretation. High permeability is required so that the particles are magnetized by relatively low leakage fields from tight cracks. High bulk permeability can be verified by a test performed on bulk powders placed in a chemical test tube.

TABLE 6. Specifications and recommended practices referring to magnetic particle testing of tubular products; except as noted, all documents were written for tests of tube body, internal upsets, external upsets and pipe couplings

Document	Use
Specification 5CT	Casing, tubing and drill pipe
Recommended Practice 5A5	Field evaluation of casing, tubing and plain-end drill pipe
Recommended Practice 7G	Drill stem design and operating limits
Specification 5L*	Line pipe

*FOR VERIFICATION OF WELD REPAIRS

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SECTION 17

CODES, STANDARDS AND SPECIFICATIONS

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PART 1
INTRODUCTION TO MAGNETIC PARTICLE SPECIFICATIONS

Definition of Terms

In general usage, a *standard* is a document written by recognized authorities to recommend actions for achieving certain goals. Theory and a broad educational foundation are sometimes included to justify the recommendations. A standard can present minimum parameters or it can suggest certain courses of action based not on minimums but on efficiencies such as cost, labor or quality. A standard is typically enforced or given authority by an agent separate from its author. When a standard becomes law, it could then be called a *code*.

In nondestructive testing, a *specification* is often written by a commercial organization, usually one of the primary parties in a purchasing agreement. A specification is product specific and may be considered a tailored form of standard. A specification can require more stringent limits than a related standard's limits. In practice, a specification provides a clearly organized list of testing parameters (a specially written procedure) that describes the technique for locating and categorizing discontinuities in a specific test object. A typical specification includes acceptance criteria and is required by the designer, buyer or manufacturer of the article it covers.

For magnetic particle tests, the term *procedure* refers to a set of brief generalized guidelines that show the technician how to perform an accurate test for a given contract. A procedure often includes details about the in-house testing setup. Other details, based on the organization's past experience, provide the practical information needed in a procedure. Occasionally, procedures are written for broad categories of material or for specific classes of test objects. These procedures are not required or restrictive but educational in intent.

Unfortunately, a *standard* is also a reference test object with known discontinuities used to verify the accuracy of a testing procedure. In addition, the words *standard*, *specification* (*spec*) and *code* are wrongly used as synonyms in some applications and they are often used differently depending on the discipline in question. The definitions above are provided only for the educational purposes of this volume.

The Need for Specifications

Specifications are written to eliminate the variable characteristics of human operators and system designs, to produce an accurate result regardless of who is performing the magnetic particle test. Specifications must be written with a full knowledge of (1) magnetic particle test techniques; (2) a technique's individual sensitivities; (3) the test object's design; (4) its material characteristics; and (5) the discontinuities critical to the test object's service life. In most manufacturing applications, nondestructive tests are considered during design and such specifications are part of the test object's original drawing.

Magnetic particle specifications are produced to standardize test results, *not to eliminate the initiative of the technician*. There is no substitute for an experienced operator who assumes personal responsibility for the quality and accuracy of the test.

Table 1 is a summary of specifications commonly used for magnetic particle testing and material selection.

Need for Review and Revision of Specifications

Advances in the sciences have a three-fold effect on nondestructive tests and their specifications: (1) new ways can be found to produce or interpret test results; (2) tests must be developed to accurately examine newly developed materials; and (3) test procedures must be designed as integral parts of the modern manufacturing environment. All of these developments affect magnetic particle tests and must be reflected in their specifications. The guidelines used in countries such as Japan and West Germany differ in many respects from those in the United States, and they may give better test results in some applications. In the United States, many specifications are being updated to make better use of artificial discontinuities and multidirectional magnetic fields.

Testing specifications are working documents that tell how to locate discontinuities in a specific test object. Even for well established and successful methods like magnetic

TABLE 1. Summary of magnetic particle testing specifications; because latest revisions always apply, contact the issuing organization for current documents

Issuing Organization	Document Title
American National Standards Institute	
ANSI/ASME B31.1	Power Piping
ANSI/ASTM A275	Magnetic Particle Examination of Steel Forgings
ANSI/ASTM A456	Magnetic Particle Inspection of Large Crankshaft Forgings
ANSI/ASTM E125	Reference Photographs for Magnetic Particle Indications on Ferrous Castings
ANSI/ASTM E269	Definition of Terms Relating to Magnetic Particle Inspection
American Petroleum Institute	
API 5CT	Specification for Casing and Tubing
API 5D	Specification for Drill Pipe
API 5L	Specification for Line Pipe
API 5LU	Specification for Ultra High-Test Heat Treated Line Pipe
API RP 5A5	Recommended Practice for the Field Inspection of New Casing, Tubing and Plain End Drill Pipe
American Society for Testing and Materials	
A275	Magnetic Particle Examination of Steel Forgings
A456	Magnetic Particle Inspection of Large Crankshaft Forgings
E45	Standard Practice for Determining the Inclusion Content of Steel
E125	Standard Reference Photographs for Magnetic Particle Indications on Ferrous Castings
E269	Definition of Terms Relating to Magnetic Particle Inspection
E709	Standard Recommended Practice for Magnetic Particle Examination
D93	Flash Point by Pensky-Martens Closed Tester
D96	Water and Sediment in Crude Oils
D445	Kinematic Viscosity of Transparent and Opaque Liquids (and the Calculation of Dynamic Viscosity)
American Society of Mechanical Engineers (Boiler and Pressure Vessel Code)	
Sec I	Power Boilers
Sec II	Material Specifications
Sec III	Nuclear Power Plant Components
Sec V	Nondestructive Examination
Sec VIII (Div 1)	Unfired Pressure Vessels
Sec VIII (Div 2)	Alternative Rules for Pressure Vessels
Sec XI	Rules for In-Service Inspection of Nuclear Power Plant Components
American Welding Society	
D1.1	Structural Welding Code
D14.6	Welding of Rotating Elements of Equipment
Society of Automotive Engineers	
AMS 2300F	Premium Aircraft-Quality Steel Cleanliness, Magnetic Particle Inspection Procedure (also MAM 2300)
AMS 2301G	Aircraft Quality Steel Cleanliness, Magnetic Particle Inspection Procedure
AMS 2303A	Aircraft Quality Steel Cleanliness, Martensitic Corrosion Resistant Steels, Magnetic Particle Inspection Procedure
AMS 2640J	Magnetic Particle Inspection
AMS 3040	Magnetic Particle Inspection, Material Dry Method
AMS 3041A	Magnetic Particles, Wet Method, Oil Vehicle
AMS 3042A	Magnetic Particles, Wet Method, Dry Powder
AMS 3043A	Magnetic Particles, Wet Method, Oil Vehicle, Aerosol Canned
AMS 3044B	Magnetic Particles, Fluorescent Wet Method, Dry Powder
AMS 3045B	Magnetic Particles, Fluorescent Wet Method, Oil Vehicle, Ready to Use
AMS 3046B	Magnetic Particles, Fluorescent Wet Method, Oil Vehicle, Aerosol Packaged
AMS 3161	Inspection Vehicle, High Flash, Odorless

CONTINUED NEXT PAGE

TABLE 1 continued

Issuing Organization	Document Title
United States Department of Defense	
MIL-STD-271	Nondestructive Testing Requirements for Metals (ACN-1)
MIL-STD-1949	Magnetic Particle Inspection
MIL-I-6867	Magnetic Inspection Units
MIL-M-23527	Magnetic Particle Inspection Unit, Lightweight
MIL-I-83387	Magnetic Rubber, Inspection Process
DOD-F-87935	Fluid, Magnetic Particle Inspection, Suspension (Metric)
MIL-M-47230	Magnetic Particle Inspection Soundness Requirements for Materials, Parts and Weldments
MIL-STD-410	Nondestructive Testing Personnel Qualification and Certification
MIL-STD-2175	Castings, Classification and Inspection of
FED-STD-595	Colors
United States Department of Energy	
E15-2NB-T	Supplementary Requirements for Sec III ASME Code
EJ5-2NC-T	Supplementary Requirements for Sec III ASME Code
E15-2ND-T	Supplementary Requirements for Sec III ASME Code
E15-2NE-T	Supplementary Requirements for Sec III ASME Code
RDT-F3-6T	Nondestructive Examination (Supplement to ASME Boiler and Pressure Vessel Code Sec V)
British Standards Institution	
BS 6072	Method for Magnetic Particle Flaw Detection
Deutsche Gesellschaft fur Zerstorungsfreie Prufung	
	Guidelines for Magnetic Particle Flaw Detection
Japanese Institute of Standards	
JIS G 0565	Methods for Magnetic Particle Testing of Ferromagnetic Materials and Classification of Magnetic Particle Indications

particle testing, specifications are in regular need of review and revision. As an illustration of this, consider one piece of peripheral equipment used in establishing test procedures: the magnetic field indicator.

The increased reliance on artificial discontinuity standards, pie gage field indicators, tool steel ring standards and tangential field indicators is driven by incidents of catastrophic failure after magnetic particle tests failed to detect critical discontinuities. These unreliable tests were performed using practices found in early specifications. A major problem was that current level equations suitable for simple geometries were applied to more complex geometries. Discontinuities in corners, radii, bearing races, grooves and other areas are *not* detected when these formulas are inappropriately applied to complex test objects.

Subsequent field strength measurements were performed in areas of known failure on test objects of similar design. In some cases, there was no magnetic leakage field in the critical areas. In other cases, the fields were very low and not strong enough to hold magnetic particles. Adjacent areas of simple geometry were often found to be magnetized to levels satisfactory for testing. These empirical data indicated that existing current level equations could be applied only to the simplest test object geometry and were unreliable for complex geometries. It is very important that this kind of knowledge be incorporated as quickly as possible into industry specifications.

As another example of the need for review and revision, consider the increased use of alternating current tests outside the United States. This has occurred because of alternating current's ability to produce a nearly uniform magnetic field over the entire surface of a test object. However, alternating current, because of its low penetrating ability, further enhances the need for field indicators and surface field measurements, and increases the demand for their inclusion in test specifications.

PART 2

SAMPLE MAGNETIC PARTICLE SPECIFICATION

The following text is provided as a simple introduction to magnetic particle specifications and is not a sample working document. It contains much useful information about performing a typical magnetic particle test, including items found in most North American specifications, plus details unique to Japanese and West German specifications. Typical parameters are given for the performance of magnetic particle tests using any of the electric current techniques.

By following the specified instructions for artificial discontinuity standards and magnetic field indicators, it is likely that all surface discontinuities can be identified or the process's inability to find discontinuities will be determined.

Arrangement of the Specification

This sample specification does not include reference documents. Typically, all such documents referenced in the body of the specification should also be detailed in Section 2.0.

Section 5.0 includes all definitions of terms needed in the specification, including general terms for discontinuity description and reporting. This section may list the terms and their definitions or may provide source documents where appropriate definitions are found.

If acceptance criteria are included in such a document, they are listed in Section 5.0 and the glossary moves to Section 6.0.

Sample Specification Text

1.0 Scope

This specification establishes minimum requirements for magnetic particle testing. When specified, the magnetic particle testing method shall be used to detect cracks, laps, seams, inclusions and other discontinuities at or near the surface of ferromagnetic materials. Magnetic particle testing may be applied to raw material, billets, finished and semifinished materials, welds and components in-service. Magnetic particle testing is not applicable to nonferromagnetic metals and alloys such as austenitic stainless steels.

2.0 Reference Documents

List of all documents addressed or referenced in the specification.

3.0 General Requirements

3.1 *Magnetizing and Demagnetizing Equipment*

Magnetization can be accomplished either by passing an electric current directly through the material or by placing the material within the magnetic flux of an external source such as a coil. The types of equipment available include yokes, portable or mobile units, stationary units and multidirectional units.

The types of currents used for magnetization are full-wave rectified unidirectional current (FWDC), half-wave rectified single-phase direct current (HWDC) and alternating current (AC). The equipment used shall adequately fulfill the magnetizing and demagnetizing requirements as outlined herein, without damage to the test object and shall include the necessary features required for safe operation.

Permanent magnets shall not be used.

3.1.1 *Equipment Calibration*

Magnetic particle testing equipment shall be checked for performance and accuracy at the time of purchase and at intervals thereafter as given in Table 2; whenever malfunction is suspected; and whenever electrical maintenance which might affect equipment accuracy is performed.

3.1.2 *Ammeter Accuracy*

To check the ammeter on a testing unit, a calibrated ammeter shall be connected in series with the output circuit. Comparative readings shall be taken at three output levels encompassing the usable range of the equipment. The equipment meter reading shall not deviate more than ± 10 percent of full scale from the current value shown by the calibrated ammeter. When measuring half-wave direct current, the current values

TABLE 2. Typical verification intervals; maximum time between verifications may be extended when substantiated by technical stability or reliability data

Test Parameter	Maximum Time Between Verifications
Lighting	
Ultraviolet light intensity	1 day
Visible light intensity	1 week
Background visible light intensity	1 week
System performance using ring standard	1 day
Wet particle concentration	8 hours
Water break test	1 week
Wet particle contamination	1 week
Equipment calibration	
Ammeter accuracy	6 months
Timer control	6 months
Dead weight check	2 months

shown by the calibrated direct current ammeter reading shall be doubled. The ammeter shall be checked according to the schedule in Table 2.

3.1.3 *Timer Control Check*

On equipment using a timer to control current duration, the timer should be checked to within ± 0.1 second using a suitable electronic timer.

3.1.4 *Dead Weight Check*

Yokes shall be dead weight tested at intervals stated in Table 2. Alternating current yokes shall have a lifting force of at least 4.5 kg (10 lb) with a 50 to 100 mm (2 to 4 in.) spacing between legs. Direct current yokes and permanent magnets shall have a lifting force of at least 13.5 kg (30 lb) with a 50 to 100 mm (2 to 4 in.) spacing between legs; or 22.5 kg (50 lb) with a 100 to 150 mm (4 to 6 in.) spacing.

3.1.5 *Tangential Field Strength Meters*

The active area of the Hall effect probe should be no larger than 5 by 5 mm (0.2 by 0.2 in.) and should be within 2 mm (0.08 in.) of the test object surface. The plane of the probe must be approximately perpendicular to the surface of the test object at the location of measurement.

If the current is applied in shots and if alternating current or half-wave direct current is used, the gaussmeter should have a frequency response from direct current greater than 300 Hz. The direction and magnitude of the field can be determined by two measurements made at right angles with this meter.

3.2 *Lighting*

3.2.1 *Ultraviolet Type and Intensity*

Unless otherwise specified, the ultraviolet light intensity at the examination surface shall be 10 $\mu W \cdot mm^{-2}$ (1,000 $\mu W \cdot cm^{-2}$) or greater when measured with a suitable ultraviolet light meter and shall have a wavelength in the range of 320 to 400 nm.

Portable or handheld ultraviolet light sources shall produce an intensity greater than 10 $\mu W \cdot mm^{-2}$ (1,000 $\mu W \cdot cm^{-2}$) when measured at 380 mm (15 in.) from the ultraviolet light source. The intensity of ultraviolet light incident on unprotected skin or eyes shall not exceed the levels established by local safety regulations.

3.2.2 *Visible Light Intensities*

Visible light shall be used when testing with nonfluorescent particles or when assessing fluorescent indications. The intensity of the visible light at the surface of the test object shall be maintained at a minimum of 2,000 lx (200 ftc). Unless otherwise specified, fluorescent magnetic particle testing shall be performed in a darkened area with a maximum visible light level of 20 lx (2 ftc).

3.2.3 *Viewing Aids*

When using fluorescent materials, inspectors shall not wear eye glasses equipped with photochromic lenses (lenses that darken when exposed to ultraviolet light or sunlight). Magnifiers may be used.

3.3 *Reference Standards and Field Indicators*

A standard shall be available for procedure development and system checks. The standard may be an actual test object with known discontinuities; a replica with discontinuities; a magnetic field indicator (see Fig. 1); a tool steel ring (see Fig. 2, Tables 3 and 4); an artificial discontinuity or shim standard (see Fig. 3 and Table 5); or a tangential field meter with an associated reference standard.

FIGURE 1. Pie gage magnetic field indicator comprising eight low carbon steel triangles, furnace brazed together and copper plated

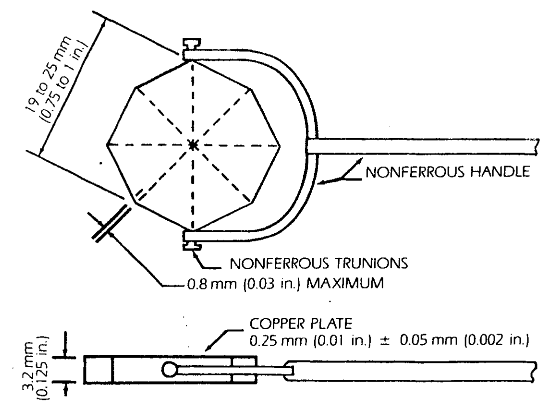
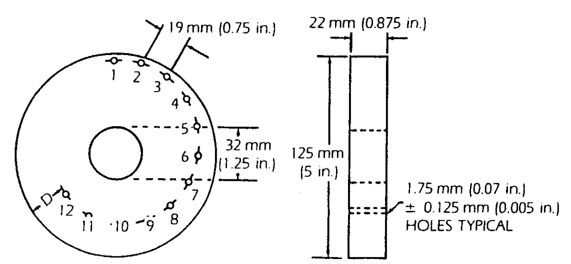


FIGURE 2. Ring standard for magnetic particle test system verification (see Table 3 and Table 4); material is AISI 01 tool steel from annealed round stock; hardness is 90 to 95 on the Rockwell B scale; dimension tolerances are ±0.8 mm (±0.03 in.)



3.3.1 *Configuration of Artificial Discontinuities and their Designations*

The configuration of the artificial discontinuities (shim standards) is shown in Fig. 3. The artificial discontinuities are labeled. The designation gives the thickness, discontinuity type and percent depth of discontinuity. For example B215 is a *bar* type discontinuity 2 milli-inches (50 μm) thick with a discontinuity depth at *15* percent of the bar's thickness.

The material is rolled, low carbon, high permeability, annealed steel with 0.05 mm (0.002 in.) and 0.1 mm (0.004 in.) thicknesses. Artificial discontinuities are 0.008 mm (300 μin.) wide at depths of 15, 30 and 60 percent of the material thickness. These three depths represent three sensitivity levels. Simulated discontinuities are machined air gaps filled with inert nonmagnetic material.

Type C (circular) standards can be used to ascertain field direction and ensure complete coverage on two or more magnetizing steps or for developing multidirectional tests. Type B (bar) standards are used when discontinuities in a particular direction are most critical. Type R (radial) standards are most useful for test objects with narrow spaces and small radii.

These artificial discontinuities should be discarded if excessively worn or misshaped.

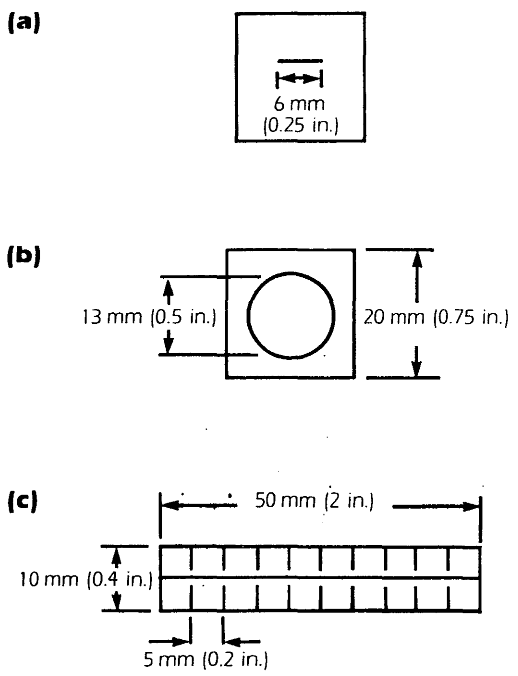
TABLE 3. Ring standard magnetic particle test indications for full-wave rectified alternating current (see Figure 2)

Magnetic Particle Type	Magnetizing Current (amperes)	Minimum Number of Holes Indicated
Black suspension	1,400	3
	2,500	5
	3,400	6
Dry powder	1,400	4
	2,500	6
	3,400	7
Fluorescent suspension	1,400	3
	2,500	5
	3,400	6

TABLE 4. Typical distances from outer edge for holes in a tool steel ring standard; distance tolerances are 0.13 mm (0.005 in.); hole numbers 8 through 12 are optional depending on manufacturer (see Figure 2)

Hole Number	Distance from Edge
1	1.8 mm (0.07 in.)
2	3.6 mm (0.14 in.)
3	5.3 mm (0.21 in.)
4	7.1 mm (0.28 in.)
5	8.9 mm (0.35 in.)
6	10.7 mm (0.42 in.)
7	12.4 mm (0.49 in.)
8	14.2 mm (0.56 in.)
9	16.0 mm (0.63 in.)
10	17.8 mm (0.70 in.)
11	19.6 mm (0.77 in.)
12	21.3 mm (0.84 in.)

FIGURE 3. Artificial discontinuity standards: (a) bar or type B standard verifies fields for discontinuities in particular directions; (b) circular or type C standard for determining field direction; and (c) radial or type R standard for small test objects (see Table 5)



3.3.2 *Use of Artificial Discontinuities*

Artificial discontinuity standards should be placed in an area of high stress concentration and in changes of section to determine levels of current density and directions of magnetizing fields needed to produce test indications.

When used for attaching artificial standards, tape should have the properties of good adhesion to steel; nonfluorescence; imperviousness to oil or solvents; and shall not cover the surface of the standard above the discontinuities. Standards shall be used with care to avoid cold working, bending or crimping.

TABLE 5. Typical dimensions for artificial discontinuity standards (see Figure 3)

Designation	Thickness micrometers (inches)	Discontinuity Depth (percent)
B215 or C215	50 (0.002)	15
B230 or C230	50 (0.002)	30
B260 or C260	50 (0.002)	60
B415 or C415	100 (0.004)	15
B430 or C430	100 (0.004)	30
B460 or C460	100 (0.004)	60
R230	50 (0.002)	30

The artificial discontinuity should be firmly attached to the test object with its back surface in intimate contact with the object's surface in locations where discontinuities are being sought. The true continuous magnetizing method must be used: applications of magnetizing force continue after application of particles ceases. In dry powder tests, blowing off the excess powder must occur while magnetizing current is flowing. Dry or wet particles may be used.

These standards should be used in conjunction with a tangential field meter. The magnetic field level shall be translated to current densities and shall be included in the written procedure.

3.3.3 *Care of Standards*

Following use, artificial discontinuity standards shall be thoroughly cleaned and checked under ultraviolet or visible light, as appropriate to the testing process, to ensure that residual indications do not remain.

3.4 *Qualification and Certification of Testing Personnel*

All personnel performing magnetic particle tests shall be qualified and certified in accordance with MIL-STD-410. Personnel making accept/reject decisions in accordance with the process described by this standard shall be qualified to at least Level II in accordance with MIL-STD-410.

Personnel performing processes described in this specification other than accept/reject decision making shall be qualified to at least Level I in accordance with MIL-STD-410.

3.5 *Acceptance Criteria*

Acceptance criteria for test objects shall be incorporated as part of the written procedure whether specifically or by reference to other documents containing the necessary information. Methods for establishing acceptance requirements for large crankshaft forgings are discussed in ASTM A456. Methods for establishing requirements for steel forgings are discussed in ASTM A275. Methods for classifying castings are given in MIL-STD-2175. MIL-M-47230 provides a classification scheme for ferromagnetic forgings, castings, extrusions and weldments. The testing of aircraft steel for cleanliness using magnetic particle testing is discussed in AMS 2300, AMS 2301 or AMS 2303 as appropriate to the type of steel being tested.

3.6 *Written Procedure*

Magnetic particle testing shall be performed in accordance with a written procedure applicable to the test objects. The procedure shall be in accordance with the requirements and guidelines of this specification. The procedure shall be capable of detecting the smallest rejectable discontinuities specified in the acceptance requirements.

The written procedure may be a general one which clearly applies to the specified objects being tested. All written procedures shall be approved by an individual qualified and certified to MIL-STD-410 Level III for magnetic particle testing, and shall be subject to the approval of the procuring agency. The written procedure shall include at least the following elements, either directly or by reference to the applicable documents.

A. Procedure identification number and date it was written.
B. Identification of the test objects to which the procedure applies, including material and alloy.
C. Areas of the test object to be examined.
D. Directions of magnetization to be used; the order in which they are applied; and any demagnetization procedures used between shots.
E. Method of establishing magnetization (prods, yoke, cable wrap, multidirectional system).
F. The type and level of magnetizing current (alternating current, half-wave direct current, full-wave direct current) and the equipment used.
G. The current level or the number of ampere-turns used and the duration of its application.
H. Test object preparation before testing.
I. Type of magnetic particle material (dry or wet, visible or fluorescent) and the method and equipment used for its application.
J. Type of records and method of marking objects after testing.
K. Acceptance criteria and disposition of objects after testing.
L. Post-test demagnetization and cleaning requirements.
M. Sequence of magnetic particle testing as related to manufacturing process operations.

3.7 *Record of Testing*

The results of all magnetic particle tests shall be recorded. Records shall be identified, filed and made available to the procuring agency on request. Records shall provide traceability to the specific test object or the lot inspected and shall identify the testing facility and the procedure used in the testing.

3.8 *Marking Test Objects*

Test objects that have passed magnetic particle testing shall be marked in accordance with the applicable drawing, purchase order, contract or as specified herein. Marking shall be applied in such a manner and location as to be harmless to the test object. The identification shall not be obliterated or smeared by subsequent handling and when practical shall be placed in a location visible after assembly. When subsequent processing removes the identification, the applicable marking shall be affixed to the record accompanying the finished assembly.

3.8.1 *Impression Stamping*

Impression stamping or vibroengraving may be used when permitted or required by written procedure, detail specification or drawing and shall be located only in the area provided adjacent to the part number or inspector's stamp.

3.8.2 *Etching*

Test objects may be etched using etching fluid or other means provided that the etching process and location do not adversely affect the object's function.

3.8.3 *Dyeing*

Identification may be accomplished by the application of dye, if the test object surface finish and subsequent handling permit.

3.8.4 *Other Identification Methods*

Other means of identification such as tagging may be used for objects that have construction or function precluding the use of stamping, vibroengraving or etching, as in the case of completely ground or polished balls, rollers, pins or bushings.

3.9 *Test Materials*

3.9.1 *Dry Particles*

Dry particles shall meet the requirements of AMS 3040. AMS 3040 particles shall be capable of producing indications (listed in Table 3) on the test ring specimen of Fig. 2 using the following procedure.

Place a conductor with a diameter 25 to 32 mm (1 to 1.25 in.) and a length greater than 400 mm (16 in.) through the center of the ring and circularly magnetize the ring by passing the current specified in Table 3 through the conductor.

Apply the particle powder to the ring using the continuous method. Examine the ring within one minute after current application. Examination of nonfluorescent baths shall be under a visible light of not less than 2,100 lx (200 ftc). Examination of fluorescent baths shall be under ultraviolet light with a minimum intensity of 10 $\mu W \cdot mm^{-2}$ (1,000 $\mu W \cdot cm^{-2}$) at the surface. The minimum number of hole indications shall meet or exceed those specified in Table 3. Hole indications exceeding 4.75 mm (0.2 in.) in width shall not be counted.

3.9.2 *Wet Particles*

Wet particles shall meet the requirements of AMS 3041, AMS 3042, AMS 3043, AMS 3044, AMS 3045 or AMS 3046, as applicable. In applying these specifications, the particle shall show indications as listed in Table 3 on the test ring specimen of Fig. 2, using the procedure described in 3.9.1.

The concentration of particles in the test bath shall be in the range of 0.1 to 0.5 mL in a 100 mL bath sample for fluorescent particles and 1.2 to 2.4 mL for nonfluorescent particles. Fluorescent particles and nonfluorescent particles shall not be used together.

3.9.3 *Water Vehicles*

Water used as a suspension vehicle shall be suitably conditioned to provide proper wetting, particle dispersion and corrosion protection. Proper wetting shall be determined by a water break test. Whenever possible, a nonionic wetting agent should be used. However, the amount of wetting agent should be limited so as not to raise the alkalinity of the suspension above 10 pH.

Use of conditioned water vehicle on cadmium plated steels with tensile strength of 1,240 MPa (180 ksi) or above is prohibited.

3.9.4 *Oil Vehicles*

The suspension vehicle for the wet method shall be a light petroleum distillate conforming to AMS 2641 or DOD-F-87935. The viscosity of the suspension shall not exceed 5 $mm^2 \cdot s^{-1}$ (5 centistokes) at the temperature of use when tested in accordance with ASTM D445.

The flash point of the suspension should be a minimum of 93 °C (200 °F) when tested in accordance with ASTM D93.

The background fluorescent of the suspension vehicle shall be less than the limit specified in DOD-F-87935.

3.9.5 *Determination of Wet Particle Concentration and Contamination*

Agitate the particle suspension a minimum of 30 minutes in order to ensure uniform distribution in the bath. Place a 100 mL sample of the agitated suspension in a parachute shaped centrifuge tube (specified in ASTM D96). Demagnetize and allow the tube to stand undisturbed for at least 60 minutes. Read the volume of settled particles.

If a fluorescent suspension is used, the liquid above the precipitate is examined with ultraviolet light. The liquid shall be nonfluorescent. Comparison may be made with fresh vehicle. If the liquid suspension with the particle settled out is seriously contaminated with cutting oil or with fluorescent pigment from the particles, the suspension will fluoresce brightly and shall be discarded.

Particle concentration and contamination shall be determined at start up; whenever the bath is changed or adjusted; and at regular intervals according to Table 2.

3.9.6 *Caution*

Dry cleaning solvents are not to be used as the vehicle for wet particles. Proper precautions must be taken to prevent the ignition of hydrocarbon suspension baths by overheating or electrical arcing. Precautions shall also be taken to prevent inhaling of dry particle materials.

4.0 Procedures

4.1 *Testing Sequence and Coverage*

Magnetic particle testing shall be performed after the completion of operations that could cause surface or near surface discontinuities such as forging, heat treating, plating, cold forming, welding, grinding, straightening, machining and proof loading.

Magnetic particle testing shall not be performed with nonferromagnetic or ferromagnetic coatings in place that could prevent the detection of surface discontinuities in a ferromagnetic substrate. Such coatings include paint or chrome plate greater than 0.075 mm (0.003 in.) in thickness or ferromagnetic coatings such as electroplated nickel greater than 0.025 mm (0.001 in.) in thickness.

When such coatings are nonconductive, they must be removed where electrical contact is to be made. Unless otherwise specified, production parts shall be magnetic particle tested prior to application of the coating. When plating operations could result in hydrogen embrittlement cracking, testing will be performed before and after the plating operation. The post plating magnetic particle test may be substituted with a penetrant test without a pickling operation.

A. When it is not possible to test the whole test surface in one operation, divide the test surface into suitable sections and perform separate tests on each section, with a ten percent overlap at the section boundaries.
B. Where the direction of discontinuities cannot be presumed or detection of discontinuities in various directions is required, magnetic fields in at least two directions shall be applied to the test object. The directions shall vary 90 degrees from one another and the fields may be imposed successively or simultaneously in a multidirectional system.
C. When the residual method is used, other ferromagnetic material shall not be brought in contact with the test surface, from the finish of the magnetizing operation to the completion of magnetic particle pattern inspection.
D. An object carrying a direct current will conduct the current throughout the whole of its cross section. Alternating current flows predominantly along the surface because of the skin effect. Regard full-wave rectified alternating current as direct current because of its high direct current proportion (63 percent). Half-wave rectified direct current and the other current types may be regarded as a superimposition of a direct current proportion with an alternating current proportion.
E. With direct current flow, the flux density is inversely proportional to the cross sectional area of the test object. In the case of alternating current, the flux density at the surface is inversely proportional to the circumference of the test object. The attenuation of the flux density with increasing circumference or cross section is *less* for an alternating current field than for a direct current field.
F. When using direct current yokes, magnetization at the surface is dependent on the thickness of the material.

   When magnetizing with alternating current yokes, the field strength at the surface is virtually independent of plate thickness for thicknesses above 10 mm (0.4 in.). For the same flux, magnetization at the surface using alternating current yokes is higher than that for direct current magnetization.

   When alternating current flows through conductors of circular cross section, the field strength at the surface is exactly the same as for a direct current flow of the same amperage. For conductors having noncircular cross sections (particularly note conductors with sharp edges), the field strength at the surface becomes more uniform with higher frequency.
G. When electrical contact is made with the test object using prods, clamps, magnetic leeches or other means, precaution shall be taken to ensure that the electrical current is not flowing while contacts are applied or removed and that excessive heating does not occur in the contact area. Verify that contact surfaces are clean.

4.2 *Preparation of Test Objects*

4.2.1 *Pretesting Demagnetization*

The test object shall be demagnetized before testing if prior operations or conditions have produced a residual magnetic field which will interfere with the test.

4.2.2 *Precleaning*

For tests performed with dry powders, the cleaning solvents or cleaning process must be capable of providing a dry surface free of oil, scale or grease. For tests performed with wet particle suspensions, the cleaning process must be capable of providing a test surface that passes a water break test.

A. The area of pretreatment shall be wider than that under test. In the case of a weld, the pretreatment area shall be enlarged about 20 mm (0.75 in.) from the area under test toward the parent material.
B. When dry magnetic particles are used or when a wet particle suspension different from the cleaning liquid is used, the test surface shall have been dried.
C. To prevent burning and to improve current transmitting efficiency, the surface of the test object and the electrodes that contact one another shall be clean.

4.2.3 *Water Break Test*

An object to be tested is flooded with conditioned water and the appearance of the surface is noted after flooding is stopped. If a continuous even film forms over the entire object surface, a suspension has sufficient wetting ability and the surface is sufficiently clean for magnetic particle testing. If the film of suspension breaks, exposing bare surface, insufficient wetting agent is present or the test object has not been adequately cleaned.

4.2.4 *Plugging and Masking*

Small openings and oil holes leading to obscure passages or cavities shall be plugged with a suitable nonabrasive material which is readily removed and, in the case of engine parts, is soluble in oil. Effective masking shall be used to protect components which may be damaged by contact with the suspension.

4.3 *Magnetization*

The current levels given in the following subparagraphs are to be used as a guide in establishing the test procedure. Actual current levels must be established by verification of adequate field strength by using one or more of the following:

A. a tangential field meter;
B. an artificial discontinuity standard;
C. a pie gage field indicator.

A field strength value measured at one point on a test object is not indicative of the field strength elsewhere, particularly if the test object has a complex shape. Therefore, field strength shall be measured at several locations on the test object and particularly in corners and grooves.

When the tangential field meter is used, the field strength should be in the range of 3 to 6 mT (30 to 60 G). If an artificial discontinuity standard or pie gage field indicator is used, the artificial discontinuities must be detectable in all tested areas at any one shot. It is typical to use the minimum current required to produce 3 to 6 mT (30 to 60 G) readings or to produce indications at the artificial discontinuities to avoid excess magnetization or overheating.

4.3.1 *Prod*

When using prods, 3.5 to 5 A per millimeter (90 to 125 A per inch) of prod spacing shall be used. Prod spacing shall not be less than 50 mm (2 in.) nor greater than 200 mm (8 in.). Verify that contact surfaces are clean and in contact before current application. Also, use one of the devices listed in 4.3 to verify that sufficient field strength is obtained.

4.3.2 *Head Shot*

When magnetizing by passing current directly through the test object, the current shall be from 12 to 32 A per millimeter (300 to 800 A per inch) of test object diameter. The diameter shall be taken as the largest distance between any two points on the outside circumference of the test object less any void areas (holes or passageways) across the line between the points. Avoid overheating and arcing. Use one of the devices listed in 4.3 to verify that sufficient field strength is obtained.

4.3.3 *Central Conductor*

When magnetizing by passing current through a conductor inside a hollow test object, alternating current is to be used only for surface discontinuities on the inside surface of the test object. If only the inside of the object is to be tested, the diameter shall be the largest distance between two points, 180 degrees apart on the inside circumference.

When the axis of the central conductor is located near the central axis of the test object, the same current levels established for a head shot shall apply, but ensure that sufficient magnetic field strength is obtained by using one of the devices listed in 4.3.

4.3.3.1 *Offset Central Conductor*

When the central conductor is placed against an inside wall of the test object, head shot current levels shall apply except that the diameter shall be considered the sum of the diameter of the central conductor and twice the wall thickness.

The distance along the test object circumference (interior or exterior) which is effectively magnetized shall be taken as four times the diameter of the central conductor (see Fig. 4). The entire circumference shall be tested by rotating the test object on the conductor, allowing for about 10 percent magnetic field overlap between shots. Use one of the devices listed in 4.3 to verify that sufficient field strength is obtained.

4.3.4 *Coil Shots*

Passing current through a coil encircling the test object or encircling a section of the test object produces a magnetic field parallel to the axis of the coil. This magnetizing method must be used when an object's width or diameter is significantly greater than its length (bearing races, disks, rotating parts).

For low fill-factor coils, the effective field extends a distance on either side of the coil center approximately equal to the radius of the coil (see Fig. 5). For cable wrap or high fill-factor coils, the effective distance of magnetization is 225 mm (9 in.) on either side of the coil center (see Fig. 6).

For test objects longer than these effective distances, the entire length shall be tested by repositioning the object within the coil, allowing for about 10 percent effective magnetic field overlap. For coil magnetization, it is essential that artificial discontinuity standards are placed to determine the extent of the effective field on either side of the coils when preparing technique documentation.

4.3.4.1 *Effect of Coil Size*

When the cross sectional area of the coil is ten or more times the cross sectional area of the test object, then in amperes through the coil, the current I shall be as follows.

A. For test objects positioned to the side of the coil:

$$I = \frac{45{,}000D}{NL} \qquad \text{(Eq. 1)}$$

Where:

L = length of the test object;
D = diameter of the test object (measured in the same units as the length); and
N = number of coil turns.

B. For test objects positioned in the center of the coil:

$$I = \frac{R43{,}000}{N\left(\frac{6L}{D}\right) - 5} \qquad \text{(Eq. 2)}$$

Where:

R = the radius of the coil.

If the cross sectional area of the coil is less than twice the cross sectional area (including hollow portions) of the test object:

$$I = \frac{35{,}000}{N\left(\frac{L}{D}\right) + 2} \qquad \text{(Eq. 3)}$$

FIGURE 4. Magnetization with an offset central conductor; region effectively magnetized for particle testing is equal to four times the diameter of the conductor

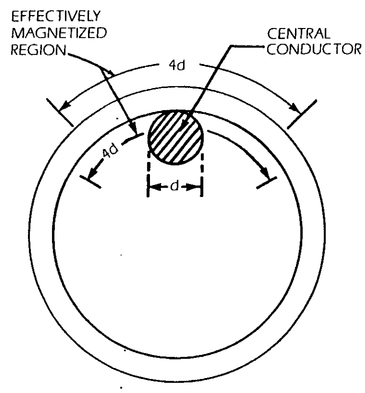


FIGURE 5. Magnetization with a low fill-factor coil; region effectively magnetized for particle testing is equal to two times the radius of the coil

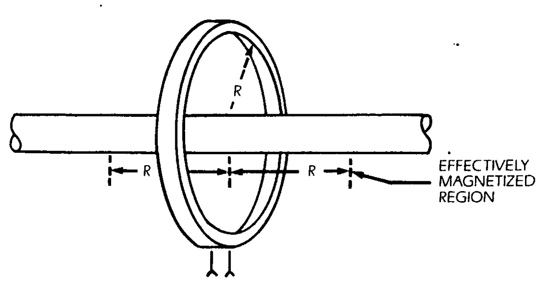
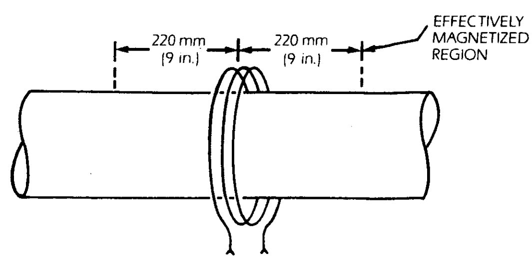


FIGURE 6. Magnetization with a high fill-factor coil



These equations hold only if the L/D ratio is greater than 3 and less than 15. If L/D is less than 3, ferromagnetic material with the same diameter as the test object shall be placed on each end of the test object to effectively increase L/D to 3 or greater. If L/D is greater than 15, use 15.

For a hollow or cylindrical test object, D shall be replaced with an effective diameter D_{eff} calculated using:

$$D_{eff} = 2\left(\frac{A_t - A_h}{\pi}\right)^{1/2} \qquad \text{(Eq. 4)}$$

Where:

A_t = the cross sectional area of the test object; and
A_h = the cross sectional area of the hollow portions of the test object.

Effective fields diminish according to the inverse square law from one pole to the other. Artificial discontinuity standards shall be used to ensure proper current levels along the entire axis of the test object. Use alternating current for magnetization of complex shapes.

4.3.5 *Multidirectional Systems*

With suitable circuitry, a multidirectional field in a test object may be established. For example, this may be done by selectively switching the magnetizing current between contact pairs positioned about 90 degrees apart. The electrical phase of the fields must be different so that the resulting field within the object changes its direction periodically. The magnetic fields must be attuned to one another with respect to their size, angle and phases. To illustrate such combined methods, two examples are given below.

A. *Superimposition of Two Alternating Fields with a Phase Shift*
By shifting the phase of the magnetization, a field is produced of changing size and changing spatial characteristics. Such a field can be produced using three-phase current with a phase difference of 120 degrees.
Phase shifts between 50 degrees and 130 degrees can be used. Phase shifts exceeding this range produce such great changes in field strength that the detection of discontinuities in random direction is reduced. With a phase shift of 90 degrees and fields of the same size perpendicular to one another, the field strength will be equal in all directions.

B. *Superimposition of Alternating Field on a Constant Field*
The resulting field direction oscillates around the direction of the uniform field. If both fields are equal in size, then the angle between the fields will approach 90 degrees. If this range is to be enlarged, set the alternating field to a higher strength than the constant field.

When two alternating fields are superimposed with the same or opposite phases, the two alternating fields interact to generate one field having a constant direction.

4.3.5.1 *Multidirectional Magnetization Current*

Alternating current, half-wave direct current and full-wave direct current may all be used separately or in combination depending on the testing application and the restrictions regarding coating thickness. The continuous method of particle application must always be used when employing multidirectional magnetization techniques.

4.3.6 *Yokes*

Yokes meeting the requirements of 3.1.4 may be used, provided discontinuity standards are used to verify field strengths.

4.4 *Particle Application*

4.4.1 *Continuous Method*

In the dry continuous method, magnetic particles are applied to the test object by blowing, brushing or dusting while the magnetizing force is present. In the wet continuous method, the magnetizing force is present or the current is on while the suspension is being applied to the test object.

4.4.2 *Residual Method*

In the residual magnetization method, magnetic particles are applied to the test object immediately after the magnetizing force has been discontinued. The residual method shall be used only when specifically approved by the procuring agency or as an interpretation aid.

4.4.3 *Dry Method*

When using dry particles, the flow of magnetizing current shall be initiated before the application of magnetic particles to the test surface and shall be terminated after powder application has been completed and any excess blown off.

The duration of the magnetizing current shall be at least 0.5 second and short enough to prevent damage to the test object from overheating or other causes. Dry powder shall be applied such that a light, uniform particle dust settles on the surface of the test object while it is being magnetized. Specially designed powder blowers or shakers using compressed air or hand power shall be used. The applicators shall introduce the particles into the air in a manner such that they reach the test object surface in a uniform cloud with a minimum of force.

Excess powder shall be removed by means of a dry air current with sufficient force to remove excess particles but not enough force to disturb particles held by leakage fields indicative of discontinuities. Observe carefully during powder proper application and during removal of the excess powder. Sufficient time for formation and examination of indications shall be allowed during the testing process.

4.4.4 *Wet Method*

Fluorescent or nonfluorescent particles suspended in a liquid vehicle at the required concentration shall be applied either by gently spraying or flowing the suspension over the area to be tested. Proper sequencing and timing of magnetization and proper application of particle suspension are required to obtain formation and retention of indications. This generally requires that the stream of suspension be applied to the test object slightly before and simultaneously with energizing the magnetic circuit.

The magnetizing current shall be applied for a duration of at least 0.5 second for each application with a minimum of two shots being used. Care shall be exercised to prevent damage to the test object due to overheating or other causes. Weakly held indications on highly finished parts are readily washed away and care must be exercised to prevent high velocity of the bath flow over critical surfaces.

4.4.5 *Magnetic Slurry or Paint*

Magnetic paints or slurries are applied to the test object with a brush, squeeze bottle or aerosol can before or during the magnetization operation. This method is for special applications such as overhead or underwater magnetic particle tests. This method shall be used only when specifically approved by the procuring agency.

4.4.6 *Magnetic Polymer*

Polymerized material (low temperature vulcanizing rubber) containing magnetic particles shall be held in contact with the test object during the period of its cure. Before curing takes place and while the magnetic particles are still mobile, the test object shall be magnetized to the specified level. This requires prolonged or repeated periods of magnetization. This method is for special applications such as bolt holes that cannot be readily tested by the wet or dry method. The method shall be used only when specifically approved by the procuring agency.

4.5 *Interpretation and Recording of Indications*

Operators must wait at least 60 seconds after entering a darkened testing booth before examining particle indications.

4.5.1 *Recording of Indications*

All indications shall be evaluated according to the applicable acceptance criteria specified in the written procedure. Relevant indications which have been evaluated and determined to be unacceptable shall be described in detail on the appropriate rejection form and submitted for disposition. The location of all indications shall be marked on the test object and permanent records of the location, direction and frequency of indications may be made by one or more of the following methods.

4.5.2 *Recording Sketch*

Record the location, length, direction and number of indications by a sketch or on a tabular form.

4.5.3 *Tape Transfer*

Apply special transparent pressure sensitive tape to the dry particle indication and then peel it off the test object. Place the tape transfer on an approved form with information giving its former location on the test object.

4.5.4 *Indication Fixing*

Cover the indication with commercially available strippable film to fix the indication in place. Strip off the film and indication after cure (use transparent pressure sensitive backing, if included with the fixing product). Place the indication on an approved form with information giving its previous location on the test object.

4.5.5 *Photography*

Photograph the magnetic particle indications, the tape transfer or the strippable fixed indication. File the photograph with information giving its location on the test object, if such information is not visible in the photograph (grid lines may be used).

4.6 *Post-Test Demagnetization and Cleaning*

Unless directed otherwise by the procuring agency, all magnetic particle test objects shall be demagnetized, cleaned and corrosion protected after testing.

4.6.1 *Demagnetization*

4.6.1.1 *Alternating Current*

When using alternating current demagnetization, the test object shall be subjected to a field with a peak value equal to and in nearly the same direction as the field used during testing. This alternating current field is then gradually decreased to zero.

When using an alternating current demagnetizing coil, hold the test object about 0.3 m (1 ft) in front of the coil and move it at least 1 m (3 ft) beyond the end of the coil. Repeat this process if necessary. Rotate and tumble test objects of complex configuration while passing them through the field of the coil.

4.6.1.2 *Direct Current*

When using direct current demagnetization, the initial field shall be equal to and in nearly the same direction as the field reached during testing. The field shall then be reversed, decreased in magnitude, and the process repeated (cycled) until an acceptably low value of residual magnetic field is achieved. Typically, a thirty step cycle shall be used.

4.6.1.3 *Yoke*

When demagnetizing with a yoke, use alternating current and energize the yoke when it is in contact with the test object. With current still applied, separate the test object from the yoke for a distance of 1 m (3 ft) while rotating the test object or yoke relative to one another.

4.6.1.4 *Field Strength Levels*

After demagnetization, a magnetic field strength meter shall not detect fields greater than ±0.3 mT (±3 G) anywhere on the test object.

4.6.2 *Cleaning and Care after Testing*

Remove all traces of magnetic particles and vehicle from the test object. Cleaning shall be done with a suitable solvent, air blower or by other means. All traces of the magnetic particles and magnetic particle test materials which might interfere with subsequent use of the test object shall be removed. Chlorinated solvents shall not be used on test objects containing crevices or on 400 series stainless steels.

Thoroughly remove all plugs in cavities and all masking. Test objects shall be protected from possible corrosion or damage during the cleaning process and shall be treated to prevent the occurrence of corrosion before continued processing.

5.0 Definitions

If acceptance criteria are included in a specification, they are listed in Section 5.0 and the definitions move to Section 6.0.

The specification may reference other documents that contain appropriate definitions for particular terms. Alternately, the specification may provide its own alphabetical glossary of words and their definitions.

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