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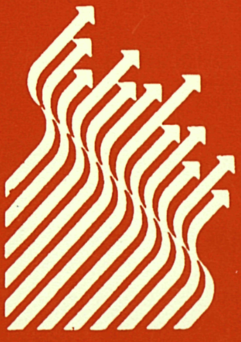
Steelmaking

Mould coatings for continuously cast billet production



Report

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STEEL RESEARCH

European Commission

technical steel research

Steelmaking

Mould coatings for continuously cast billet production

F. Faries, J. Rawson, A. Rose, M. Bugdol

Davy McKee (Poole) Ltd
Wallisdown Road
Poole
Dorset
United Kingdom

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MOULD COATINGS FOR CONTINUOUSLY CAST BILLET PRODUCTION

British Steel plc

ECSC Agreement No. 7210.CA/828

SUMMARY

A study has been made of the use of coatings applied to the interior of continuous casting billet moulds, with the objective of improving billet surface quality, particularly for oil lubricated casts, and extending mould service life.

The range of coatings available was restricted by the need to avoid softening of the copper, precluding the use of a number of oxide and carbide deposition techniques. The constraint on internal accessibility imposed by the mould geometry further restricted the choice of possible coatings.

Coated 140 mm section moulds have been used in commercial trials to produce a range of carbon and low alloy steel billets. The mould coatings comprised Cr plating, Cr plating overlaid with TiN and CrTiN, and primary electroless Ni overlaid with ZrN and a series of proprietary low temperature deposits, including Ni/PTFE.

Comparisons have been made of the quality of billet surfaces produced with each coating and mould service performance has also been assessed in each case.

Only the nitrides on Cr plating and Ni/PTFE coatings on electroless Ni showed satisfactory resistance to damage in service, with the Ni/PTFE providing some evidence of advantages to both mould condition and billet surface quality.

Plant measurements have included mould friction and heat transfer. Metallographic assessment has been made both of billets produced during the trials and of moulds after service.

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British Steel plc

Accord ECSC No. 7210.CA/828

RESUME

On a étudié l'emploi de revêtements appliqués à l'intérieur des moules pour coulée continue de billettes, dans le but d'améliorer la qualité superficielle des billettes, particulièrement pour les moulages lubrifiés à l'huile, ainsi que pour prolonger la vie utile des moules.

La gamme des revêtements disponibles a été limitée par la nécessité d'éviter tout ramollissement du cuivre, ce qui a interdit l'utilisation de plusieurs techniques de dépôt d'oxydes et de carbures. La géométrie des moules a imposé une autre contrainte, en ce que la difficulté d'accès à l'intérieur des moules a limité davantage encore le choix des revêtements possibles.

On a utilisé, dans des essais industriels, des moules revêtus de 140 mm de coupe transversale pour produire une gamme de billettes en aciers au carbone et faiblement alliés. Les revêtements utilisés ont été le placage Cr, le placage Cr recouvert de TiN et CrTiN et du nickel primaire autoélectrolytique recouvert de ZrN, ainsi que plusieurs couches à dépôts à basse température de marques spéciales, y compris le Ni/PTFE.

On a comparé la qualité superficielle des billettes produites avec chaque revêtement et, dans chaque cas, on a évalué les performances des moules.

Seuls les nitrures sur placage Cr et les revêtements Ni/PTFE sur nickel autoélectrolytique ont démontré une résistance satisfaisante aux avaries en service; par ailleurs, le Ni/PTFE semble offrir certains avantages en ce qui concerne l'état des moules et la qualité superficielle des billettes.

Les mesures effectuées en usine ont porté sur la friction des moules et le transfert de chaleur. On a réalisé une évaluation métallographique au niveau des billettes produites pendant les essais, ainsi qu'à celui des moules après le service.

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Kokillenbeschichtungen für Produktion stranggegossener Knüppel

British Steel plc

EGKS Vertrag-Nr. 7210.CA/828

Zusammenfassung

Man hat den Einsatz der Beschichtungen untersucht, die auf der Innenseite stranggegossener Knüppelkokillen aufgetragen werden und zwar mit dem Ziel, die Knüppeloberflächengüte zu verbessern und besonders im Falle von ölgeschmierten Güssen und auch wegen verbesserter Haltbarkeit der Kokillen.

Die Auswahl der existierenden Beschichtungen war begrenzt, weil man Erweichung des Kupfers vermeiden mußte, und deshalb konnten verschiedene Oxyd- und Karbidablagerungstechniken nicht verwendet werden. Außerdem hat der beschränkte Zugang zur Innenseite aufgrund der Kokillengeometrie die Auswahl möglicher Beschichtungen ebenfalls limitiert.

Beschichtete Kokillen zur Fertigung von 140 mm Vierkantknüppeln sind in handelsüblichen Versuchen eingesetzt worden, um verschiedene Kohlenstoff- und niedriglegierte Stahlknüppel zu produzieren. Als Kokillenbeschichtungen hat man eine Cr-Plattierung, eine Cr-Plattierung mit überlagertem TiN und CrTiN sowie eine primäre chemische Ni-Plattierung mit überlagertem ZrN und eine Reihe von Niedrigtemperatur-Ablagerungen von Markenherstellern einschließlich Ni/PTFE verwendet.

Man hat die Güte der Knüppeloberflächen verglichen, die mit jeder Beschichtung produziert wurden, und das Verhalten der Kokillen ist auch in jedem Falle untersucht worden.

Nur die Nitride auf der Cr-Plattierung und die Ni-/PTFE-Beschichtungen auf der chemischen Ni-Plattierung haben zu zufriedenstellender Beständigkeit gegen Beschädigung im Einsatz geführt, und mit der Ni-/PTFE-Beschichtung konnte man gewisse Vorteile für den Kokillenzustand und die Knüppeloberflächengüte nachweisen.

Im Werk hat man die Kokillenreibung und den Wärmeübertrag gemessen. Die während der Versuche produzierten Knüppel und die Kokillen sind nach Einsatz metallographisch bewertet worden.

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MOULD COATINGS FOR CONTINUOUSLY CAST BILLET PRODUCTION

British Steel plc

ECSC Agreement No. 7210.CA/828

FINAL TECHNICAL REPORT

1. INTRODUCTION

Surface distortions and bleeds leading to the formation of 'double skins' and surface imperfections frequently occur in oil lubricated billet continuous casting. Such effects are believed to be due to the solidifying steel at the meniscus position rupturing/adhering to the copper mould wall, which is conventionally plated with chromium. The problem can be reduced by avoiding the use of moulds showing meniscus craze cracking or by improving surface contact conditions and lubrication. The latter can be influenced by the type of mould lubricating oil employed or, in the case of larger sections, the mould powder composition.

A complementary approach not previously studied in detail is that of alternative mould coatings to provide improved contact conditions primarily in the steel meniscus region. Previous IRSID(1) work in this area, with relatively thick coatings, has considered the effect of modified heat transfer on surface quality.

The objective of the current project has been a study of the durability and effects on billet quality of different mould coatings, based on steel plant performance. A wide range of coatings has been considered and where appropriate, applied to 140 mm square billet moulds for production trials to produce rerolling billets of different steel grades on the 6-strand billet caster at Rotherham Engineering Steels (RES) Templeborough. Plant measurements have included assessment of mould friction and heat flux, and the billet surface quality has also been assessed. After withdrawal from service, moulds have been metallographically examined to determine coating and mould durability characteristics.

2. PROCESS DETAILS

2.1 Billet Moulds

The standard 140 mm mould used at RES is 800 mm long with a wall thickness of 12.5 mm, and complies with the machine radius of 8 m. When a single taper is applied this is normally 0.9%/metre. Typical casting times in the region of 70 min are required to discharge a 120 t heat. Standard mould tubes are made of phosphorised sulphur-free copper, DIN 1787, of 99.9% Cu, 0.015-0.050% P, with a hardness of 70-90 HB. Hard chromium plating is applied to a depth of up to 0.1 mm.

Moulds of this type have been included in the study for reference purposes though it has not been practicable to employ reference moulds and trial moulds simultaneously.

Dual taper moulds have also been used for a number of trials, in principle providing more intimate strand shell/mould contact, reducing breakouts and minimising depressions which are often associated with billet cracking, particularly on boron grades. The mould design chosen had a top taper of 2.5%/meter for the initial 300 mm and a taper of 1.0%/metre over the remaining 500 mm. The mould copper composition and the chromium plating were the same as for the standard chromium plated moulds described above. However, a number of moulds to this design were produced in high temperature, deformation-resistant CuCrZr (0.65% Cr, 0.10% Zr) appropriate to trials of coatings deposited at temperatures approaching 500°C (Appendix 1).

The trial moulds for individual coating assessment were located on strand 6 of the caster.

2.2 Mould Lubrication and Stirring

The plant normally employs oil lubrication (details given in tables of results) and rotational electromagnetic mould stirring is used to enhance both surface and internal quality.

During the course of the project, sliding gate metal flow control was introduced on the tundish together with a submerged nozzle. This enabled powder to be used for mould lubrication for some of the trials, with stirring intensity also greatly reduced. Some of the billets produced in trial moulds were cast with powder lubrication, and the surface quality of these billets was compared with those cast using oil lubrication.

2.3 Mould Oscillation

For most of the duration of the project the mould stroke length was constant at 12.5 mm. Upgrading of the caster during the project to produce 180 mm billets enabled this condition to be relaxed, and a stroke length of 8.5 mm was used for some trials.

The standard cycle rate (with 12.5 mm stroke) is 80 cpm. Trials with 8.5 mm stroke also had an increased cycle rate, frequencies of 95 and 125 cpm being applied.

2.4 Steel Grades

The grades of steel cast during these trials comprised a range of free-cutting and fine-grained steel compositions, with low carbon free-cutting and medium carbon fine grained types predominating.

3. TRIAL DATA

3.1 Casting Conditions

Details such as average casting speed, mould water flow and inlet-outlet water temperature differentials (ΔT°C) were obtained from computer records for each cast, and summarised for each of the main steel grades produced.

3.2 Mould Friction

Mould oscillation monitoring has been pursued on the billet casting plant to provide information on the mechanical performance of the oscillation mechanism for the early detection of any instabilities and if possible identify changes in friction with respect to mould condition, steel type etc.

Mould condition monitoring was undertaken with the use of Bruel and Kjaer equipment. With this, Type 8315 accelerometers are mounted close to the meniscus level on all six strands. Signals from each accelerometer are scanned by a Type 2514 multiplexer, giving a monitoring period of 16 s for each strand. The signal from the multiplexer is split into two parts which pass through filters in two Type 2505 monitors. One unit monitors the mould oscillation at the lower filtered frequencies of up to 25 Hz. The other monitors a filtered signal between the higher frequencies of 800 and 1100 Hz. From past trials this high frequency region was thought to be sensitive to friction.

In addition to this equipment, a portable B&K Type 7616 analyser was used. This is capable of monitoring the energy levels over a full range of frequencies between 0 and 20 kHz. It was used to analyse:-

(a) The lower filtered frequency spectrum up to 25 Hz, relating to oscillation.

(b) The higher filtered frequency spectrum between 800 and 1100 Hz.

(c) The full frequency spectrum from 0 to 20 kHz which is obtained as a raw unamplified signal from the Type 2514 multiplexer.

The spectra are temporarily stored on the 7616 analyser and then unloaded to the installed B&K software for permanent storage and further analysis. For the purposes of the project, friction was assessed in terms of the high frequency filtered spectrum between 800 and 1100 Hz, though it is evident from related trials that this spectrum is not uniquely a function of mould friction. Differences in the oil lubricant were employed. For medium carbon fine grained (Al treated) steels and boron treated steels a 5% IL2544 synthetic addition to Essotherm 500 mineral oil was used. For the remainder, the IL2544 addition was raised to 30%. The 5% synthetic addition corresponds to a 0.15% ester level and the 30% addition to an ester level of 3.0%.

3.3 Heat Transfer Characteristics

Efforts were made to define the heat transfer characteristics in the meniscus region of the mould in order to identify possible changes associated with coating type, using a heat flux sensor installed in the trial moulds.

The heat flux was measured using a factory calibrated sensor initially developed by Electronite UK Ltd and subsequently supplied by Boiler Management Ltd.. The sensor comprises a single copper block 13 mm long × 4 mm wide × 5 mm deep, drilled on the 4 mm × 5 mm face to accept two Inconel sheathed NiCr/NiAl thermocouples, cemented into place.

The moulds were machined to accept the sensor which was located centrally on the water cooled face of the inner mould radius, 154 mm from the mould top. As a result the thermocouples were located at 9 and 12 mm from the solidifying metal surface position. Following a modification to the design, these positions were subsequently revised to 8 and 11 mm from the hot face.

The thermocouples from the sensor passed through the water jacket and out through pressure entry glands located on the mould assembly, water-outlet manifold. A mV output corresponding to the heat flux between the thermocouples is transmitted from the sensor to a chart recorder via compensation cables. The temperature indicated by the thermocouple in closest proximity to the steel is also recorded.

During the course of the project it became evident that the sensor was insufficiently robust, with failure of the thermocouple leads frequently taking place at an early stage, resulting in very limited heat flux data for many of the trial moulds. Modifications involving reinforcement of the thermocouple sheaths eventually resolved the difficulties.

3.4 Mould Dimension Checks

A mould profile monitoring instrument, developed by British Steel, was used to check mould internal dimensions before use and at frequent intervals during the life of the mould. This instrument accurately measures the internal profile of the tubular mould, working on the principle of deflection of precision transducers which measure the dimensions between both the curved and side faces along the mould.

The mid-face, longitudinal profiles of selected moulds are presented in graphical form, over a range of service levels. Each line represents the separation distance between either curved mould faces or straight mould faces and are thus the sums of the deviations from the mould axis of both faces, as distinct from the specific contours of an individual surface. As the trace could not be relocated at precisely the same traverse position at each repeated measurement the displacements of the various traces cannot necessarily be referenced to a given position with respect to the initial measured profile.

3.5 Billet Surface Quality

All billets were subjected to scale removal by shot blasting to facilitate surface defect detection. Surface finish was assessed and graded against a standard chart which depicts different reciprocation mark severity levels (see Fig. 1). Although it is recognised that this is a fairly basic assessment technique and gives an average index of surface quality, it has been successfully used for some years to identify differences due to e.g. carbon content and lubrication problems.

Surface quality was reported with respect to steel grade.

4. PERFORMANCE ASSESSMENTS

4.1 Standard Chromium Plating

Reference trials were carried out on moulds with the standard coating, of electroplated chromium. Three single and one dual taper Cr plated moulds were assessed. Single taper mould service lives were in the range 100 to 160 with the dual taper mould held in service for 153 heats.

Casting conditions are summarised in Tables 1, 2, 3 and 4.

4.1.1 Mould Friction

Comparison of the available mould friction results (Tables 3-4) for the chromium plated moulds indicates that the dual taper mould gave consistently lower values than found with the single taper mould. This is consistent with an improved match of mould profile with progressive billet dimensional changes.

With both mould types, casts produced using powder lubrication showed reduced friction.

4.1.2 Heat Transfer Characteristics

The lowest mould water temperature differences (ΔT) were generally obtained in the low carbon categories, including the low carbon free-cutting steel grades, which is consistent with an increased shrinkage on solidification. A comparison of powder casting with oil lubrication, allowing for steel grade, showed, as expected, reduced ΔT values with powder casting. Trends between the single tapered and dual tapered chromium plated moulds were not self consistent.

4.1.3 Mould Dimensional Checks

The longitudinal mould dimensional profiles showed considerable stability for both the conventional and dual tapered moulds. Examples of the traces taken from these moulds at different stages of their lives are given in Figs. 2 and 3. (Note that the mould interior is to the left side of each of the traces).

The service life of the dual tapered mould was extended to 153 heats at which point the mould had to be withdrawn from service owing to the development of meniscus zone cracking. The steeper meniscus taper was nevertheless preserved throughout the service life. Moulds would normally be withdrawn from service at 100-120 lives to minimise surface quality problems.

4.1.4 Mould Metallography

Longitudinal sections were cut from the outer radius of each of the chromium plated moulds and examined metallographically. An inherent characteristic of Cr plating is the presence of microcracks associated with the columnar deposition structure. In the case of the single tapered moulds, these cracks propagated into the parent copper, in one case (18196, Table 1, Fig. 4) to a depth of up to 0.6 mm, and in another (TB2066, Table 2) to a depth of 5 mm, but were restricted to a region approximately 100-140 mm from the top of the mould (0-40 mm below the metal meniscus position) corresponding to the region of greatest thermal/mechanical stressing.

Otherwise, there was no cracking of the parent copper, though at the mould exit severe disruption and loss of the plating were apparent, attributable to dummy-bar/strand impingement.

With the most extensive cracks, under metallographic examination, traces of a brass coloured phase (Fig. 5) were found on the exposed crack faces, with oxidation developed along the full crack length. Electron probe microanalysis showed sulphur as well as zinc to be present. While the cracking was obviously associated with the formation of an embrittling brass phase, the high concentration of sulphur found within the cracks suggests that deterioration had been compounded by formation of copper sulphides.

High purity copper is particularly prone to sulphur attack especially in the presence of hydrocarbons(2,3). It is therefore considered significant that, together with the use of oil lubricant, a significant proportion of high sulphur free-cutting steels was produced during the campaign life (Table 2). The source of zinc was uncertain but traces found in the oil suggest this as a primary source. Zinc contamination in the steel used for start up mould packing is a further possibility.

Despite the low friction values, in the case of the dual taper mould, (and with other contemporary Cr plated moulds) mould internal cracking also developed at the meniscus/submeniscus region. Nevertheless there appeared to be a lower incidence of billet bleed type defects, particularly evident with the low carbon free-cutting steels.

4.1.5 Billet Surface Quality

The results of billet surface quality assessment are included in Tables 1-4. With the exception of the boron casts, surface quality was generally rated lowest in low carbon casts, especially the low carbon free-cutting steels. The effect of carbon on surface quality is well known, a consequence of increased shrinkage of the billet shell. Surface quality was adversely affected by the continuation of mould service after the onset of craze cracking.

4.2 Chromium on Electroless Nickel

Recognising the problems of crack propagation from the chromium layer into the copper, a possible remedial approach is the introduction of an electroless nickel substrate.

Electroless nickel is lamellar and free from microcracks, and can therefore be expected to inhibit propagation of cracks from the chromium layer into the copper. On this basis, a mould was coated with electroless nickel, giving an excellent surface finish and good uniformity and subsequently overplated with a normal hard chromium coating. The quality of the plating was however unacceptable, and this option was not pursued further. Electroless nickel was used as a substrate for several of the other trial coatings used in this work. Process details are given in Section 4.8.1.

4.3 'Crack-Free' Chromium on Electroless Nickel

An alternative approach to elimination of cracking of the coating is to ensure that no microcracks are present initially. Claims were made for a 'crack-free' chromium coating,estimated to contain less than 1 crack per 100 mm length, a major improvement over the standard chromium plating, in which cracks are inevitable due to tensile stresses created during the plating operation. To assess the potential of this claim copper test coupons were coated with a 50 micron thickness of electroless nickel and a further 50 microns of a 'crack-free' chromium overlay applied. Examination revealed that there was in fact very little difference from a normal hard chromium plating. The development of cracking, as with the standard coating is attributed to the pronounced difference between the coefficients of expansion of the underlying copper and the deposited chromium; other than for test coupons, 'crack-free' chromium coating has therefore not been pursued.

4.4 Densification of Chromium Coatings

Test coupons with standard and 'crack-free' chromium coatings were processed with the second stage Monitox densification medium (see Section 4.11) in an attempt to fill the microcracks in the chromium layer. Metallography of these samples indicated that penetration and filling of the fissures was reasonably successful, but that there was no effective bonding with the Cr deposit. No further work of this type was carried out.

4.5 Titanium Nitride Coated Chromium Plated Moulds

4.5.1 Coating Technique

Titanium nitride has been successfully used to produce a very hard (3000 HV), thin coating on wear-prone steel products such as machine tools and its potential in continuous casting cannot be ignored.

For assessment purposes a standard (single taper) Cr plated mould tube was coated with titanium nitride using a physical vapour deposition technique (PVD). This is a process for the application of relatively thin metal or ceramic coatings to components placed within a vacuum chamber. PVD employs a low pressure gas, ionised by a high dc voltage to produce a plasma glow discharge. Any metal atoms introduced into the glow discharge become ionised and are attracted towards the negative electrode. Accordingly, the items to be coated are made the negative electrode, with the chamber itself being earthed.

Normally, the low pressure gas is argon and the ionisation can be used to 'sputter-clean' components before coating. The argon ions are attracted to the components and surface contaminants and oxide are removed, atom by atom, by momentum transfer. After cleaning, the deposit metal can be introduced (usually by evaporation) into the argon glow discharge and coating begins.

To produce ceramics like TiN, a process of 'reactive physical vapour deposition' is used. Nitrogen is added to the argon and, when titanium is evaporated into the chamber, the ionisation energy promotes the reaction to TiN. In the case of the continuous casting moulds, the process used was 'arc-evaporative' PVD. The titanium is evaporated from a 76 mm diameter block by striking an electric arc to its surface.

A typical process time is 1 h, depositing around 2 to 3 µm of TiN (imparting a golden colouration to deposited surfaces). The mould tube for the initial trial was manipulated within the chamber in such a way as to encourage deposition on the internal surface. (Exterior surface deposition is the normal application of this technique). Deposition temperature can be varied between 200°C and 500°C (depending on ionisation energy). The initial trial mould tube was coated at 400-450°C, producing a coating of approximately 5 µm.

Hardness measurements with this mould and thermal softening experiments (Appendix 1) made it clear that the coating treatment of 400-450°C had reduced the hardness from approximately 100 to 51-63 HB, promoting subsequent excessive distortion in the region of the steel meniscus position.

A repeat of the TiN deposition was carried out, applied at a temperature insufficient to soften the copper significantly. The temperature range was restricted to 250-300°C with the mould held at 300°C for $1\frac{1}{2}$ h, producing a thinner final coating, 3 µm compared with a nominal 5 µm for the initial trial.

4.5.2 Casting Conditions

The casting conditions, along with the mould friction and surface quality assessments, are listed in Tables 5 and 6 for the two TiN coated trial moulds.

4.5.3 Mould Friction

The results for mould friction in TiN coated moulds, included in Tables 5 and 6,demonstrate little overall difference in comparison with the standard moulds (Table 3).

4.5.4 Heat Transfer Characteristics

Heat transfer characteristics in the TiN coated mould were monitored for comparison with data obtained for standard Cr plated single taper moulds. The results(4,5) did not show consistent trends between coating types. A comparison between mould water inlet/outlet temperature difference (ΔT) indicated that for low carbon free-cutting steels lower values of this parameter were obtained for the TiN coated mould. (Unfortunately no carbon free-cutting steels were monitored during the life of the heat flux probe in the TiN coated mould).

4.5.5 Mould Dimensional Checks

Monitoring of the mould dimensions showed that the first TiN coated mould, coated at the higher temperature, suffered severe distortion at a relatively early stage, illustrated in Fig. 6. As a result, to avoid a possible breakout problem it was withdrawn from service after 66 lives, although no loss of billet quality had been seen at this stage. The second such mould, TiN coated at a reduced deposition temperature was used for 114 lives before being withdrawn from service owing to a breakout. Subsequent profiling of this mould showed that little distortion had taken place (Fig. 7).

4.5.6 Mould Metallography

Examination of the first TiN coated mould showed that cracking was again evident at the meniscus/submeniscus region, though the affected depth of the parent copper was markedly reduced (30 µm, compared to 600-5000 µm in standard chromium plated moulds). Initiation of the cracks could be seen to coincide with fissures in the chromium under-layer. Although the TiN layer, 2-3 µm thick at this position, remained substantially intact, the mould cracks invariably passed through the deposit to the surface. The extent to which submeniscus crack development was inhibited by either the presence of the TiN layer or the softening of the underlying copper is difficult to assess in view of the limited usage of the TiN coated mould, (66 heats compared with 100-160 for the reference moulds).

The second TiN coated mould likewise showed that the extent of severe submeniscus zone cracking was considerably less than for the reference moulds (Fig. 8). The cracks were again oxidised, with some evidence of sulphur contamination, but no brass formation was detected. It seems likely that the coating is initially able to bridge incipient cracks or fissures in the chromium plating, inhibiting any sulphur transfer at an early stage. As thermally induced strain occurs in the copper, the effect will, however, be to open up cracks in the Cr layer, which will not be resisted by the TiN, and penetration into the copper follows.

It would therefore appear that TiN has a beneficial effect on mould performance by delaying the onset of craze cracking. The worst crack encountered in the second TiN coated trial mould does not exceed 30 µm: this compares favourably with the cracks found in the reference moulds, particularly in the second example where severe cracking developed.

4.5.7 Billet Surface Quality

Despite the improved integrity of mould surface, the billet surface quality ratings were not obviously superior to those recorded for billet from the Cr plated moulds (Tables 1-6).

4.6 CrTiN Coated Chromium Plated Moulds

4.6.1 Coating Technique

A variant on TiN is a coating of CrTiN, a mixed nitride of chromium and titanium. This coating is applied by a physical vapour deposition technique similar to that used for TiN.

It is claimed that CrN (giving a silvering effect) produced with a Cr target is equally hard, but has a denser structure. Mixing of metal nitrides changes the deposition kinetics and promotes the growth of ultra hard, glassy structures of obvious relevance to the present study.

Accordingly, a single taper mould, pre-plated with standard chromium, was provided for overlaying with a CrTiN coating using two Cr evaporators near each end of the mould together with a more remote Ti evaporator. As a result, the coating structure was strongly biased towards CrN, with a uniform deposit restricted to the top and bottom 200 mm of the mould. The temperature of the mould was maintained at a maximum of 300°C during deposition to avoid consequential distortion in service.

A small copper plate test coupon (150 × 150 mm) was included in the coating assembly with this mould enabling a check to be made on initial thickness and quality of coating. The deposit overlying the Cr was approximately 4 µm and appeared to bridge inherent microfissures in the chromium layer.

4.6.2 Casting Conditions

The casting conditions, along with mould friction measurements and assessments of billet surface quality, are listed in Table 7. Unfortunately, use of this mould was restricted to only 66 lives owing to a number of production problems resulting in metal skulls in the trial mould. On removal of the last of these the mould was damaged precluding further use.

4.6.3 Mould Friction

The mould friction results obtained during casting with the single taper CrTiN coated mould, are listed in Table 7, and were broadly comparable to those from the dual taper Cr coated mould (Table 4).

4.6.4 Mould Heat Transfer

Heat flux data for the CrTiN mould(5) were restricted to a total of 16 casts and, comparing results for different steel grades, appeared to be roughly similar to values recorded with the TiN coated mould.

4.6.5 Mould Dimensional Checks

Profiling of the CrTiN coated mould showed slight distortion (Fig. 9) particularly on the straight face. Unfortunately the mould was gouged at the bottom end after only 28 lives as a result of removal of a skull from the mould caused by a metal eruption. Clearly, the modified coating was of insufficient thickness to resist gross mechanical damage.

4.6.6 Mould Metallography

Examination of the CrTiN coated mould (Fig. 10) showed no evidence of the cracking exhibited in the TiN coated moulds . This is probably favoured by the limited service (66 heats) attained by this mould as a result of premature withdrawal from service, though also may be indicative of an improved protective benefit from this nitride coating. Crack formation clearly does not begin as soon as a mould enters service, but requires a considerable induction period. The CrTiN overlay, with a thickness that reduced with distance down the mould (as a consequence of the deposition process), was still intact.

4.6.7 Billet Surface Quality

The overall assessment of the product from the mould with the CrTiN facing was limited by premature withdrawal of the mould from service, but the indications are that the quality is of the same order as for billet produced with the best of the standard single tapered chromium plated moulds. In every case, powder casting produced oscillation marks of a more uniform nature with a complete absence of the bleeds and laps which are a feature of oil lubrication.

4.7 Zirconium Nitride on Electroless Nickel

4.7.1 Coating Technique

A CuCrZr single tapered mould (with the standard chromium plating omitted and replaced by an electroless nickel deposit) was used for this coating, produced by Advanced Surface Engineering Technologies Ltd. (ASET) of Newcastle-Upon-Tyne. Thermal softening results for this heat resisting alloy are appended: clearly treatments in excess of 350°C are acceptable. Zirconium nitride is deposited at approximately 350°C using the PVD process (essentially as described for TiN coating). ZrN has a somewhat lower hardness than the more frequently publicised and previously evaluated TiN deposit, but ZrO_2, which subsequently forms in service as the operating temperature is increased, is claimed to have excellent low friction and anti-stick properties. For this mould, an approximately 10 µm ZrN layer was applied onto the primary layer of electroless nickel, with the PVD deposition temperature being sufficient to precipitation harden the nickel.

The mould required re-nitriding as there were some areas of poor adhesion of the initially deposited ZrN. This resulted in a rougher appearance of the coating at the mould ends compared with the central region. As with TiN, the coating was of a light gilded appearance.

4.7.2 Casting Conditions

The casting conditions, and the assessments of billet surface quality are listed in Table 8. This mould was used for a total of 116 casts before being withdrawn from service, the life span again being comparable to that required from a standard chromium plated mould.

4.7.3 Mould Friction

Damage to the accelerometers precluded the acquisition of adequate mould friction data from this mould.

4.7.4 Mould Heat Transfer

Mould water temperature difference for medium carbon steels were generally similar to those for the Cr plated moulds. A reduced difference for LCFCS was again evident with this coating. Powder lubrication (medium carbon steels) also reduced the ΔT values.

4.7.5 Mould Dimensional Checks

Profiling of the ZrN coated mould after use showed little distortion except at the mould exit, largely attributable to dummy bar damage.

4.7.6 Mould Metallography

Examination of the mould revealed that the ZrN overlay had been effectively lost from the nickel substrate below a position corresponding to that of the meniscus. Cracking of the nickel in the submeniscus region was evident but there was no penetration into the underlying copper. Zinc penetration of the nickel with subsequent brass formation at the nickel/copper interface was present. In the absence of craze cracking, as would be expected, oxidation of the copper was minimal.

4.7.7 Billet Surface Quality

The surface quality of billets produced in the ZrN coated mould was generally satisfactory and was comparable to that for billet produced from standard Cr plated moulds. Surface quality was maintained throughout the mould life.

4.8 Nickel/Nickel-PTFE

4.8.1 Coating Technique

CuCrZr dual tapered moulds supplied without the standard chromium plating were used for this coating. Two trials with individual moulds on one strand of the caster were followed by a third stage in which three Ni/Ni-PTFE coated moulds were employed concurrently on separate strands.

The moulds were coated with a primary deposit of electroless nickel (0.050 mm) and overlaid with Ni-PTFE (0.015 mm) by Armourcote Ltd. (Leeds). The plating process for the primary deposit employs the autocatalytic reduction of nickel salts by hypophosphite ions in an aqueous bath and produces a primary deposit containing 4-12% phosphorus. A similar technique is employed for the secondary Ni-PTFE coating, the PTFE being deposited in conjunction with the nickel and present to a volume of 25% as sub-micron particles. The primary plating acts as a reinforcement to this deposit and both are subjected to a heat treatment process of 300°C for 3 h to produce an increase in the coating hardness and also to 'sinter the PTFE present.

4.8.2 Casting Conditions

On introducing the Ni/Ni-PTFE mould into service, fume was emitted from the mould for the initial 10-15 minutes of casting. Examination of the mould surface after this first cast did not reveal any coating damage and after consultation with the coating supplier the fume evolution was attributed to the burning off of excess PTFE. This behaviour occurs each time a new PTFE coating is placed in service.

Details such as average casting speed, mould friction measurements and assessments of billet surface quality are summarised in Tables 9 and 10 for the two individually used Ni/Ni-PTFE moulds. Mould water flows are higher than for earlier trials, a consequence of the increased pump capability following the introduction of 180 mm square casting at the plant. Commissioning of the associated tundish sliding gate system made it possible to produce several casts in the trial moulds employing casting powder rather than the conventional mould lubricating oil. These casts are summarised separately within the tables.

Only 94 casts were produced with the first of these moulds before it was withdrawn from service after a succession of breakouts. The second mould produced 125 casts, a service life equivalent to the standard for Cr plated moulds, and was withdrawn from service at that stage. The apparent success of these two moulds led to a further trial in which three moulds coated with Ni/Ni-PTFE were used concurrently: the casting data for these three moulds are given in Tables 11-13. Campaigns of 140-159 heats were achieved producing billets with good surface quality throughout. The moulds were withdrawn from service owing to recurrent breakouts and the development of billet rhomboidity, both induced by bottom end damage.

4.8.3 Mould Friction

Results from the dual taper Ni/Ni-PTFE coated mould (Table 9) indicated that the friction levels were lower than for Cr plated moulds (Tables 3 and 4) and also other coatings employed in this work (Tables 5 and 6). Friction results were not obtained from the other Ni/Ni-PTFE moulds owing to damage to the accelerometers.

4.8.4 Mould Heat Transfer

The heat flux probe installed in the first Ni/Ni-PTFE mould failed early in the campaign, and results were obtained from only 18 casts.

All steel grades gave higher heat flux values(6) than did previous standard chromium plated moulds(4,5). The mould heat extraction results measured in terms of the rise in mould water temperature (ΔT) are similar to those from previous moulds for a given steel grade. An increased heat flux could be explained by a reduction in localised shell adherence and detachment (reduced friction) and consequent reduction in billet surface irregularities compared to those observed with previous coatings, allowing more consistent steel shell - mould contact, sufficient to outweigh any thermal barrier effects introduced by the Ni/Ni-PTFE.

4.8.5 Mould Dimensional Checks

Longitudinal mould dimensional profiles obtained from the dual taper Ni/Ni-PTFE mould are shown in Fig. 11. Despite the use of the heat resistant CuCrZr alloy mould, the mould measurements after the coating deposition and subsequent heat treatment at 300°C showed some flattening of the bottom taper after the initial casts (not shown in Fig. 11). After 85 lives the mould exhibited considerable distortion and loss of taper and, not surprisingly, gave breakout problems. It was not possible to measure the final mould profile owing to the skull formed in the mould following the last breakout (94 lives) immediately prior to withdrawal from service.

Profiling of the single taper Ni/Ni-PTFE individual mould showed only limited distortion except at the exit end where dummy bar damage had taken place. Profiles obtained from the three-mould trial showed very limited distortion over the meniscus zone.

4.8.6 Mould Metallography

Each of the Ni/Ni-PTFE moulds was sectioned longitudinally and transversely to enable visual and metallographic examination to be made of the coated surface after withdrawal from service. With the dual taper mould, severe erosion of the coating and exposure of the parent copper was apparent at the mould exit region (600-800 mm from mould entry) and, to a lesser extent, in a region extending over 150 mm immediately above this. Visual examination of the meniscus region showed none of the obvious craze cracking associated with the standard chromium plating reference moulds previously examined. Subsequent metallography did however reveal a degree of fissuring in the coating and subsequent minor cracking and oxidation of the copper substrate (Fig. 12). These cracks were, as previously, associated with zinc/sulphur penetration and the formation of embrittling brass phases as seen in the chromium plated moulds. The PTFE impregnated nickel overlay (originally 0.015 mm) in the meniscus region also showed localised signs of erosion; the primary nickel had, however, otherwise remained intact. The degree of deterioration was clearly minor and not of the order of that found previously with chromium plating. No explanation of the unexpected mould distortion was apparent from the metallographic examination.

Examination of the single taper individual trial Ni/Ni-PTFE mould showed that the coating had been largely retained throughout the mould length with the exception of a band approximately 20 mm wide (following the curved profile induced by EMS) in the submeniscus region (approx. 140 mm from mould entry) and also in the vicinity of the mould exit where abrasion had occurred. Within the band the Ni-PTFE was eroded but the underlying nickel remained, although reduced in thickness.

Cracking of the Ni/Ni-PTFE layer was found, predominantly in the submeniscus band and a thin layer of α/β brass was evident over parts of the copper/nickel interface. The cracks were restricted to the coating and had not penetrated the parent copper.

It is evident that while the coating does not prevent reactions at the copper interface, any crazing of the underlying copper is delayed well beyond the 80 lives typical for its onset in standard Cr plated moulds and significantly extended service life can be anticipated. This was shown to be the case with the three Ni/Ni-PTFE coated moulds used concurrently, where campaigns up to 159 lives were achieved.

4.8.7 Billet Surface Quality

Assessment of billets from the individual Ni/Ni-PTFE moulds showed that the average surface quality was generally good, and in a majority of cases the product was superior to the billet produced from the other five strands using the standard chromium plated moulds. Subjectively this improvement was most pronounced in the early part of the mould usage and the quality level was generally considered better than that arising from other experimental coatings. The only instance of poor surface quality found was on a brief sequence of LCFCS produced with the dual taper mould where heavy reciprocation marks were observed (Grade 2/3); this was tentatively ascribed to an oil distribution problem. Billet quality from the three Ni/Ni-PTFE moulds running concurrently was satisfactory, notably with LCFCS casts.

4.9 Armourcote 5100

4.9.1 Coating Technique

This coating is a dry film lubrication deposit based on molybdenum disulphide, graphite and fluorocarbons bonded directly to the substrate and is claimed to offer excellent friction reduction, good temperature tolerance, and resistance to corrosion. Preliminary examination of test coupons revealed satisfactory adhesion and coating uniformity, and led to mould trials with the coating.

Two moulds of dual and single tapered CuCrZr, without the standard chromium plating, were coated with a primary deposit of electroless nickel (0.050 mm). These coatings were overlaid with the proprietary deposit to a depth of approximately 0.1 mm. A baking treatment was carried out using a temperature of 150/200°C for 2 hours.

4.9.2 Casting Conditions

Details such as average casting speed, mould friction measurements and assessments of billet surface quality are summarised in Tables 14-15 for the main steel grades produced from the moulds. As previously, each trial mould was located in strand 6 of the Templeborough billet caster, with oil lubrication replaced by powder and slide gate metal flow control for selected grades.

The first (dual taper) molybdenum disulphide-type coated mould was used for a total of 54 lives but was withdrawn from service at that point owing to an increasing problem with heavy oscillation marks on the billets produced. The second (single tapered) molybdenum disulphide mould produced only 10 casts before having to be withdrawn following 4 successive breakouts. For both of these moulds a stroke length of 12.5 mm and a frequency of 80 cpm were used.

4.9.3 Mould Friction

Mould friction results obtained from the mould coated with Armourcote 5100 were comparable with the results obtained from most of the other applied coatings used in this work.

4.9.4 Mould Heat Transfer

No results for mould heat transfer were obtained from the Armourcote 5100 moulds owing to failure of the connections to the sensor.

4.9.5 Mould Dimensional Checks

Traces obtained from profiling of the Armourcote 5100 coated moulds are shown in Figs. 13-14. The dual tapered mould showed good stability around the meniscus but loss of taper was indicated at the mould exit on the straight faces, attributed principally to dummy bar wear. The single tapered mould treated with the same coating and baked at a similar temperature, around 150/200°C, showed localised distortion at the meniscus level on the radiused faces and evidence of dummy bar impact damage, deforming the mould exit region. Meniscus distortion cannot readily be explained as the mould was manufactured from CuCrZr alloy which is resistant to softening at temperatures up to 400°C. Breakout problems at the start of the mould campaign were unexplained, but were presumably associated with these distortions.

4.9.6 Mould Metallography

The moulds were sectioned longitudinally and transversely to enable visual and metallographic examination of the coated surfaces to be made after withdrawal from service. Severe erosion of the coating and exposure of the underlying copper was apparent at the mould exit region in both cases.

Typical micrographs taken from the top ends of the moulds (above the meniscus) are presented in Fig. 15 and reveal good uniformity of coating, although there was a slight difference in deposit thickness between the two moulds.

Samples from the meniscus region from both moulds exhibited a deposit on the working surface (Fig. 15). Microanalysis using a Cameca SX50 Electron Probe Microanalyser revealed high levels of zinc, manganese and sulphur with an absence of molybdenum indicating that, even in the case of the single taper mould (withdrawn after only 10 lives), the coating had failed to withstand the casting process. Although there was little evidence of the coating, a small amount of fluorine was detected on the mould surface.

Oxidation and cracking in the case of the dual taper mould (54 lives) was slight and absent in the single taper mould.

Penetration of zinc through the fissured nickel substrate occurred along the nickel/copper interface in the dual taper mould . Examination of samples from the mid-height region of the moulds showed no deterioration in the nickel plating but even at this location, no evidence of retention of molybdenum disulphide/graphite coating.

4.9.7 Billet Surface Quality

Assessment of billets cast through the Armourcote 5100 coated moulds showed that surface quality was not obviously improved over that found with billets cast in conventional moulds. The quality tended to deteriorate as the campaigns progressed, particularly for low carbon free-cutting steels, (ultimately leading to the withdrawal of the dual taper mould from service).

4.10 Armourcote CFX

4.10.1 Coating Technique

This coating was originally described as a ceramic, but subsequent evaluation showed it to be based on metallic aluminium, incorporating fluorocarbons. Coupon tests indicated that it could be considered for plant trials.

A CuCrZr dual tapered mould was plated with a primary deposit of electroless nickel (0.050 mm) and then sprayed with the proprietary coating to a depth of 0.025 mm, followed by a baking treatment (400°C for 15 minutes). The work was again carried out by Armourcote Ltd. (Leeds).

4.10.2 Casting Conditions

Details such as average casting speed, mould friction measurements and assessments of billet surface quality are summarised in Table 16 for the steel grades produced with this mould. As in the case of Armourcote 5100, oil was the normal lubricant, but powder was used for selected grades.

During the trial work with the CFX coated mould, the mould oscillation conditions were varied as described in Section 2.3. For the initial production heats an 8.5 mm stroke was used with an oscillation rate of 125 cpm. With this configuration, three consecutive breakouts occurred. For the next production series, the stroke length was restored to 12. 5 mm with oscillation at 80 cpm. No casting problems were experienced at this setting. A later series employed a stroke length of 8.5 mm and an oscillation rate of 95 cpm. Again no problems were experienced until lives 49 and 50 at which stage two consecutive breakouts caused the mould to be withdrawn from service.

4.10.3 Mould Friction

The mould friction when using the CFX-coated mould, based on the small number of results available, was exceptionally low. The reliability of these data are questionable, however, in view of the subsequent mould inspection (4.10.6).

4.10.4 Mould Heat Transfer

No results for mould heat transfer could be obtained for this mould on account of failure of the connections to the sensors.

4.10.5 Mould Dimensional Checks

The results from the profiling of the CFX mould are shown in Fig. 16. These showed that the profile at the top of the mould was still good after 50 lives, but some wear and distortion had taken place at the mould exit on the straight faces. This could have contributed to the poor breakout performance. It was observed that a tendency to breakouts in dual tapered moulds increased with a reduction of stroke length (from 12.5 mm to 8.5 mm), indicative of a need to optimise the mould design for the shorter stroke length.

4.10.6 Mould Metallography

The trial mould was sectioned longitudinally and transversely to enable visual and metallographic examination of the coated surfaces to be made after withdrawal from service. Severe erosion of the coating and exposure of the parent copper was apparent at the mould exit region (600-800 mm from mould entry).

Visual examination of the meniscus region showed no obvious craze cracking.

Metallography revealed a thin grey deposit on the working face of the mould (see Fig. 17) which was at first thought to be the result of burnishing of the CFX coating. Microanalysis of these deposits showed high levels of zinc, manganese and sulphur, almost certainly arising from steel grades produced, but there was no obvious evidence of the coating material present. Only traces of aluminium and fluorine were found at the exposed surface of the mould. These could have originated from the coating, although other sources are also possible. Clearly the CFX coating had failed to withstand the aggressive environment encountered in the continuous casting process, raising doubt as to the validity of the low frictional loads indicated. Some disruption of the nickel plate in the meniscus/sub-meniscus region had occurred with minor oxidation and cracking of the the parent copper. The formation of brass phases, as a result of zinc contamination and penetration through the cracked nickel, was in evidence at the nickel/copper interface. Examination of samples taken from approximately mould mid-length revealed no trace of the CFX coating, but the underlying nickel plating was generally intact.

4.10.7 Billet Surface Quality

The surface quality of billets cast in the CFX-coated mould was found to be comparable with billets cast in conventional moulds,despite the apparent rapid loss of the coating.

4.11 Monitox

Monitox is a proprietary, oxide-based coating manufactured by Monitox Coatings, Wallsend, UK. The coating process involves the deposition of Cr_2O_3-Al_2O_3-SiO_2 slurry onto a grit blasted substrate, followed by a series of baking and liquid impregnation treatments.

Two attempts were made to coat CuCrZr moulds with this material, using electroless nickel as a substrate. For the first of these the normal thickness of electroless nickel was used, while for the second, this thickness was increased to 150 µm. In each case, however, the coating spalled away from the mould during the densification process. It is therefore concluded that this process is unlikely to be suitable for coating small section billet moulds.

4.12 Chromium Carbide Dispersion in Electroless Nickel/Cobalt

This is a deposit which can be applied to a depth of 0.075 mm. The coating consists of a dispersion of chromium carbide particles in a nickel/cobalt matrix producing a hard, wear resistant coating with good adhesion and uniformity of deposit. A mould was supplied for coating, but no progress was made as the company involved ceased trading.

5. DISCUSSION

5.1 Previous Work and General Considerations

Mould coating has been the subject of interest for several years in relation both to increasing mould life and to improving strand surface quality. Chromium plating is widely applied to billet casting moulds to reduce surface deterioration and correspondingly avert the risk of copper pick-up by the steel, thus avoiding hot workability problems that might otherwise arise. Work on slab and bloom moulds(7,8) has shown the potential of Ni plating, particularly when strengthened by small iron or phosphorus additions.

Alumina dispersions in nickel overlying Ni-Fe have also been described as a means of reducing mould wear(9), though to avoid thermally induced cracks the copper was left uncoated in the meniscus region. In a study reported by French workers(10), reduced oscillation mark depth was shown to result from modification of the heat transfer conditions, specifically in the vicinity of the meniscus, achieved by the use of layers of nickel, chromium carbide or stainless steel. With reference to measurements made on slabs, significant melt back was achieved of the initially solidified ingrowing rim ('thumbnail' in longitudinal section) formed at the meniscus periphery on each oscillation cycle.

With billet casting, particularly of sections up to 140 mm, oil lubrication is frequently required and the surface quality is generally less uniform than that seen in powder lubricated casts of larger section size. Mould electromagnetic stirring, commonly applied at small sections also complicates and disturbs the uniformity of the initial meniscus soldification especially with rectangular sections. The effectiveness of coatings in this context does not appear to have been studied extensively, although since the commencement of the present work additional pertinent information has been reported.

A Polish study(11) described in some detail the surface aluminising of 140 mm copper moulds, albeit using powder lubrication. Good results were claimed, though only 600 t were cast. Unfortunately treatment temperatures of 800°C were required, which would have produced softening of the copper in the moulds used in the present work and rapid distortion of the moulds in service.

A laboratory study briefly described by Concast AG(12) provides an interesting complement to the present development trials. Eight potential mould coatings were deposited onto copper plates, representing mould surfaces, and charges of molten steel were brought into static contact. Unprotected copper and coatings of Cr, Ni/SiC and Ni/PTFE gave smooth surfaces to the cast steel; the more complex and alloyed coatings gave porous surfaces. Frictional comparisons were achieved by drawing a heated (950°C) steel block over the coated plates (250°C) and measuring the loads required to induce sliding. For the surfaces noted above, frictional coefficients of 0.48, 0.33, 0.43 and 0.25 respectively were recorded. Other coatings gave results in the range 0.35 to 0.43.

As distinct from a generalised view of mould wear, in the present study three specific aspects of mould service life were identified for scrutiny:

(a) meniscus zone cracking

(b) mould profile distortion, and

(c) bottom end wear

(The practical constraints of proneness to breakouts or rhomboidity of billet section also limited the life achieved under plant conditions).

Billet quality was defined in a qualitative manner, recognising the general irregularity of surface markings generated with oil lubricated casting. The introduction of powder lubrication, for several of the coatings assessed, resulted in less disruption of the surface. An accompanying reduction in EMS intensity also improved the uniformity of meniscus solidication profile.

A laboratory simulation or coating evaluation test was not incorporated into the project in view of the perceived difficulty of reproducing the interface conditions existing within the casting mould. Correspondingly, an appraisal of the physical conditions applicable to the meniscus periphery has not been attempted. (Various simpler, physical sorting tests were however made on coatings deposited on copper test coupons cut from a rejected mould in order to identify, e.g. friable, weakly bonded coatings prior to any commercial scale trial).

The nature of the strand surfaces produced on oil lubricated billet casting, together with the known sensitivity to lubricant composition (ester content)(13) are indicative of the significance of steel wetting of the mould and the consistency of wetting conditions around the meniscus. Clearly, factors such as steel and mould surface oxidation, lubrication or heat transfer, in addition to the surface properties, micro and macroscopic uniformity of the coating surface, will influence wetting and thus the critical initial stage of meniscus soldification. Billet subsurface structures were therefore examined in an attempt to provide practical evidence of such differences.

Mould friction is of obvious relevance to mould wear: the extent to which friction will relate to surface quality is less certain. Interpretation of results will depend on whether frictional loads are generated in response to possible disruptions of the initially formed solid shell or to mould/shell contact over the bulk of the mould length, (at which stage the detailed surface quality is already established).

5.2 Coating Constraints

A wide range of coatings has been considered for application to billet moulds in the current programme, but the practical possibilities have been restricted by consideration of deposition temperature and mould geometry. The coatings used for plant trials are itemised in Table 17(a). Coatings found unsuitable are identified in Table 17(b). The initial work with a TiN deposit showed that softening of the drawn copper tube moulds could not be accepted, leading to process temperature limitation and the use of higher hot strength CuCrZr materials for much of the project work. As indicated in the Appendix, process temperatures were restricted to approximately 350°C for SF copper and to approximately 525°C for CrZr alloyed copper. In practice this eliminated detonation and plasma techniques, in addition to a range of proprietary powder coating methods, precluding the application of hard facings of oxides and carbides.

The requirement to produce a deposit on the interior of the 140 mm section mould also proved a considerable limitation. Deposits confined to the extremities of either end of a mould or produced non-uniformly from corners to mid-faces were not acceptable.

5.3 Billet Quality

5.3.1 Surface Quality Rating

In addition to coating type, factors of lubricant (oil or powder), steel type and mould taper have to be taken into account in comparing billet surface quality. Casting conditions were generally held constant, though with specific changes introduced to oscillation practice in some cases. Table 18(a) summarises billet quality (0 good - 5 unacceptable) for the two steel types most commonly produced, for each of the moulds employed in the study. For the purposes of comparing results the temperature differences have been normalised with respect to casting speeds and cooling water flow rates in Table 18(b) (Section 5.4).

The ratings of billet produced with the monitored single taper Cr plated moulds are seen to be rather variable, the mean values ranging from 0/1 to 2/3 for medium C steel and 1 to 2/3 for LCFC steels. In terms of standard production ratings, the lower values of 0 or 1 are viewed as unusually low, particularly when derived from moulds with lives extended beyond 100-120, with the attendant development of meniscus cracking and distortion. Ratings of 1-2 (medium carbon) and 2-3 (LCFC) are considered as representative of these grades with standard Cr plated moulds.

The introduction of a dual tapered Cr plated mould again gave unusually good results despite the extension of mould service (153 lives) beyond the normal standard of 120. Comparison with the range of results from the single taper moulds does suggest however that the dual taper confers improved surface ratings. This could be expected if the initially solidified strand shell was inadequately supported at a

0.9%/m taper, but more firmly consolidated by an initial 2.5%/m taper. The possibility of numerous small scale ruptures, with bleeding from an initial shell prone to bulging in the mould would help to explain this difference. Consistent with this, the lower friction recorded (Tables 3 and 4) for the dual taper design is indicative of billets of improved surface uniformity: increased taper would otherwise tend to increase the frictional force.

On the basis of recorded surface quality it is difficult to identify a significant improvement from the use of TiN overlays on Cr plated single taper moulds, despite a reduction in observed frictional forces (to a level below that found with the standard Cr plated dual taper mould). For precautionary reasons each of the two TiN coated moulds was not used for protracted service and showed a reduced level of meniscus zone cracking. Nevertheless the extremely thin TiN layer was insufficient to prevent bottom end abrasion and wear.

Similar comments apply to the CrTiN and ZrN coated moulds, though the better than normal standard for the quality of LCFC steel billets certainly suggests a contribution from retarded development of meniscus-zone cracking.

As sulphur reduces surface tension in liquid steel, free-cutting grades will tend to wet the mould to a greater extent. Consequently modification of the wetting characteristics of the steel in contact with nitrides, and with the underlying Ni following erosion of the ZrN coating, may have some significance.

Inspection of the relevant tables of results indicates that it is difficult to relate systematic differences in heat transfer to coating type. Consistent differences are, however, seen with respect to steel grade or lubricant (i.e. reduced ΔT with LCFCS, or with powder casting). Note that of the nitride overlays, the ZrN coating was substantially lost after 16 lives and therefore cannot be considered as a practical option.

Billets produced from the Ni-PTFE coated moulds showed a high standard of surface quality. With low carbon free-cutting steel there was again a suggestion of advantage of a dual taper mould over single taper.

It should be stressed that the Ni-PTFE individual trial moulds were withdrawn from service as a precautionary measure to minimise the possible risk of breakout problems. Subsequent mould inspection and metallography revealed that deterioration of the underlying copper was minimal, and that in principle the moulds were capable of extended service life, with billet quality maintained. This can be seen to have been justified by the subsequent results of simultaneous trials with three Ni/Ni-PTFE moulds.

In each case, after service, metallographic inspection revealed mould cracking to be negligible. In one instance distortion due to bottom end mechanical damage (inward displacement of one face) was identified with a succession of breakouts, circumstances which required withdrawal of the mould after 160 lives.

While billets cast from the CFX and Armourcote 5100 moulds were rated as of good quality, this would appear likely to reflect advantages of the underlying electroless Ni (Ni-P) deposit, since, as with the ZrN, the overlying coatings were found to have been substantially lost at relatively low mould service lives.

It is interesting to note that the electroless nickel deposits have shown little sign of deterioration other than in the vicinity of the mould exit.

5.3.2 Billet Structure

Metallographic inspection failed to reveal specific grain or dendrite structural features that could be related to surface characteristics. In particular it was not possible to identify the nature of solid shell development with each oscillation cycle, from any of the billets examined and therefore to distinguish whether any changes resulted from the introduction of different billet mould coatings.

There was evidence of differences in subsurface dendritic orientation but this did not appear to change in a systematic manner and was not associated with the periodicity of oscillation. Some examples were found of an evident overlapping surface mark, possibly indicative of the local surface bleed events typical of oil lubrication. A frequent feature in many of the billets inspected was that of a succession of ghost lines below the surface, presumed to indicate the interrupted development of solidification with succeeding oscillation cycles in the initially forming shell. These were often indistinct and tended to be closer to the surface at positions identified with oscillation marks, indicative of retarded solid shell development at these positions (reduced heat loss at indicated oscillation mark depressions). The general lack of any evidence of ingrowing 'thumbnail' shell marks together with the surface profile revealed in longitudinally sectioned samples suggests that a 'bendback' rather than a cusp remelting process occurs. While inspection of the billet oscillation marks revealed a profile indicative of a conventional, non-wetting steel meniscus, observation of meniscus behaviour in the mould during the casting operation revealed that incidents such as non-uniform oil flow over the mould wall could lead to intermittent localised wetting of the mould. Mould wall deposits or damage can give similar effects, contributing to the generally imperfect appearance of the resulting billet. Observations made with coated moulds during casting, particularly with Ni/Ni-PTFE, suggest a much lower incidence of such sporadic wetting.

While the detail of the oscillation marks and initial shell formation with oil lubrication, notably with EMS applied, may differ from that for powder lubricated casts, it is clear from the metallographic studies that the steel solidification process was not materially affected by the coatings applied to the mould in the present study.

5.4 Mould Performance

Distortion occurred in a number of the moulds studied as a result of thermal effects in the region of the metal meniscus position and of abrasion or impact damage at the exit end of the mould.

A characteristic pattern(14) of top end distortion was observed in only a few cases. The mid-face positions bow inwards to accommodate plastic strain due to thermal cycling under conditions of a temperature gradient, reversing the intended taper over the upper part of the mould. A flattening of taper developed with a dual taper mould coated with Ni/Ni-PTFE.

In several of the moulds the extreme bottom end was flared owing to abrasion, attributable primarily to damage by the solid dummy bar introduced at the start of each cast. If misaligned, the leading end of the bar can impact onto the end face of the mould. In one case (Armourcote 5100, single taper) damage of this type produced a pronounced exaggeration of the taper at the bottom end of the mould. Other than as a result of prior thermal treatment it appears that distortion is not directly connected to mould coating type.

The most severe case of distortion arose with a TiN coated mould softened during the deposition treatment. This did not appear to suffer from enhanced meniscus zone distortion, but was subject to a serious loss of taper over the lower half of the mould across both straight and radiused faces. The implication is that any loading due to billet or dummy bar could not be adequately resisted by the copper, which ultimately flared by more than 1 mm.

In a majority of cases mould service life was limited by concern over breakouts induced by bottom end distortion, meniscus zone cracking or rhomboidity of the billet section.

Meniscus zone cracking was found in Cr plated moulds, eventually resulting in a macroscopically rough surface. Overlaid TiN effectively bridged incipient defects in the chromium deposit but did not prevent their subsequent propagation into the parent copper. Penetration of this coating by zinc, to form a brass phase at the interface with the copper surface, and also of sulphur, aggravated the cracking tendency.

Thermal cycling at the meniscus position and the development of plastic strain due to creep/stress relaxation processes then allows the cracks to open, macroscopically roughening the working surface.

Replacement of chromium by nickel and the introduction of a further wear resistant or lubricating layer gave a clear advantage in avoiding, or at least reducing the development of cracking of the copper.

A reduced heat transfer associated with a given coating will reduce the copper hot face temperature and correspondingly minimise distortion. Such an effect would however favour a reduced rate of solidification, producing a thinner billet shell potentially more prone to rupture if thermal and frictional effects are not constant around the meniscus.

A comparison of the mould cooling water temperature difference characterising specific steels in different moulds can give an indication of any possible thermal effects of mould coatings. Table 18(b) gives a summary of mean data for all of the trial moulds used in service in this report, subdivided by steel type, including values proportional to the temperature differential ΔT, normalised for water flow rate (W) and casting speed (V); the values for the quantity WΔT/V (litre °C/m), are given for the two most frequently cast steel types. Results for powder lubricated casts of different grades are also given.

Lower values of the normalised ΔT indicate lower mould copper hot face temperatures i.e. a thermal barrier due to the coating. Similarly, with steel grade to grade variations, lower ΔT values imply reduced steel to mould heat transfer and thus thinner, more damage-prone initial solid shells. It is interesting to note that ΔT values for low carbon free-cutting steels are, with two exceptions, lower than for medium carbon steel.

The three Ni/Ni-PTFE moulds yielded unrepresentative values of normalised ΔT for oil lubricated casts. The results are substantially higher than for the individual trial moulds with Ni/Ni-PTFE coatings. Results for a contemporary Cr plated mould included in Table 18 are also evidently from a different population to that previously seen for standard moulds.

Contamination of the oil lubricant is suspected as the explanation of the discrepancies: previous studies at RES Templeborough have shown ΔT values to increase markedly when impurities are present. The manifestation of this in terms of the product is normally not a modification of surface quality but a tendency to corner cracking. This appears to result from increased heat transfer over the bulk of the section, prompting withdrawal of the billet solidification shell from the mould corners causing local thinning and subsequent stressing. For this reason the thermal data for the Ni/Ni-PTFE trials have to be treated with circumspection. It will be seen from Table 17 that values of the normalised ΔT parameter are substantially similar over a wide range of moulds when powder is used as lubricant, giving added credence to the argument that oil purity is the dominant factor in the wide distribution of results.

With this proviso it is evident that the results do not indicate a consistent or large effect of coating on heat transfer and therefore a significant effect of the present, relatively thin coatings on mould distortion or indirectly on billet surface quality would not be expected.

The broad spectrum of results showed little change in ΔT values for medium C steels cast in moulds with Cr plating, nitride coatings overlying Cr or Ni, or Ni-PTFE overlying Ni. With free-cutting steels, however, the results are some 10% lower for moulds with nitride coatings than for moulds with primary Cr plating. A possible explanation of this effect may lie with differences in meniscus wetting. The coatings may have much greater effect on meniscus behaviour in the free-cutting steels, which, compared with medium carbon steels, are inherently more prone to wet the mould surface with Cr plated copper. This would imply that the heat transferred at the meniscus is a sufficiently large proportion of the total to produce the differences recorded in ΔT.

Available heat flux sensor measurements obtained for Cr plated moulds tend to endorse the above point. With each mould, available values of heat flux were, as for most of the ΔT values, consistently lower for LCFC steels than for medium C steels. Meniscus heat flux was substantially reduced when TiN or CrTiN was deposited over Cr. With a Ni-PTFE deposit on nickel (207490, Table 18(b)) the heat flux was significantly higher than for the Cr plated moulds: the implied improvement in meniscus zone heat transfer (for the dual taper mould) is clearly not consistent with the respective ΔT values.

It is difficult to explain the increase in recorded heat flux (meniscus region) in the observed order: nitrided, Cr-plated, Ni-PTFE treated mould surfaces. Reduced steel wetting of the mould surface could explain the effect of nitriding over chromium plating. Ni-PTFE would, however, also be expected to reduce wetting, again reducing rather than increasing heat flux. A possible explanation may lie with the structure of the deposit which has PTFE particles in nickel, the metal in this case being able to maintain a thermally continuous conductive path to the copper, particularly in the meniscus region where some of the PTFE is initially fumed away.

It is uncertain if, or to what extent, the PTFE degenerates at the hot face of the mould in service. The precise role of the PTFE in the nickel deposit remains unclear: in the context of continuous casting further work is required to identify the mechanism and extent to which improvement is produced in the nickel by the presence of this additive.

As would be expected, the introduction of casting power as lubricant for medium C steels also gave a reduction in ΔT in each of the moulds for which powder was employed (with one exception this reduction was considerably greater than that seen with oil lubricated low carbon free-cutting steels). While a thinner shell would also be expected with powder lubrication, the billet surfaces showed much less evidence of drag or tear marks, attributable to the lower wetting tendency, increased consistency of meniscus conditions and improved lubrication with a powder practice. (Free-cutting steels, most prone to surface defects with oil lubrication, were not produced with a powder practice to avoid the development of subsurface porosity). It would appear from the results obtained that the use of powder does not produce a consistent heat loss independent of mould type, but on the other hand it is difficult to identify a systematic thermal effect associated with coating type. The number of casts produced with powder was insufficient for any deductions to be made as to effects of coatings on mould life when operating a powder practice with a given mould coating and steel type.

5.5 Cost Effectiveness

On the basis of the trial data, the Ni/Ni-PTFE coating appears to justify further use with regard to both billet quality and extended mould service potential. The economic merit of this requires consideration, however, before adoption of the coating is recommended for production, particularly bearing in mind that the principal benefits arise with oil lubricated casting. Although the Ni/Ni-PTFE trials described in the report involve CrZr alloyed copper moulds, the ability to restrict treatment temperatures to only approximately 300° will allow this coating to be applied to conventional phosphorised SF copper mouldswithout risk of deterioration.

Clearly it is difficult to justify the use of CrZr alloyed moulds since these are twice as expensive as the standard phosphorised moulds and despite their higher strength showed wear and flaring over the exit regions, as for standard moulds. This wear is due primarily to dummy bar damage, but can also result from strand movement within the mould. Unfortunately the wear progressively reduces strand support leading to billet shape problems ultimately necessitating mould withdrawal. This appears effectively to limit mould mould service to around 150 lives. However with an increasing use of powder casting, which produces a more consistently uniform billet surface profile, billet/mould abrasion should be reduced, offering the potential for further extension of mould life.

The cost premium identified for use of Ni/Ni-PTFE coating is confined to the cost relative to Cr plating: with no accommodation for possible price reduction with an increased order load this is approximately £375 per mould. In terms of general plant operation, with Cr-plated moulds, using oil as lubricant, rejection due to meniscus zone deterioration produces an average mould service life approaching 120 heats. Accordingly, an extension of mould life by 30 heats with no loss of billet surface quality during this period is the payback in terms of mould service.

In terms of mould costs alone, a standard mould life of 120 heats would give a cost of £0.23 per tonne of steel cast. Based on current prices for the Ni-Ni/PTFE coating, the mould cost would increase to £0.31 per tonne of steel cast, assuming an improved mould life average of 150 heats. This cost disadvantage is offset by better mould availability and consequently a reduction in the skilled engineering effort required for mould tube changes. Above all, the coating would appear to provide an insurance against meniscus cracking which often leads to expensive billet dressing when the onset of cracking goes undetected during the latter part of the mould life. It can be seen that there is reason to expect an overall economic benefit from the use of Ni/Ni-PTFE coating even for the case of oil lubrication alone.

6. CONCLUSIONS

(1) A wide range of potential coatings for the internal surfaces of billet moulds has been considered. Six of these have been assessed in trials on the Rotherham Engineering Steels Templeborough billet caster.

(2) Three of the coatings used in the trial work did not survive a campaign and are therefore considered unsuitable for practical application. These are Armourcote 5100 (MoS_2 based), Armourcote CFX (Aluminium-fluorocarbon) and ZrN, each deposited on electroless nickel.

(3) CrTiN deposited on Cr plated copper did not give an advantage in surface quality or mould friction. Possible benefits of this coating in limiting cracking of the chromium could not be established, as the mould was used only for a short campaign.

(4) TiN gave no direct benefit in billet surface quality or mould friction. The coating appeared to inhibit, but not prevent craze cracking of the copper.

(5) Ni/Ni-PTFE gave consistent improvements in billet surface quality, commensurate with a reduction observed in mould friction. Meniscus zone mould heat flux was increased and there was a reduction in the tendency for mould cracking to appear at the meniscus zone. In the trials, mould life was not restricted by meniscus zone deterioration. This coating is therefore regarded as offering advantage provided that cost and other factors such as mould damage in service do not present an overriding constraint.

(6) The coating process required for CrTiN and TiN introduces a risk of softening of the mould, leading to distortion in service. This does not arise with the Ni-PTFE coating.

(7) Heat transfer, as defined by mould water temperature difference was less for low C free-cutting steels than for medium C steels in a majority of the trials regardless of mould coating type. In all cases heat transfer was further reduced by substitution of oil lubricant by casting powder.

(8) Use of a Ni/Ni-PTFE coated mould offers a 25% improvement in mould life without deterioration in billet quality when used solely in association with oil casting. Despite this improvement, there is a premium of around £0.08 per tonne of steel cast due to the higher initial cost of this coating over the standard Cr plating. The deficit is more than offset by improved mould availability, a reduction in costly mould tube changes and an elimination of billet dressing due to malformed reciprocation marks and bleeds associated with the onset of meniscus cracking.

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TABLE 1
CASTING DATA: CHROMIUM PLATED STANDARD MOULD (181916)

(Oil Lubrication)

No. of Casts	Steel Type	Average Casting Speed m/min	Average Mould Water Flow litre/min	Mould Heat Extraction ΔT°C	Mould Friction %	Surface Quality Recip. Grade	
						Ave.	Range
10	≤0.12%C fine grain	1.85	1399	6.49	N/A	2	1-3
16	0.13-0.20%C fine grain	1.96	1394	7.43	N/A	2	1-2
51	0.21-0.50%C fine grain	1.93	1388	8.86	N/A	1	0-2
4	>0.50%C fine grain	1.77	1386	8.38	N/A	1	0-1
24	Low carbon free cutting steels	1.97	1393	8.08	N/A	2/3	1-3
11	Medium carbon free cutting steels	1.87	1385	7.59	N/A	2	1-2
41	Other grades	1.94	1390	7.37	N/A	1/2	0-2

TABLE 2
CASTING DATA: CHROMIUM PLATED STANDARD MOULD (TB2066)

(Oil Lubrication)

No. of Casts	Steel Type	Average Casting Speed m/min	Average Mould Water Flow litre/min	Mould Heat Extraction ΔT°C	Mould Friction %	Surface Quality Recip. Grade	
						Ave.	Range
11	≤0.12% CF/G	1.880	1387	6.8	N/A	1/2	1-2
15	0.13-20% CF/G	1.902	1392	7.5	N/A	1/2	1-2
31	0.21-50% CF/G	1.928	1395	8.5	N/A	2/3	1-5
1	>0.50% CF/G	1.938	1398	8.5	N/A	2	2
19	LCFCS	1.872	1395	7.7	N/A	1/2	1-3
5	MCFCS	1.876	1397	7.7	N/A	1/2	1-2
45	Other Grades	1.872	1396	7.5	N/A	2	1-5

TABLE 3
CASTING DATA: CHROMIUM PLATED STANDARD MOULD (TB388)

Oil Lubrication Casts

No. of Casts	Steel Type	Average Casting Speed m/min	Average Mould Water Flow litre/min	Mould Heat Extraction ΔT°C	Mould Friction %	Surface Quality Recip. Grade	
						Ave.	Range
2	≤0.12% C F/G	1.867	1323	6.4	37	1/2	1-2
9	0.13-0.20% C F/G	1.830	1371	6.8	36	1	1-2
21	0.21-0.50% C F/G	1.937	1363	8.7	40	0/1	0-1
1	>0.50% C F/G	1.803	1330	8.5	52	1	1
19	LCFCS	1.814	1395	7.1	45	1	0-2
6	MCFCS	1.798	1397	7.3	56	N/A	N/A
5	Boron Casts	1.884	1361	7.94	39	2/3	2-3
30	Other Grades	1.904	1383	7.7	37	N/A	N/A

Powder Casts

No. of Casts	Steel Type	Average Casting Speed m/min	Average Mould Water Flow litre/min	Mould Heat Extraction ΔT°C	Mould Friction %	Surface Quality Recip. Grade	
						Ave.	Range
1*	0.15-0.20% C F/G	1.895	1403	2.5	N/A	N/A	N/A
2	0.35-0.40% C F/G	1.876	1398	6.8	12	1	0-1
2	0.15-0.20% C C/G	1.876	1325	6.0	10	1	0-1

* Broke out after 16 m

TABLE 4
CASTING DATA: CHROMIUM PLATED DUAL TAPER MOULD (207483)

Oil Lubrication Casts

No. of Casts	Steel Type	Average Casting Speed m/min	Average Mould Water Flow litre/min	Mould Heat Extraction ΔT°C	Mould Friction %	Surface Quality Recip. Grade	
						Ave.	Range
9	≤0.12% C F/G	1.964	1363	6.5	24	0/1	0-1
12	0.13-0.20% C F/G	1.897	1367	7.5	27	0/1	0-1
41	0.21-0.50% C F/G	1.883	1364	8.4	25	0/1	0-2
2	>0.50% C F/G	1.727	1366	8.6	25	0/1	0-1
33	LCFCS	1.865	1364	8.0	24	0/1	0-3
8	MCFCS	1.860	1369	8.1	14	0	0-1
6	Boron Casts	1.889	1360	8.1	22.5	0/1	0-1
36	Other Grades	1.858	1366	7.5	20	0/1	0-2

Powder Casts

No. of Casts	Steel Type	Average Casting Speed m/min	Average Mould Water Flow litre/min	Mould Heat Extraction ΔT°C	Mould Friction %	Surface Quality Recip. Grade	
						Ave.	Range
6	0.21-0.50% C F/G	1.853	1371	5.9	13	0	0-1

TABLE 5
CASTING DATA: TiN COATED MOULD (TBJ388)

(Oil Lubrication)

No. of Casts	Steel Type	Av. Casting Speed m/min	Av. Mould Water Flow litre/min	Mould Heat Extraction ΔT°C	Mould Friction %	Surface Quality Recip. Grade	
						Ave.	Range
3	≤0.12%C fine grain	1.91	1378	6.53	19	2	2-3
10	0.13-0.20%C fine grain	2.02	1378	7.73	24	2	1-3
13	0.21-0.50%C fine grain	1.95	1370	8.87	26	1	0-2
2	>0.50%C fine grain	2.00	1374	9.50	31	1	0-1
10	Low carbon free cutting steels	1.91	1374	7.12	15	2/3	2-3
4	Medium carbon free cutting steels	1.92	1376	7.70	20	2	2
24	Other grades	1.93	1375	7.88	22	1/2	1-3

TABLE 6
CASTING DATA: TiN COATED MOULD (TBJ387)

(Oil Lubrication)

No. of Casts	Steel Type	Average Casting Speed m/min	Average Mould Water Flow litre/min	Mould Heat Extraction ΔT°C	Mould Friction %	Surface Quality Recip. Grade	
						Ave.	Range
9	≤0.12% CF/G	1.919	1389	6.3	14.75	1/2	1-2
9	0.13-20% CF/G	1.889	1391	6.8	16.33	1	0-2
29	0.21-50% CF/G	1.953	1390	7.7	16.00	1	0-2
4	>0.50% CF/G	1.947	1394	8.5	16.33	N/A	-
23	LCFCS	1.876	1393	6.8	13.38	1/2	0-2
9	MCFCS	2.260	1385	7.0	16.00	0/1	0-2
29	Other Grades	1.997	1391	7.2	17.35	0/1	0-2

TABLE 7
CASTING DATA: CrTiN COATED MOULD (TB461/89)

Oil Lubrication Casts

No. of Casts	Steel Type	Average Casting Speed m/min	Average Mould Water Flow litre/min	Mould Heat Extraction ΔT°C	Mould Friction %	Surface Quality Recip. Grade	
						Ave.	Range
3	≤0.12% C F/G	2.155	1392	5.9	N/A	1/2	1-2
1	0.13-0.20% C F/G	1.282	1410	1.6	N/A	N/A	N/A
28	0.21-0.50% C F/G	1.992	1361	8.8	24	0/1	0-2
2	>0.50% C F/G	1.979	1402	8.3	N/A	1	1
11	LCFCS	1.930	1355	7.3	22	1	0-3
5	MCFCS	1.986	1352	7.3	20.6	1	0-2
5	Boron Casts	1.967	1353	7.8	19	0/1	0-1
11	Other Grades	1.921	1366	6.8	22.1	0/1	0-2

Powder Casts

No. of Casts	Steel Type	Average Casting Speed m/min	Average Mould Water Flow litre/min	Mould Heat Extraction ΔT°C	Mould Friction %	Surface Quality Recip. Grade	
						Ave.	Range
1	0.16/0.19% C C/G	1.914	1347	6.3	12	0/1	0-1

TABLE 8
CASTING DATA:- ZIRCONIUM NITRIDE COATED MOULD (237845)

Oil Lubrication Casts

No. of Casts	Steel Type	Average Casting Speed m/min	Average Mould Water Flow litre/min	Mould Heat Extraction ΔT °C	Surface Recip. Grade	
					Ave.	Range
1	<0.12% C FG	N/A	N/A	N/A	0/1	0/1
18	0.13/0.20% C FG	1.910	1423	7.5	1	0/2
22	0.21/0.50% C FG	1.912	1476	8.1	1/2	0/2
25	LCFCS	2.079	1544	6.6	1	1/2
20	MCFCS	1.943	1533	7.2	1/2	0/3
3	Boron casts	1.942	1448	8.0	N/A	N/A
3	Other	1.753	1601	5.5	0/1	0/2

Powder Casts

No. of Casts	Steel Type	Average Casting Speed m/min	Average Mould Water Flow litre/min	Mould Heat Extraction ΔT °C	Surface Recip. Grade	
					Ave.	Range
7	<0.12% C FG	1.837	1532	5.2	1/2	1/2
15	0.21/0.50% C FG	1.901	1587	6.0	0/1	0/1
1	>0.50% C FG	1.849	1401	7.1	N/A	N/A
1	Boron casts	1.828	1602	5.9	1	1

TABLE 9
CASTING DATA: Ni/Ni-PTFE COATED MOULD - DUAL TAPERED (207490)

Oil Lubrication Casts

No. of Casts	Steel Type	Average Casting Speed m/min	Average Mould Water Flow litre/min	Mould Heat Extraction ΔT°C	Mould Friction %	Surface Quality Recip. Grade	
						Ave.	Range
1	<0.12% CF/G	1.89	1445	5.8	12	0/1	0/1
7	0.13/0.20% CF/G	1.90	1504	6.13	14	0/1	0/2
36	0.21/0.50% CF/G	1.90	1500	7.6	15	0/1	0/2
1	>0.50% CF/G	2.0	1538	8.2	18	N/A	N/A
17	LCFCS	2.0	1504	6.6	15	1	0/3
7	MCFCS	1.94	1521	6.4	12	1	1
6	Boron casts	1.98	1503	7.5	15	N/A	N/A
15	Other grades	1.89	1445	5.8	12	0/1	0/3

Powder Casts

No. of Casts	Steel Type	Average Casting Speed m/min	Average Mould Water Flow litre/min	Mould Heat Extraction ΔT°C	Mould Friction %	Surface Quality Recip. Grade	
						Ave.	Range
2	0.13/0.20% CF/G	1.92	1537	5.4	10	1	1
2	0.21/0.50% CF/G	1.83	1472	5.8	8	1	1

TABLE 10
CASTING DATA:- Ni/Ni-PTFE COATED MOULD (237843)

Oil Lubrication Casts

No. of Casts	Steel Type	Average Casting Speed m/min	Average Mould Water Flow litre/min	Mould Heat Extraction ΔT °C	Surface Quality Recip. Grade	
					Ave.	Range
4	<0.12% C FG	1.652	1508	5.6	0/1	0/1
24	0.13/0.20% C FG	1.861	1489	7.3	1	0/2
21	0.21/0.50% C FG	1.859	1496	8.0	0/1	0/2
23	LCFCS	2.062	1514	7.3	1/2	1/3
9	MCFCS	2.028	1527	6.9	N/A	N/A
4	Boron casts	1.730	1557	7.4	N/A	N/A
14	Other	1.983	1434	6.3	0/1	0/2

Powder Casts

No. of Casts	Steel Type	Average Casting Speed m/min	Average Mould Water Flow litre/min	Mould Heat Extraction ΔT °C	Surface Quality Recip. Grade	
					Ave.	Range
20	0.21/0.50% C FG	1.865	1494	6.4	0/1*	0/1
3	>0.50% C FG	1.936	1522	6.7	0/1	0/1
3	Boron casts	1.894	1487	6.7	0/1	0/1

TABLE 11
CASTING DATA: Ni/Ni-PTFE COATED MOULD (237846)
(THREE MOULD TRIAL)

Oil Lubrication Casts

No. of Casts	Steel Type	Average Casting Speed m/min	Average Mould Water Flow litre/min	Mould Heat Extraction ΔT°C	Mould Friction %	Surface Quality Recip. Grade	
						Ave.	Range
14	0.13/0.20% C FG	1.929	1595	6.8	N/A	1	0/2
39	0.21/0.50% C FG	1.879	1581	7.9	N/A	1	0/2
26	LCFCS	1.877	1553	7.2	N/A	1/2	0/2
11	MCFCS	1.946	1561	7.5	N/A	N/A	N/A
11	Others	1.780	1573	6.0	N/A	1	0/2

Powder Casts

No. of Casts	Steel Type	Average Casting Speed m/min	Average Mould Water Flow litre/min	Mould Heat Extraction ΔT°C	Mould Friction %	Surface Quality Recip. Grade	
						Ave.	Range
4	<0.12% C FG	1.842	1636	5.1	N/A	1/2	1/2
29	0.21/0.50% C FG	1.870	1572	5.8	N/A	1	0/2
2	>0.50% C FG	1.808	1579	6.2	N/A	1	1
7	Boron casts	1.812	1562	5.9	N/A	N/A	N/A
1	Others	1.875	1574	5.5	N/A	N/A	N/A

TABLE 12
CASTING DATA: Ni/Ni-PTFE COATED MOULD (237848)
(THREE MOULD TRIAL)

Oil Lubrication Casts

No. of Casts	Steel Type	Av. Casting Speed m/min	Av. Mould Water Flow litre/min	Mould Heat Extraction ΔT°C	Mould Friction %	Surface Quality Recip. Grade	
						Av.	Range
1	<0.12% C FG	1.704	1583	6.1	N/A	1	1
17	0.13/0.20% C FG	1.958	1634	7.0	N/A	1	0/2
29	0.21/0.50% C FG	1.886	1625	7.9	N/A	1	0/2
30	LCFCS	1.835	1591	7.0	N/A	1/2	1/2
12	MCFCS	1.972	1621	7.2	N/A	N/A	N/A
13	Others	1.872	1597	6.5	N/A	1	0/2

+Oil lubrication Tank 1 5% IL2544 in Essotherm 500
Oil lubrication Tank 2 30% IL2544 in Essotherm 500

Powder Casts

No. of Casts	Steel Type	Average Casting Speed m/min	Average Mould Water Flow litre/min	Mould Heat Extraction ΔT°C	Mould Friction %	Surface Quality Recip. Grade	
						Av.	Range
7	<0.12% C FG	1.780	1620	5.1	N/A	1/2	1/2
25	0.21/0.50% C FG	1.832	1617	5.8	N/A	1	0/2
1	>0.50% C FG	1.811	1525	6.4	N/A	N/A	N/A
5	Boron casts	1.856	1575	6.2	N/A	N/A	N/A

TABLE 13
CASTING DATA: Ni/Ni-PTFE COATED MOULD (237847)
(THREE MOULD TRIAL)

Oil Lubrication Casts

No. of Casts	Steel Type	Average Casting Speed m/min	Average Mould Water Flow litre/min	Mould Heat Extraction ΔT°C	Mould Friction %	Surface Quality Recip. Grade	
						Av.	Range
1	<0.12% C FG	1.662	1573	5.8	N/A	1	1
18	0.13/0.20% C FG	1.992	1662	7.1	N/A	1	0/2
34	0.21/0.50% C FG	1.929	1660	7.9	N/A	1	0/2
33	LCFCS	1.926	1631	7.2	N/A	1/2	1/2
13	MCFCS	1.982	1692	7.3	N/A	N/A	N/A
14	Others	1.955	1618	6.5	N/A	1	0/2

Powder Casts

No. of Casts	Steel Type	Average Casting Speed m/min	Average Mould Water Flow litre/min	Mould Heat Extraction ΔT°C	Mould Friction %	Surface Recip. Grade	
						Av.	Range
7	<0.12% C FG	1.885	1653	5.1	N/A	1/2	1/2
29	0.21/0.50% C FG	1.905	1642	5.9	N/A	1	0/2
1	>0.50% C FG	1.849	1587	6.6	N/A	N/A	N/A
8	Boron casts	1.878	1633	5.8	N/A	N/A	N/A
1	Others	1.884	1613	5.5	N/A	N/A	N/A

TABLE 14
CASTING DATA: ELECTROLESS NICKEL/ARMOURCOTE 5100 - DUAL TAPER MOULD (207491)

Oil Lubrication Casts

No. of Casts	Steel Type	Average Casting Speed m/min	Average Mould Water Flow litre/min	Inlet/Outlet Temperature Differential ΔT°C	Mould Friction %	Surface Recip. Grade
2	<0.12% C FG	1.75	1607	5.7	29	1
5	0.13/0.20% C FG	1.77	1613	6.7	29	1-2
13	0.21/0.50% C FG	1.67	1605	7.4	29	0-1
12	LCFCS	1.76	1620	6.8	26.5	1-3
2	MCFCS	1.95	1615	7.3	N/A	0-1
9	Boron Casts	1.68	1591	7.3	28	N/A
10	Others	1.74	1610	6.6	26	1-2

Powder Casts

No. of Casts	Steel Type	Average Casting Speed m/min	Average Mould Water Flow litre/min	Inlet/Outlet Temperature Differential ΔT°C	Mould Friction %	Surface Recip. Grade
1	0.21/0.50% C FG	1.78	1587	5.3	N/A	0-1

TABLE 15
CASTING DATA: ELECTROLESS NICKEL/ARMOURCOTE 5100 (237844)

Oil Lubrication Casts

No. of Casts	Steel Type	Average Casting Speed m/min	Average Mould Water Flow litre/min	Inlet/Outlet Temperature Differential ΔT°C	Mould Friction %	Surface Recip. Grade
-	<0.12% C FG	-	-	-	-	-
1	0.13/0.20% C FG	2.05	1420	9.0	N/A	0-1
4	0.21/0.50% C FG	1.86	1440	6.7	N/A	1
3	LCFCS	1.83	1420	7.4	N/A	1
-	MCFCS	-	-	-	-	-
-	Boron Casts	-	-	-	-	-
-	Others	-	-	-	-	-

Powder Casts

No. of Casts	Steel Type	Average Casting Speed m/min	Average Mould Water Flow litre/min	Inlet/Outlet Temperature Differential ΔT°C	Mould Friction %	Surface Recip. Grade
2	0.21/0.50% C FG	1.901	1412	6.5	N/A	0-1

TABLE 16
CASTING DATA: ELECTROLESS NICKEL/CFX - DUAL TAPER MOULD (207489)

Oil Lubrication Casts

No. of Casts	Steel Type	Average Casting Speed m/min	Average Mould Water Flow litre/min	Inlet/Outlet Temperature Differential ΔT°C	Mould Friction %	Surface Recip. Grade
3	<0.12% C FG	1.89	1266	5.65	4	1
3	0.13/0.20% C FG	1.69	1287	U/S	4	0-1
11	0.21/0.50% C FG	1.72	1328	5.68	4	0-1
11	LCFCS	1.78	1287	6.52	4.5	1-2
5	MCFCS	1.75	1276	7	4	0-1
4	Boron Casts	1.73	1273	6.9	U/S	N/A
8	Others	1.72	1296	6.13	U/S	1

Powder Casts

No. of Casts	Steel Type	Average Casting Speed m/min	Average Mould Water Flow litre/min	Inlet/Outlet Temperature Differential ΔT°C	Mould Friction %	Surface Recip. Grade
5	0.21/0.50% C FG	1.99	1301	5.6	U/S	0-1

TABLE 17(a)
COATINGS EMPLOYED FOR CONTINUOUS CASTING BILLET MOULD TRIALS

Type of Coating	Thickness, mm	Technique	Application/Treatment Temperature, °C	Details
Standard Chromium	0.1	Chemical Deposition	100	Commercial application
TiN on Standard Cr	0.002/0.003	Physical Vapour Deposition (PVD)	250 - 300	Ti evaporation into ionised nitrogen and argon. TiN deposition on cathode surface
CrTiN on Standard Cr	0.004	PVD	300	As above but with simultaneous evaporation of Cr and Ti. Coating biased towards CrN
ZrN on Electroless Ni	0.01 ZrN 0.05 Ni	PVD	360	Lower hardness than TiN but forms ZrO_2 in service
Ni/Ni PTFE	0.05 Ni 0.015 Ni PTFE	Chemical Deposition	300	Auto catalytic reduction of nickel salts
Armourcote 5100 on Electroless Ni	0.05 Ni 0.1 Coating	Dry Film	150/200	MoS_2, graphite and fluorocarbons
Armourcote CFX on Electroless Ni	0.05 Ni 0.025 Coating	Sprayed Film	400	Metallic Al and fluorocarbons

TABLE 17(b)
COATINGS UNSUITABLE FOR BILLET CASTING APPLICATIONS

Type of Coating	Application	Reason for Failure
Cr on Electroless Ni	Standard Cr plating overlaid on crack-free Ni deposit	Quality of plating unacceptable
Crack-free chromium	Similar to Standard Cr	No reduction in microcracks seen
Densification of chromium coating	Infill of microcracks in the Cr layer	No effective bonding with the Cr deposit
Monitox	Deposition and baking of Cr_2O_3 - Al_2O_3 - SiO_2 slurry	Coating spalled from mould during densification
Chromium carbide dispersion in Electroless Ni/Co	deposit of 0.075 mm	Company ceased trading

TABLE 18
SUMMARY OF RESULTS OBTAINED FOR COATED MOULDS USED IN TRIALS

(a) Billet Surface Quality Data

Coating		Mould Identity	Substrate	Taper	Mould Material	Service Life	Surface Quality Results (Oil Lubricated Casts)			
							0.20/0.50% C		LCFCS	
							Ave.	Range	Ave.	Range
Standard Cr	1	181916	-	Single	SF-Cu	160	1	0-2	2/3	1/3
	2	TB2066	-	Single	SF-Cu	127	2/3	1-5	1/2	1/3
	3	TB388	-	Single	SF-Cu	100	0/1	0-1	1	0/2
	4	207483	-	Dual	SF-Cu	153	0/1	0-2	0/1	0/3
	5	*	-	Single	SF-Cu	N/A	N/A	N/A	N/A	N/A
TiN	1	TBJ388	Cr	Single	SF-Cu	66	1	0-2	2/3	2/3
	2	TBJ387	Cr	Single	SF-Cu	114	1	0-2	1/2	0/2
CrTiN		TB461/89	Cr	Single	SF-Cu	66	0/1	0-2	1	0/3
ZrN		237845	Ni	Single	CuCrZr	116	1/2	0-2	1	1/2
Ni/Ni-PTFE	1	207490	Ni	Dual	CuCrZr	94	0/1	0-2	1	0/3
	2	237843	Ni	Single	CuCrZr	125	0/1	1-2	1/2	1/3
	3	237846	Ni	Single	CuCrZr	144	1	0-2	1/2	0/2
	4	237848	Ni	Single	CuCrZr	140	1	0-2	1/2	1/2
	5	237847	Ni	Single	CuCrZr	159	1	0-2	1/2	1/2
Armourcote 5100	1	207491	Ni	Dual	CuCrZr	54	0/1	1/3	1/3	1/3
	2	237844	Ni	Single	CuCrZr	10	1	1	1	
Armourcote CFX		207489	Ni	Dual	CuCrZr	50	0/1	1/2	1/2	2

* Comparator for heat flux measurements with respect to Ni/Ni-PTFE 3,4,5

(continued)

TABLE 18
(continued)

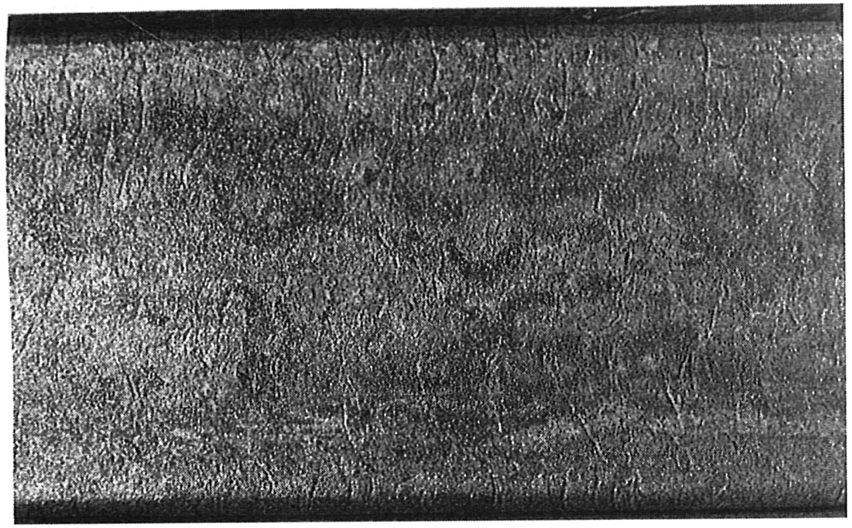
(b) Temperature and Heat Flux Data

Coating	Mould Identity	Sub-strate	Taper	Mould Material	Service Life	Normalised Mean ΔT Values (litre °C/m)				Mean Heat Flux (MW/m^2)			
						Oil-Lubricated Casts		Power-Lubricated Casts		Oil-Lubricated Casts		Power-Lubricated Casts	
						0.20/ 0.50% C	LCFCS	0.20/ 0.50% C	0.16/ 0.19% C	0.20/ 0.50% C	LCFCS	0.20/ 0.50% C	0.16/ 0.19% C
Standard Cr 1	181916	-	Single	SF-Cu	160	6372	5713						
2	TB2066	-	Single	SF-Cu	127	6150	5738						
3	TB388	-	Single	SF-Cu	100	6122	5460	5067		1.765	1.605		
4	207483	-	Dual	SF-Cu	153	6085	5851	4365		1.761	1.642		1.873
5	*	-	Single	SF-Cu	N/A	7068†	6387†						
TiN 1	TBJ388	Cr	Single	SF-Cu	66	6232	5122						
2	TBJ387	Cr	Single	SF-Cu	114	5840	5049			1.29			
CrTiN	TB461/89	Cr	Single	SF-Cu	66	6012	5125		4438	1.172	0.991		0.980
ZrN	237845	Ni	Single	CuCrZr	116	6253	4902	5099					
Ni/Ni-PTFE 1	207490	Ni	Dual	CuCrZr	94	6000	4963	4665		2.18	2.15		
2	237843	Ni	Single	CuCrZr	125	6438	5360	5127					
3	237846	Ni	Single	CuCrZr	144	6647†	5957†	4876		1.876†	1.747†	1.489	
4	237848	Ni	Single	CuCrZr	140	6807†	6069†	5119					
5	237847	Ni	Single	CuCrZr	159	6798†	6097†	5085					
Armourcote 5100 1	207491	Ni	Dual	CuCrZr	54	7112	6259	4725					
2	237844	Ni	Single	CuCrZr	10	5187	5742	4828					
Armourcote CFX	207489	Ni	Dual	CuCrZr	50	4396	4714	3661					

* Comparator for heat flux measurements with respect to Ni/Ni-PTFE 3,4,5

† Oil Contamination believed to be present

Grade 0 = NO recip. marks



1

2

3

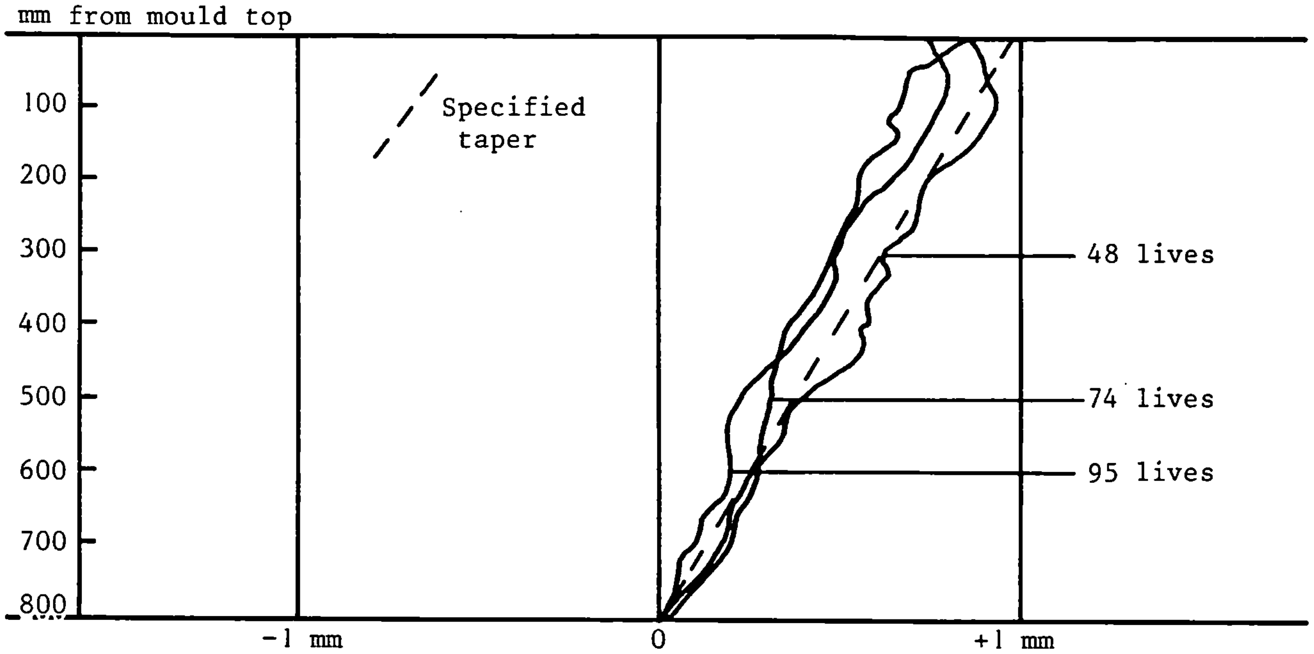
4

Grade 5 = Worse than 4

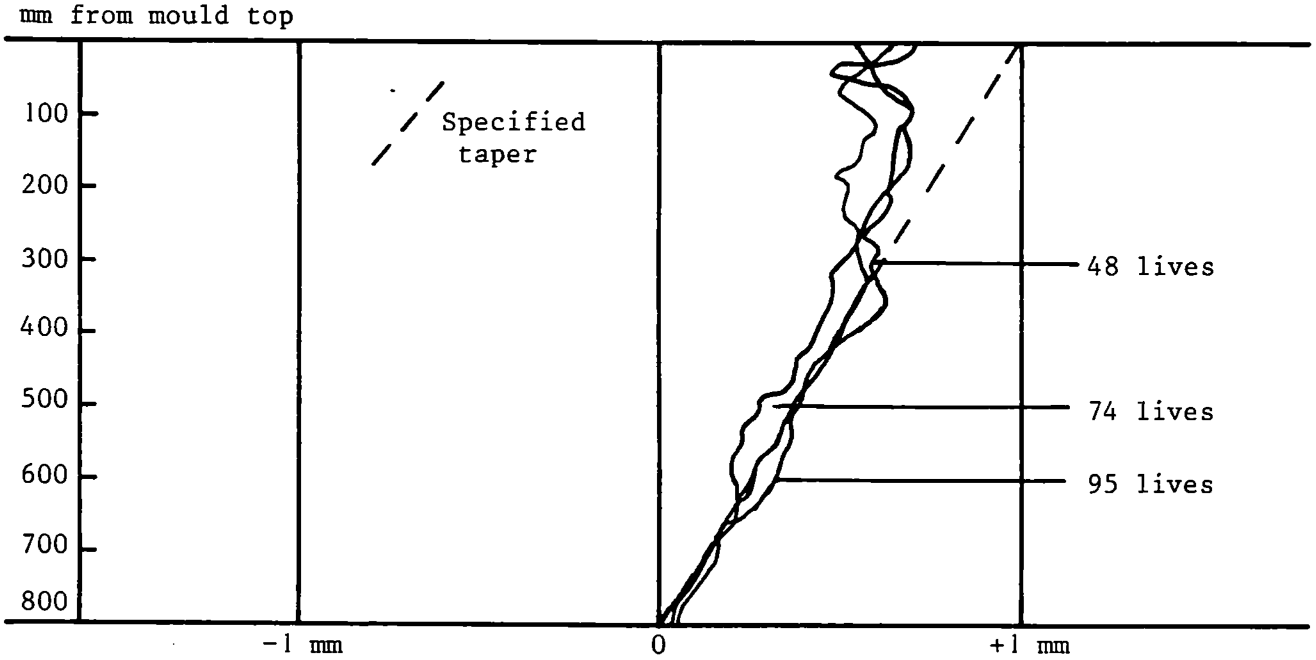
TEMPLEBOROUGH BILLET RECIPROCATION MARK CHART (140 mm sq BILLET)

Figure 1

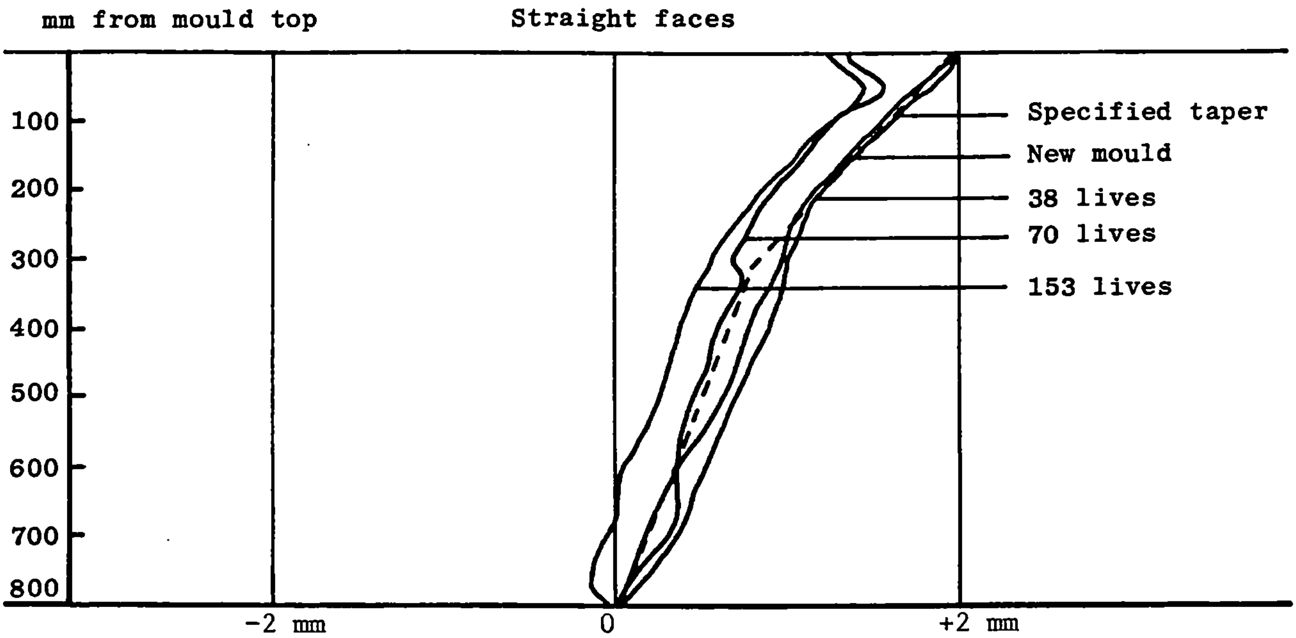
Straight faces

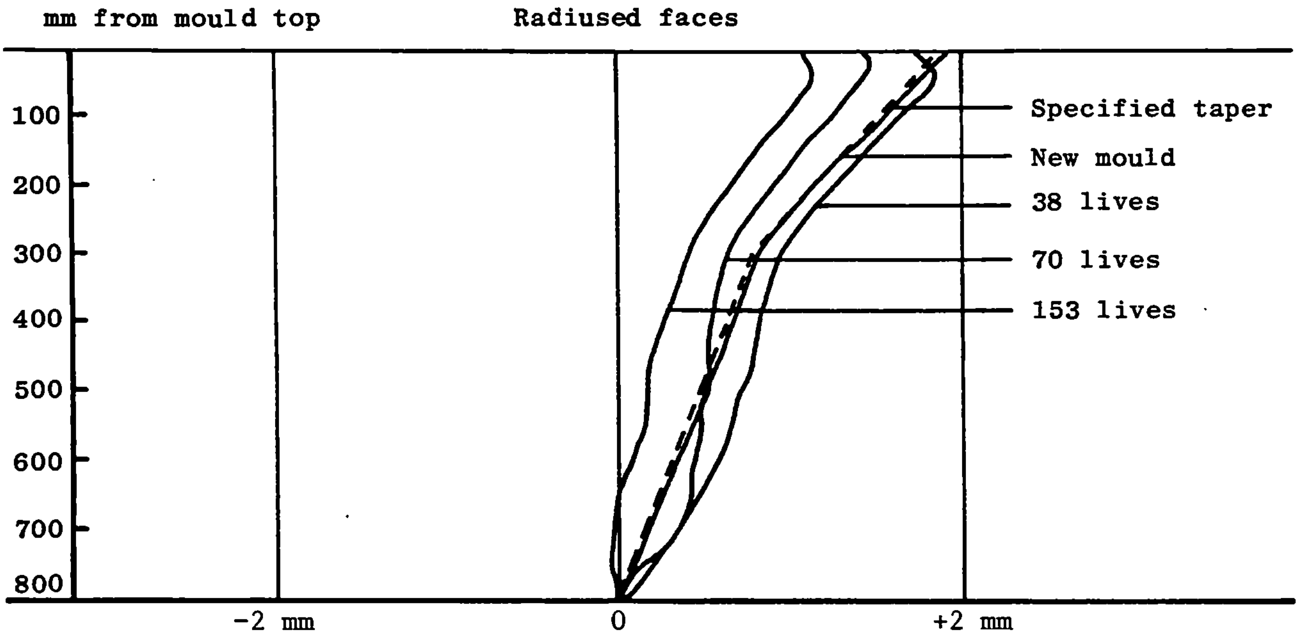


Radiused faces

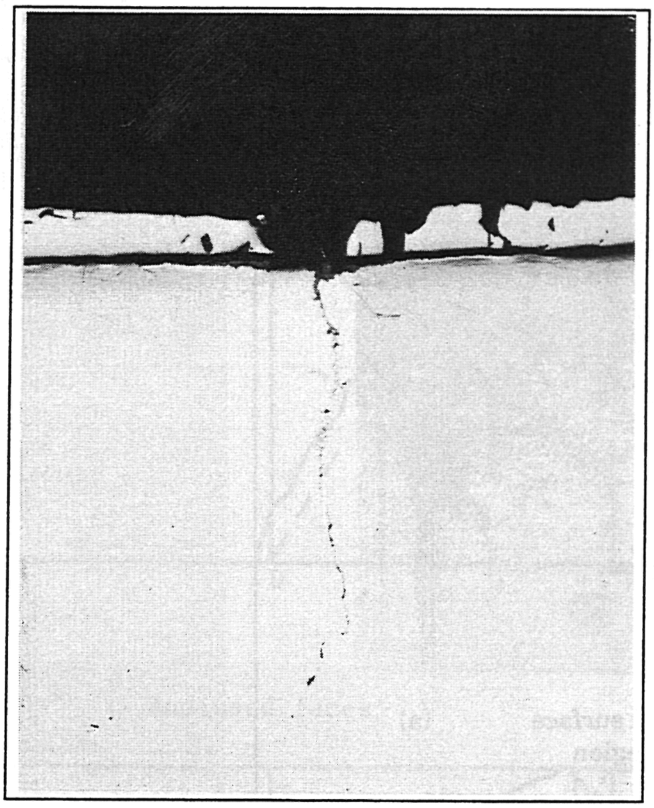


Cr-PLATED STANDARD SINGLE TAPER MOULD TB388 **FIG. 2 (R3/8888)**





Cr-PLATED DUAL TAPER MOULD 207483 FIG. 3
(R3/4202)

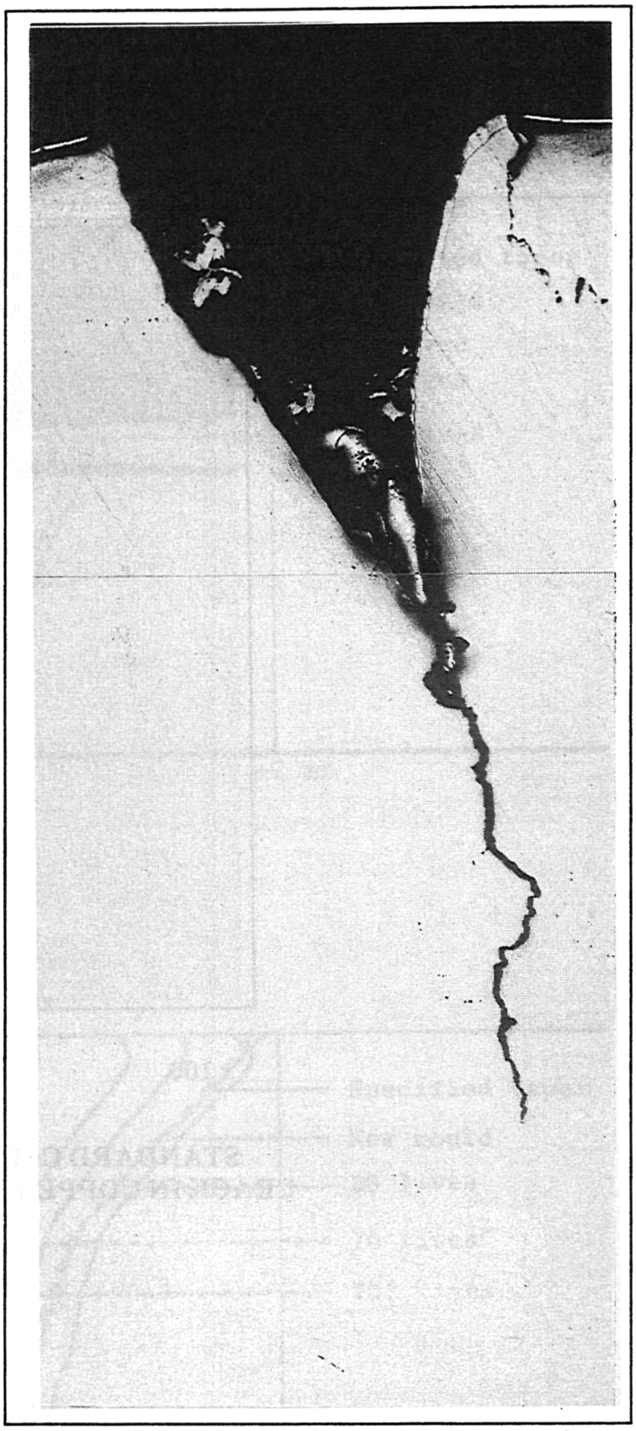


x 100

STANDARD Cr PLATED MOULD (181916)
CRACK IN COPPER IN SUBMENISCUS REGION

FIG. 4

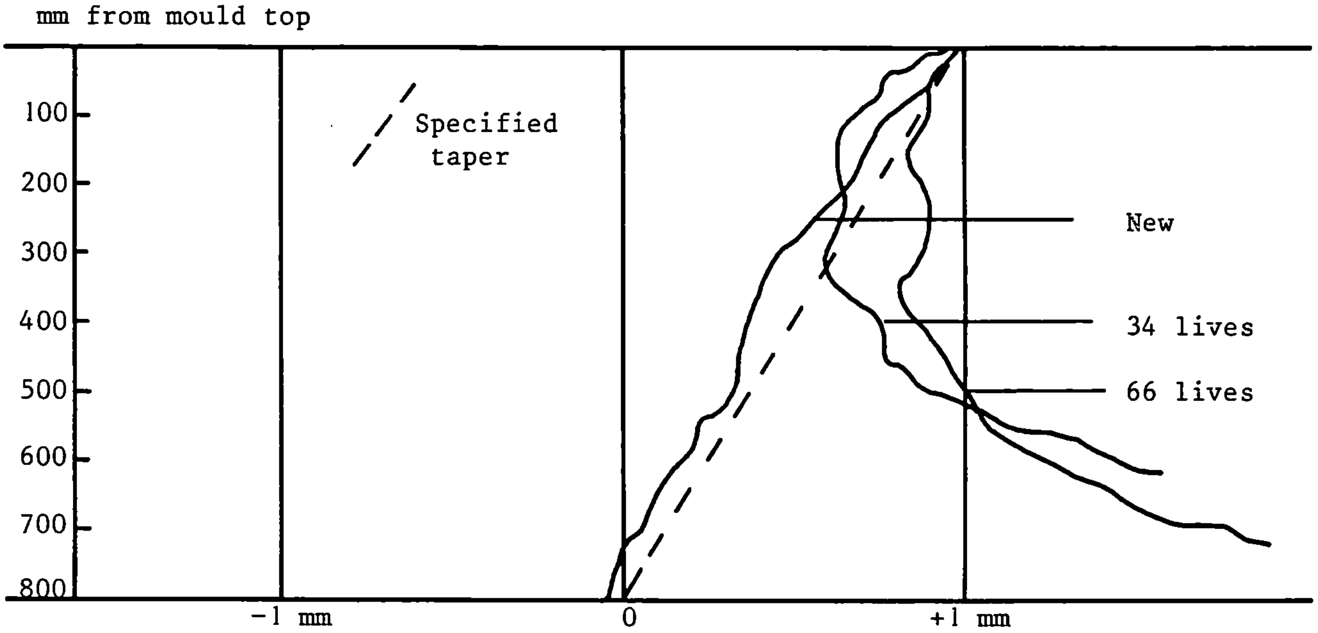
x 3.5 Mould internal surface meniscus region (a)



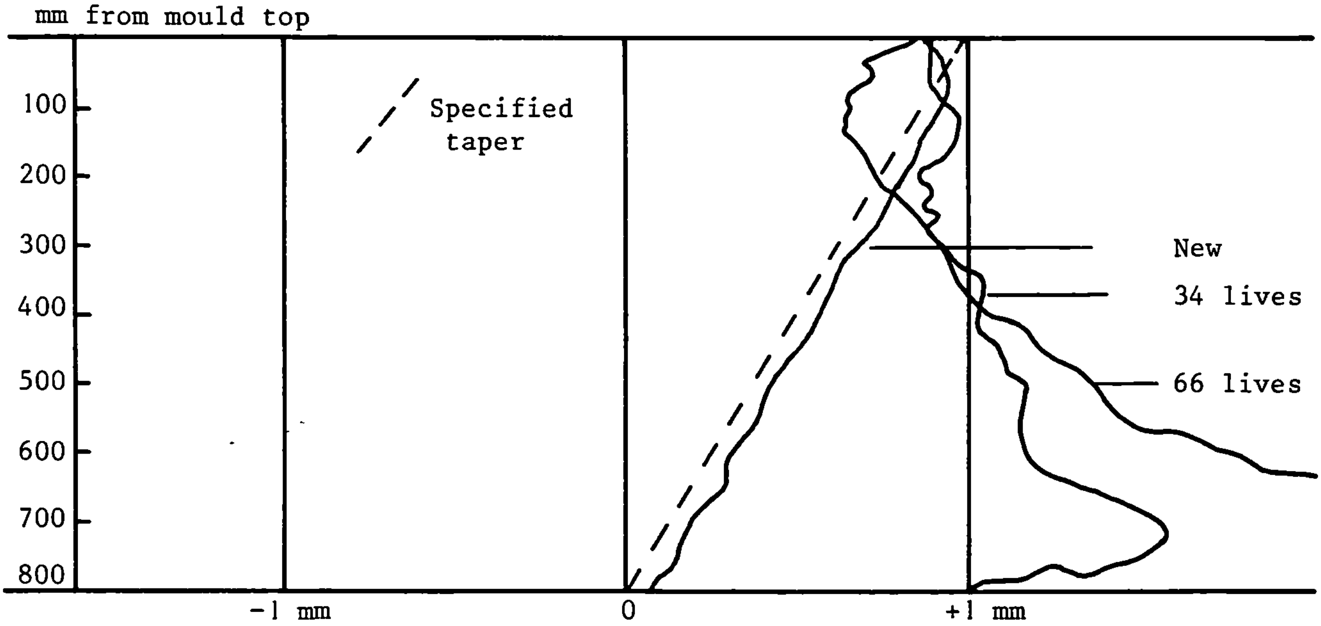
x 50 Longitudinal section through mould at internal surface meniscus region (b)

CHROMIUM PLATED MOULD TB2066: SEVERE CRACKING ASSOCIATED WITH SULPHUR PENETRATION AND BRASS FORMATION FIG. 5

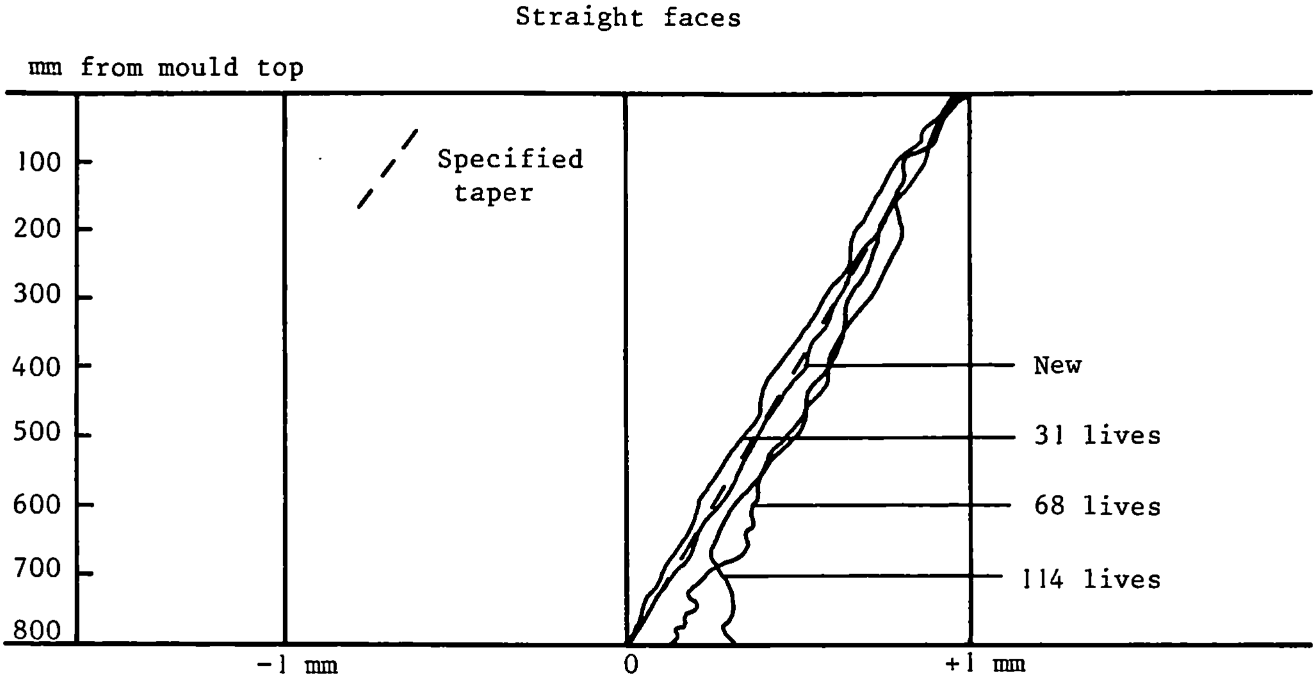
Straight faces

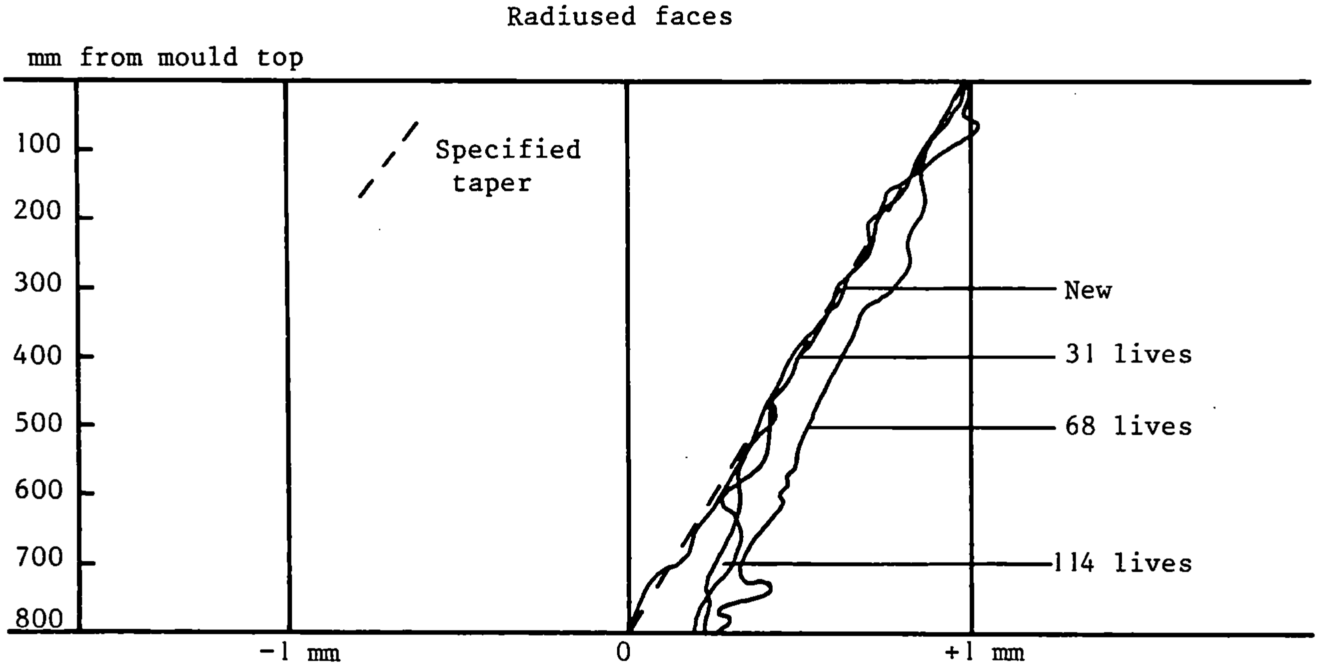


Radiused faces

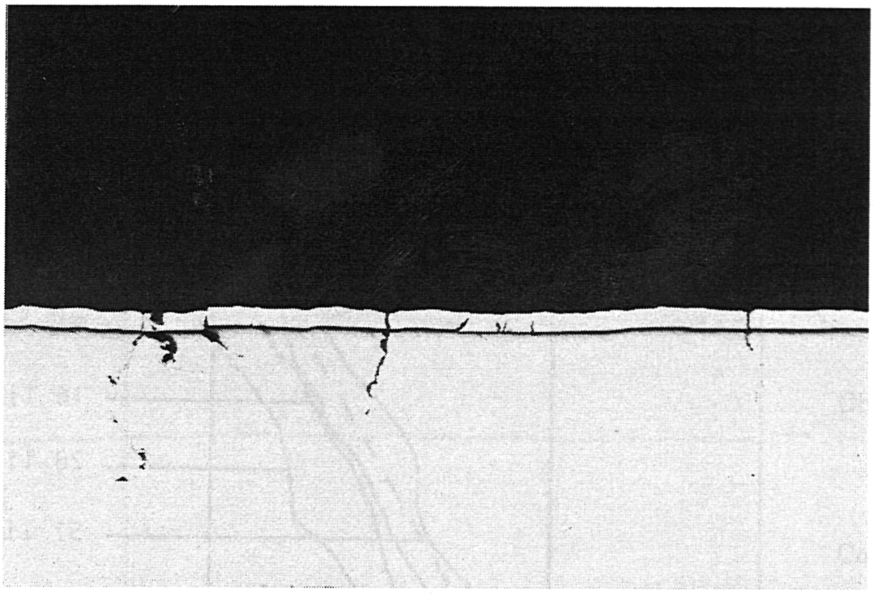


FIRST TiN COATED SINGLE TAPER MOULD TBJ388 **FIG. 6**
(R3/8889)



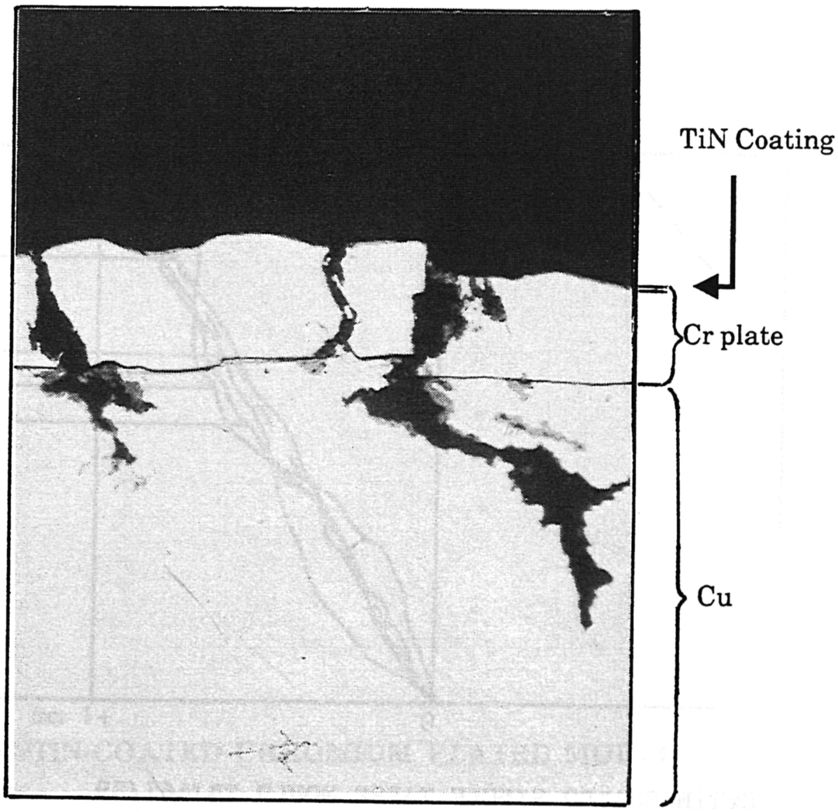


SECOND TiN COATED SINGLE TAPER MOULD TBJ387 **FIG. 7**
(R3/8890)



x 50

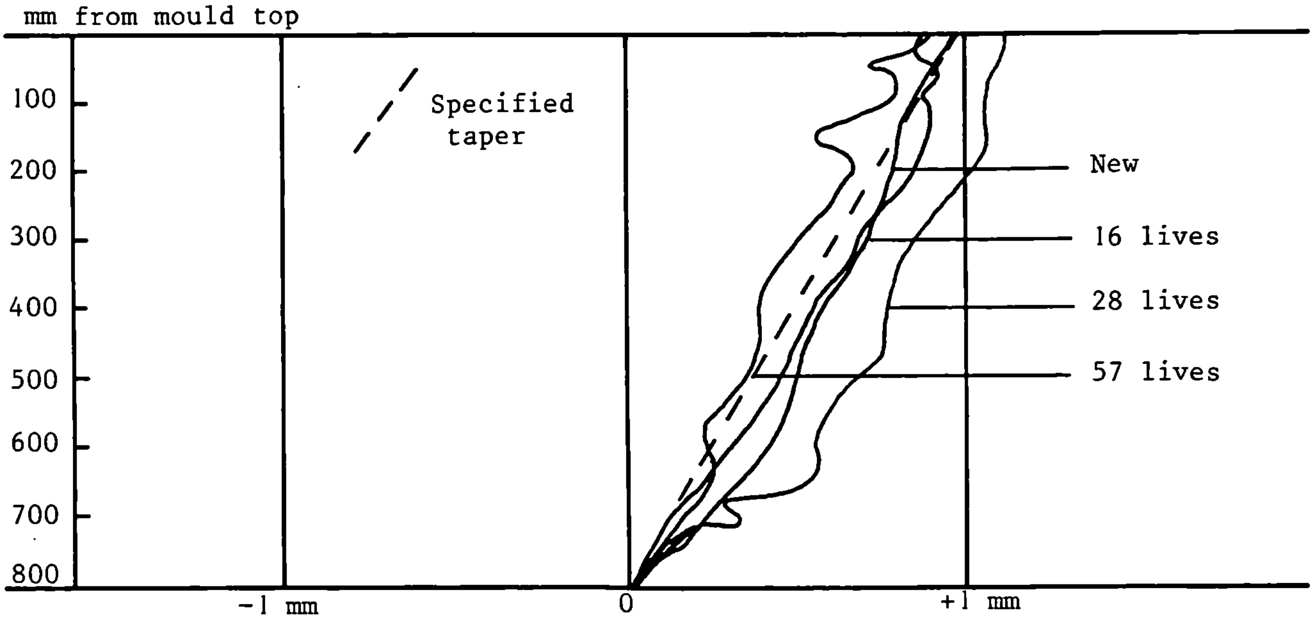
SECOND TiN MOULD SHOWING DEVELOPMENT OF CRACKS INITIATED AT MICROCRACKS IN Cr PLATE FIG. 8(a)



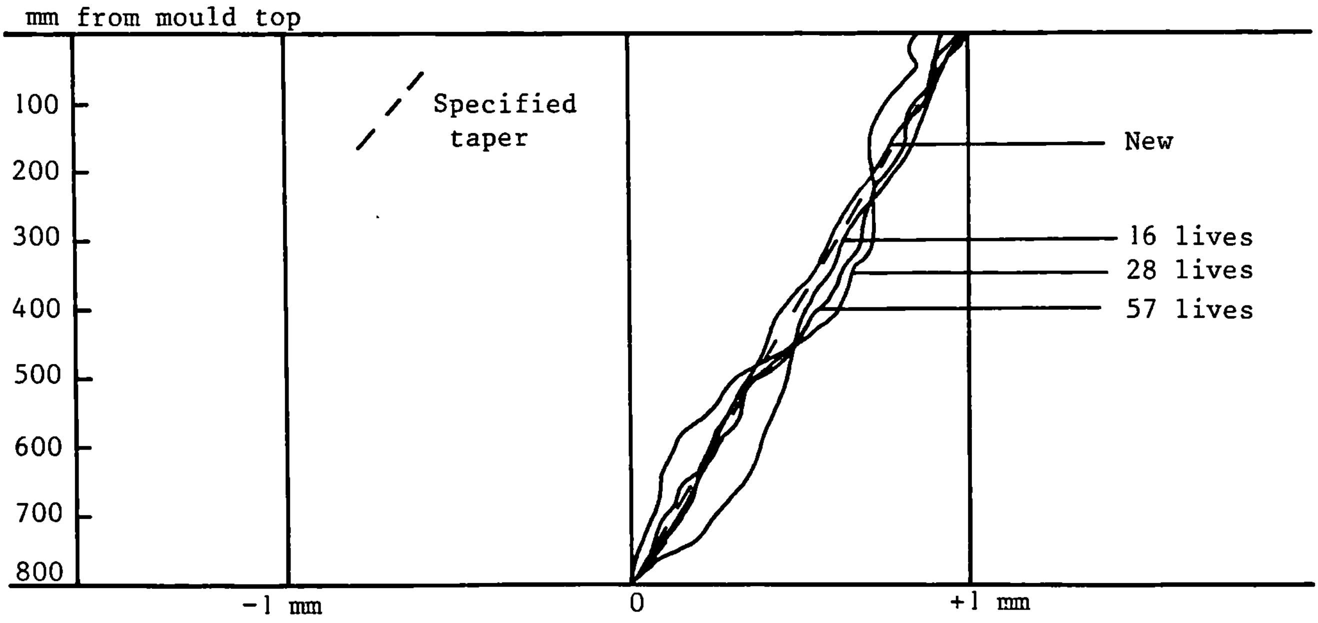
x 300

SECOND TiN COATED MOULD SHOWING OXIDISED CRACKS IN UNDERLYING COPPER FIG. 8(b)

Straight faces

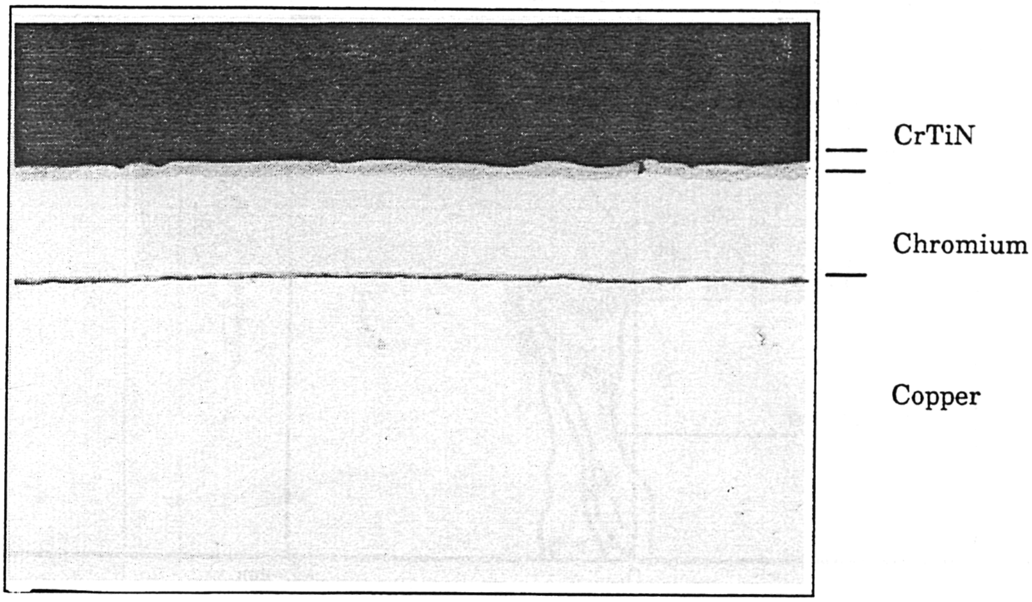


Radiused faces



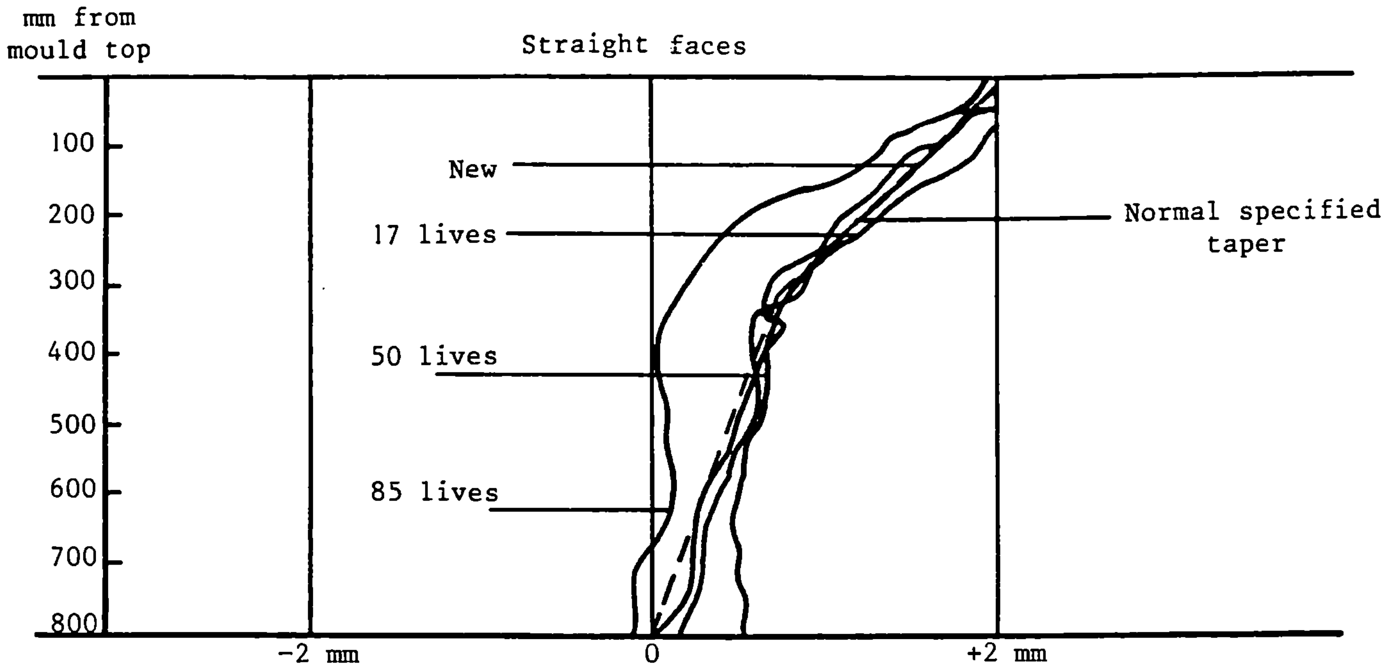
CrTiN COATED SINGLE TAPER MOULD TBJ461/89

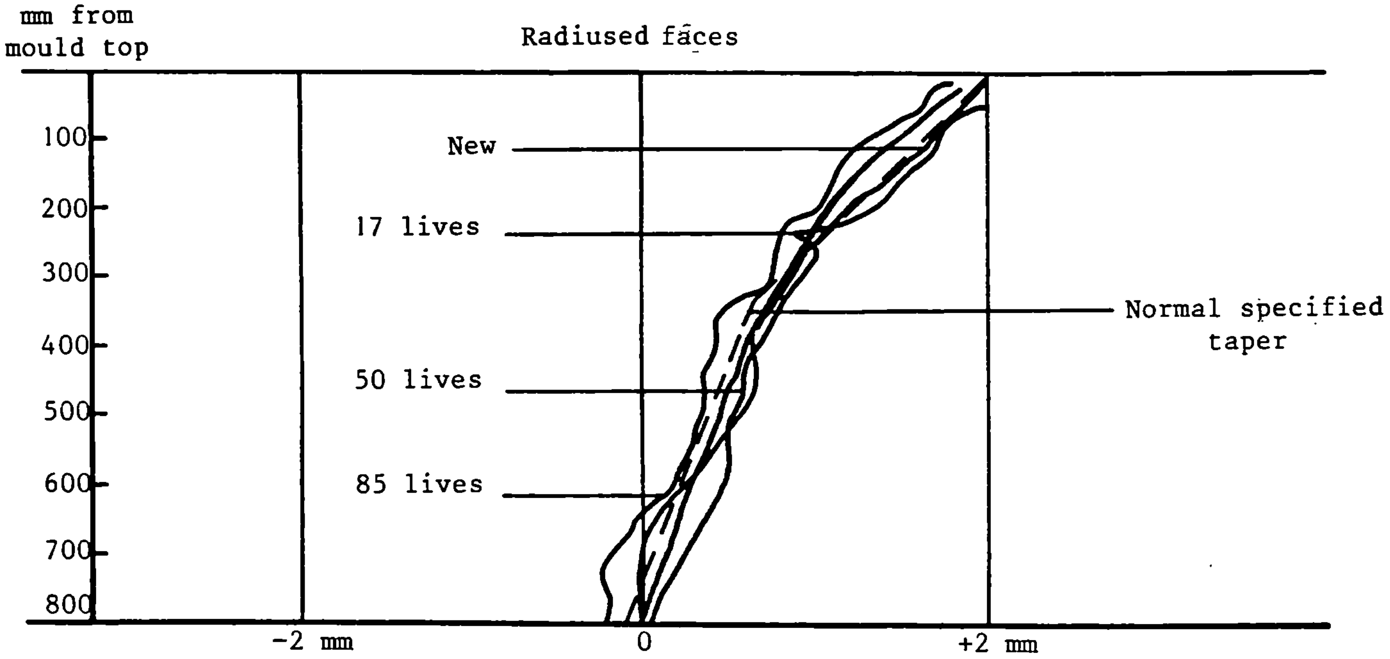
FIG. 9
(R3/8891)



x 300

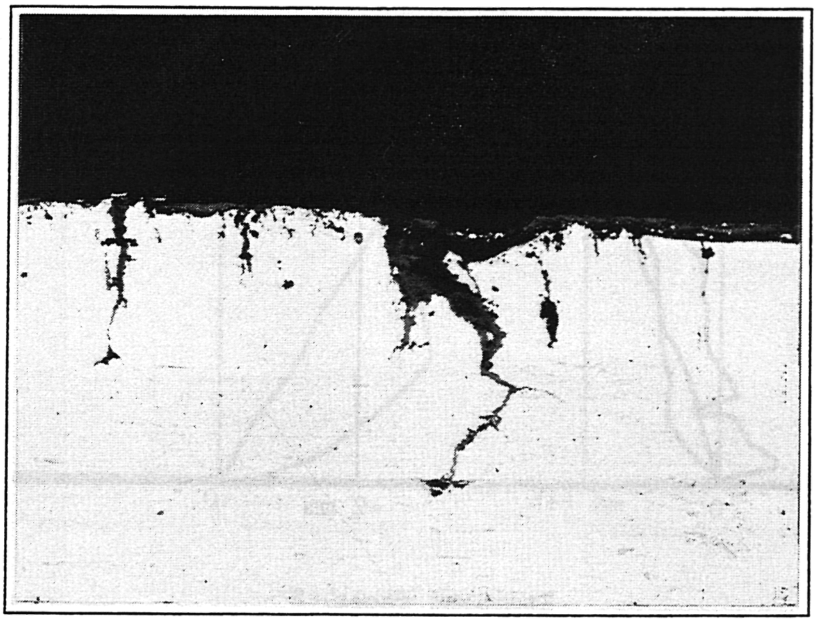
CrTiN-COATED CHROMIUM PLATED MOULD FIG. 10





Ni/Ni-PTFE COATED MOULD DUAL-TAPERED

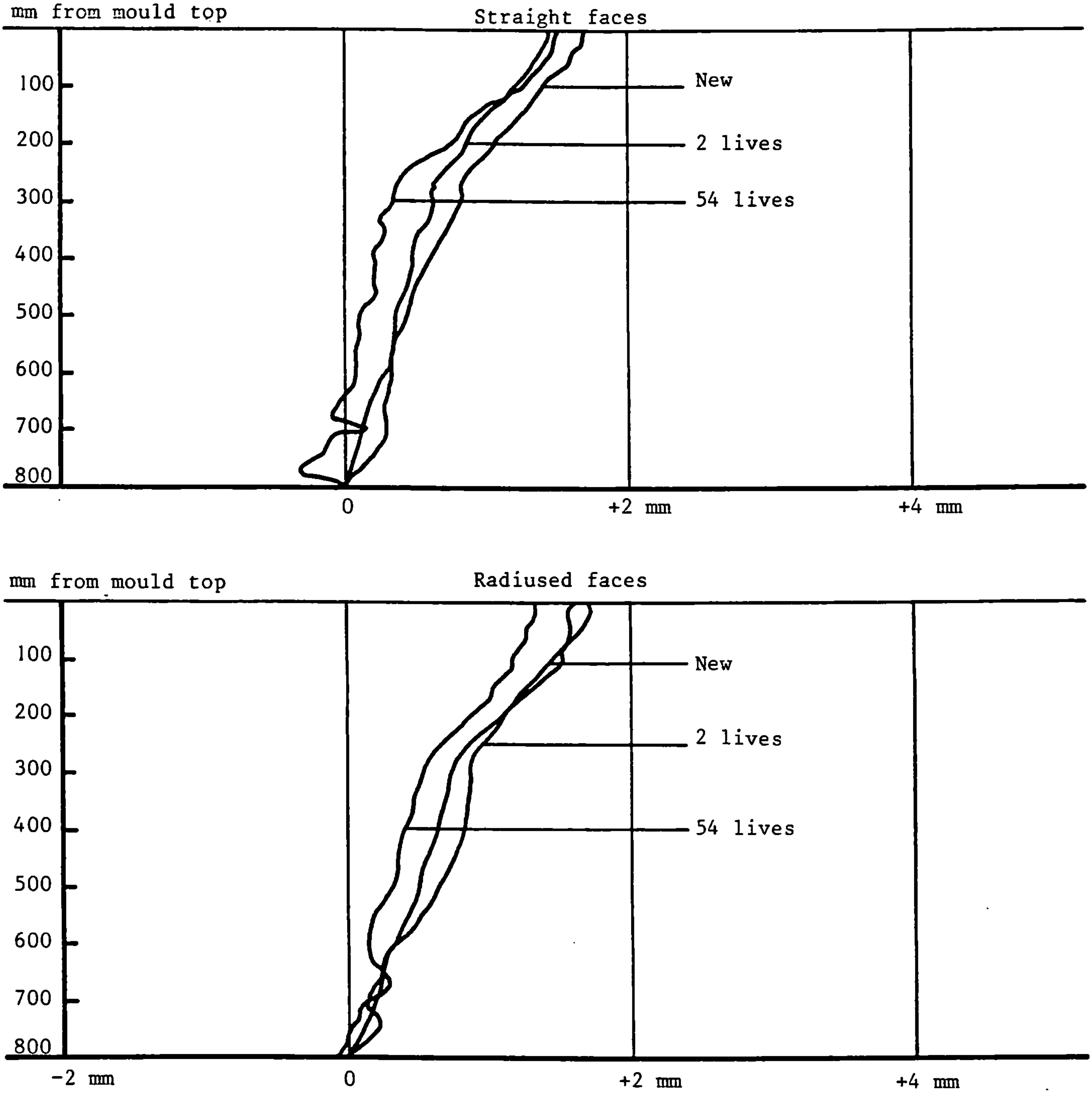
FIG. 11 (R3/5990)



x 300

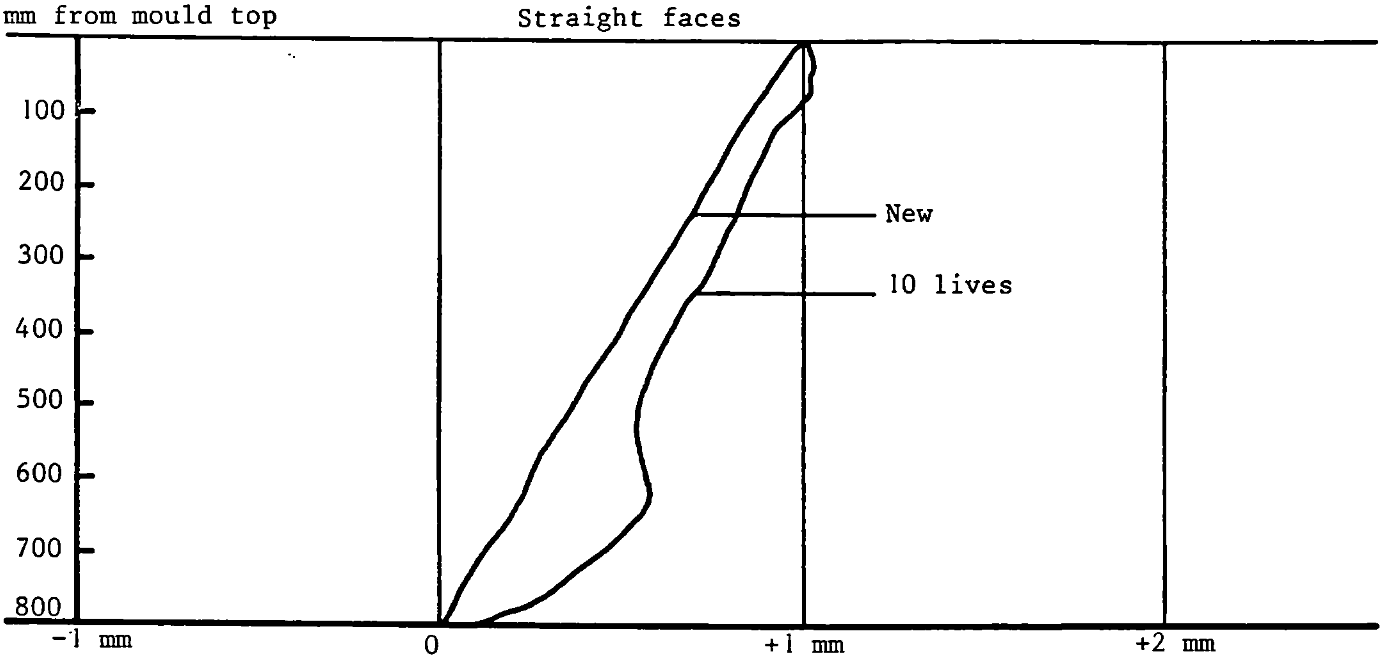
NICKEL/NICKEL-PTFE MOULD
MENISCUS REGION

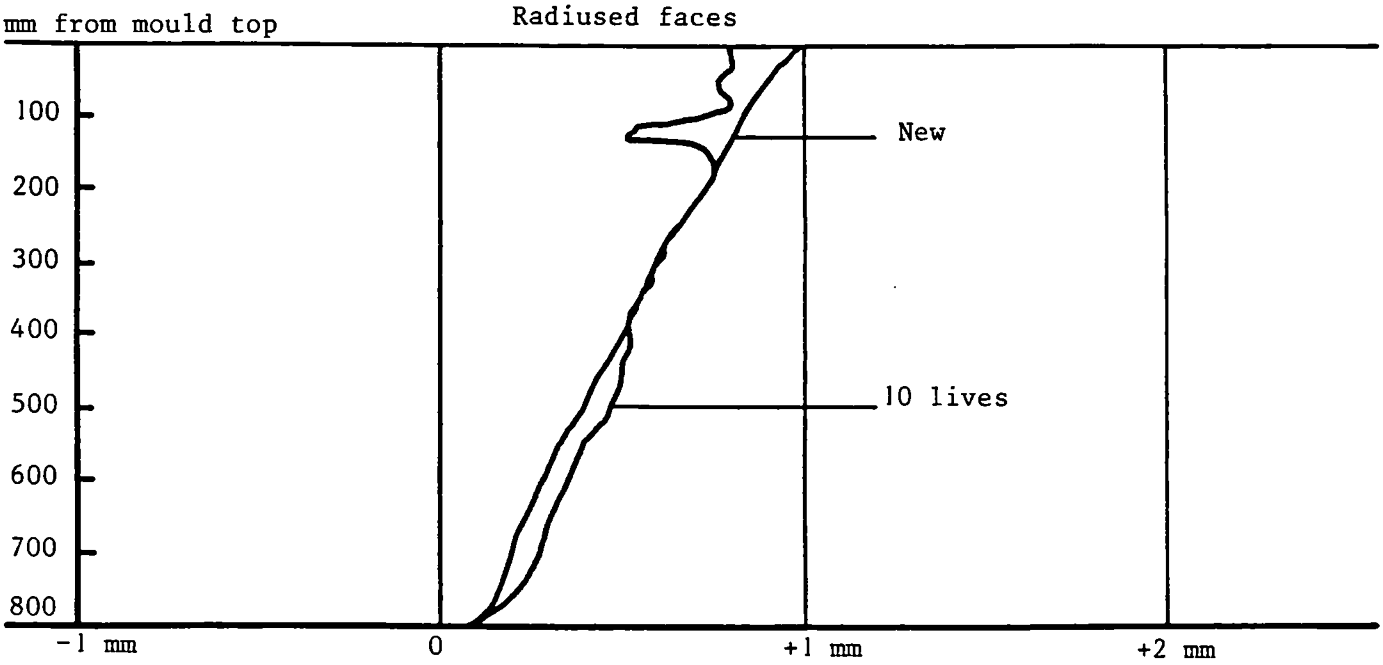
FIG. 12



ELECTROLESS NICKEL/5100 COATED
DUAL TAPER MOULD 207491

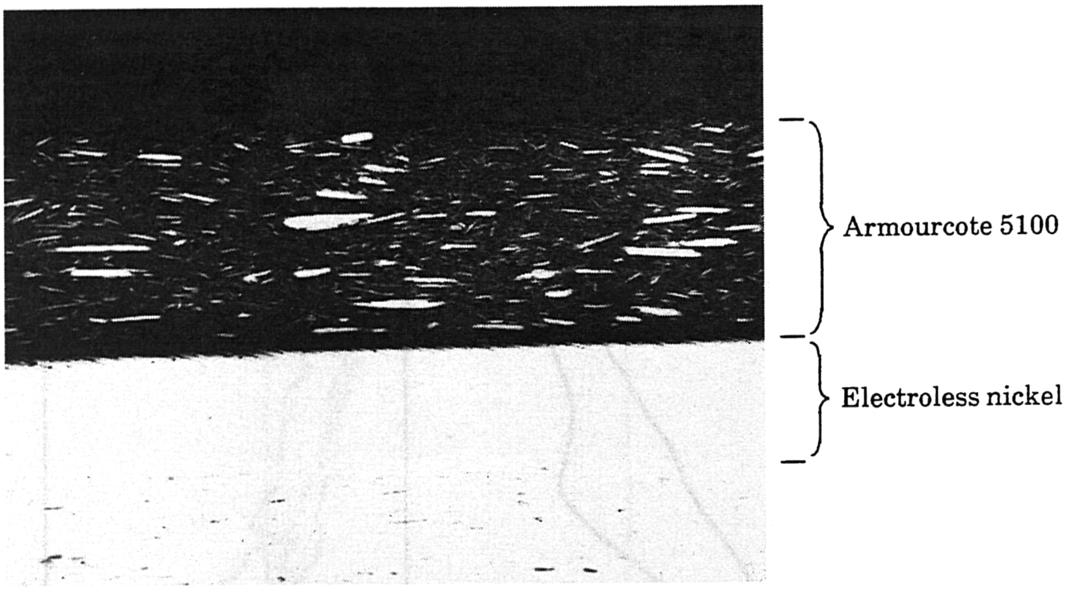
FIG. 13
(R3/7520)



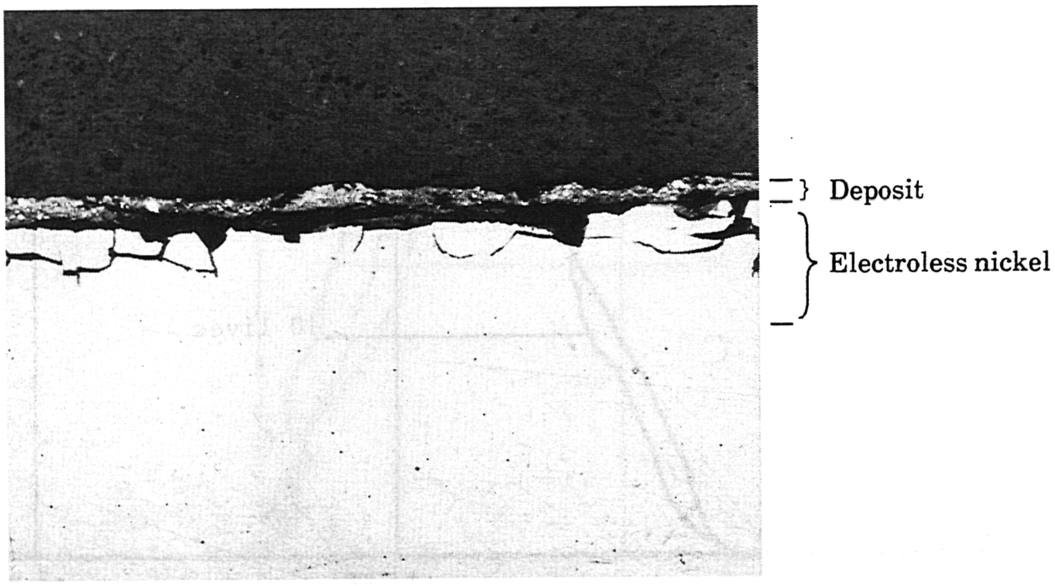


**ELECTROLESS NICKEL/5100 COATED
SINGLE TAPER MOULD 237844**

**FIG. 14
(R3/7521)**

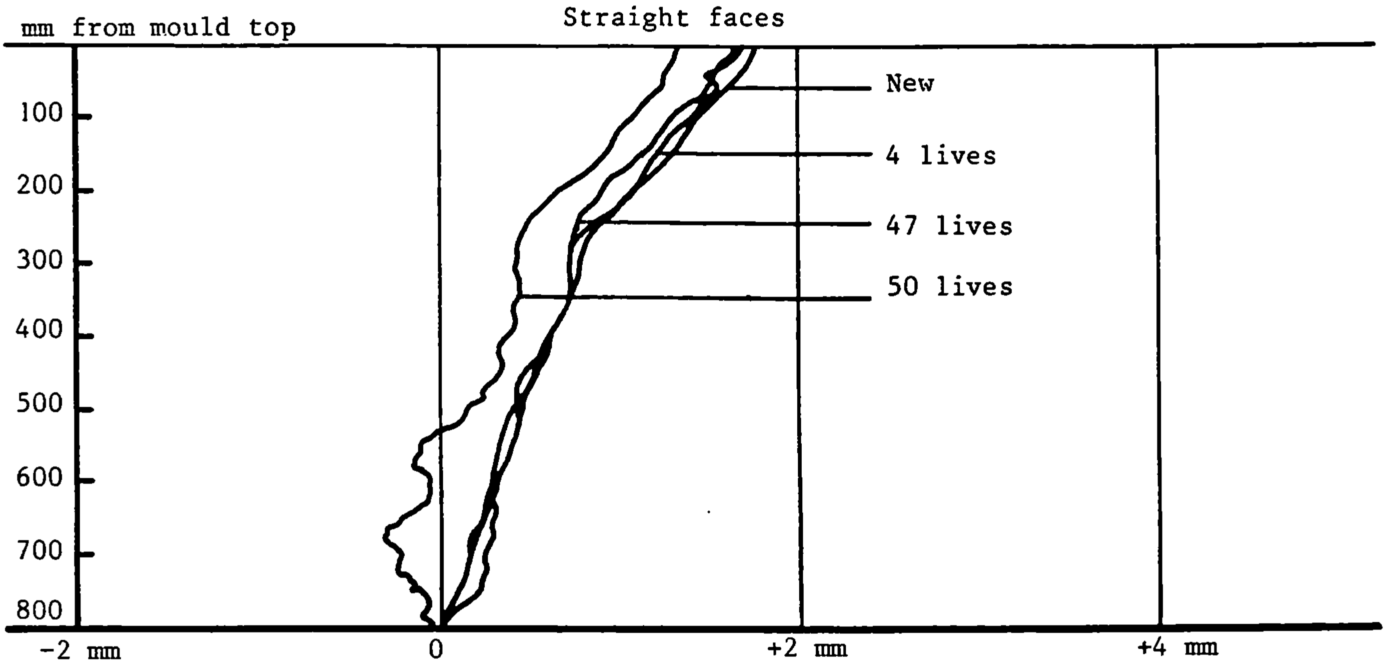


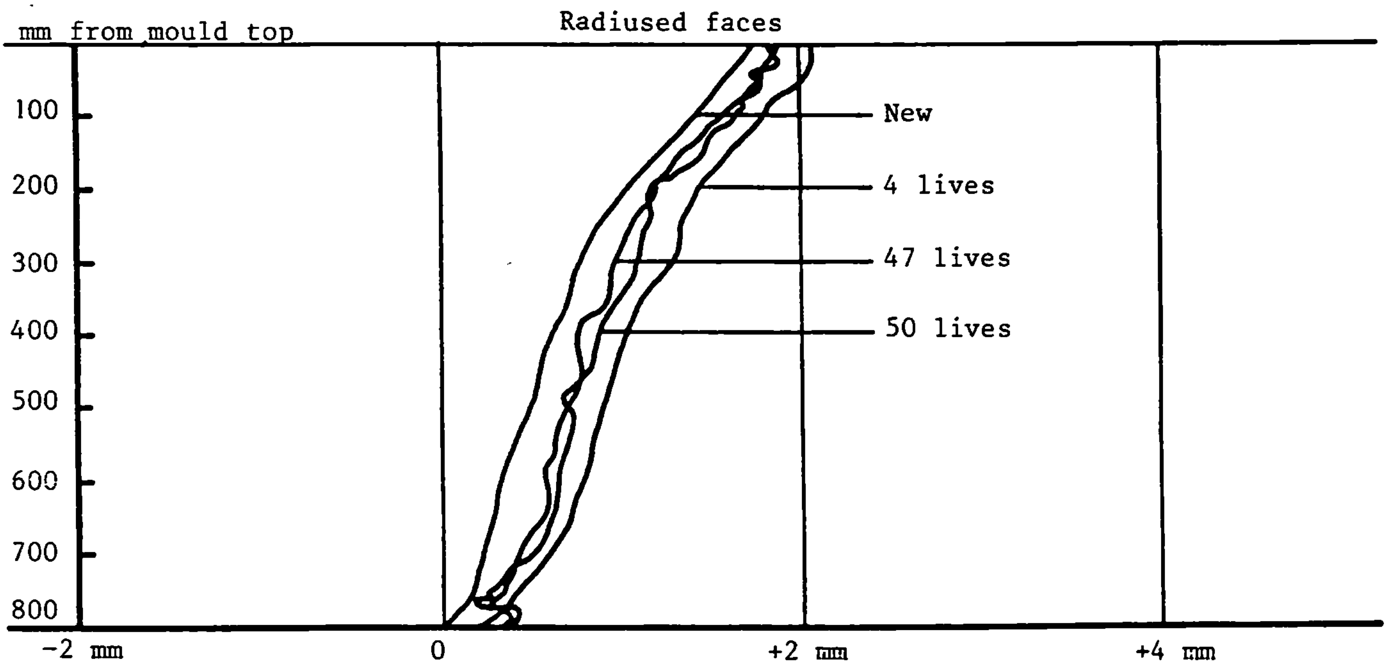
x 300 Sample from area of mould not in contact with steel (a)



x 300 Sample from meniscus region showing deposit of Zn, Mn and S (b)

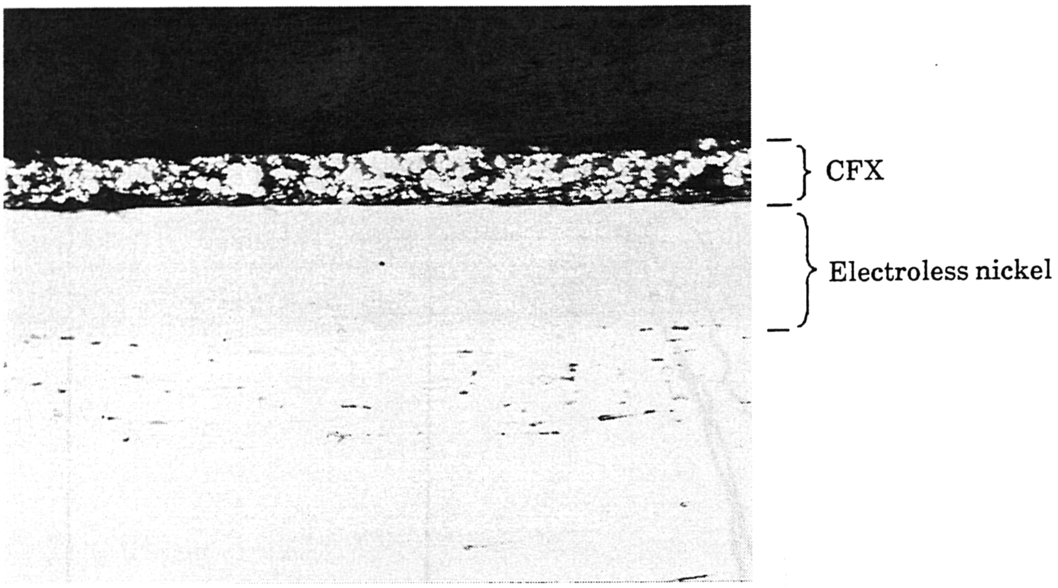
ARMOURCOTE 5100 COATED MOULD **FIG. 15**



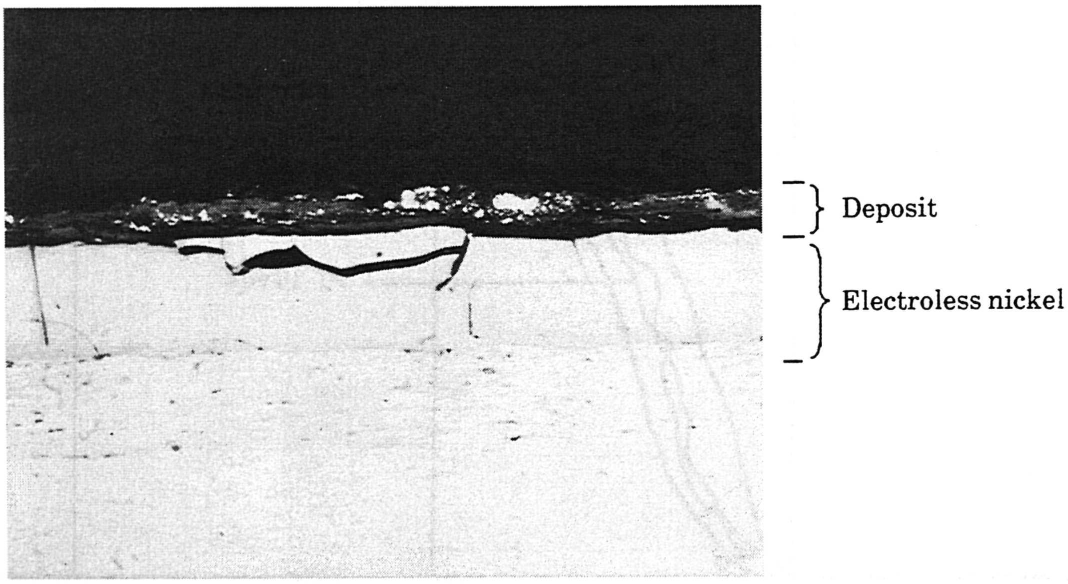


ELECTROLESS NICKEL/CFX COATED
DUAL TAPER MOULD 207489

FIG. 16
(R3/7519)



x 300 Sample from area of mould not in contact with steel (a)



x 300 Sample from meniscus region showing deposit of Zn, Mn and S (b)

ARMOURCOTE CFX COATED MOULDS **FIG. 17**

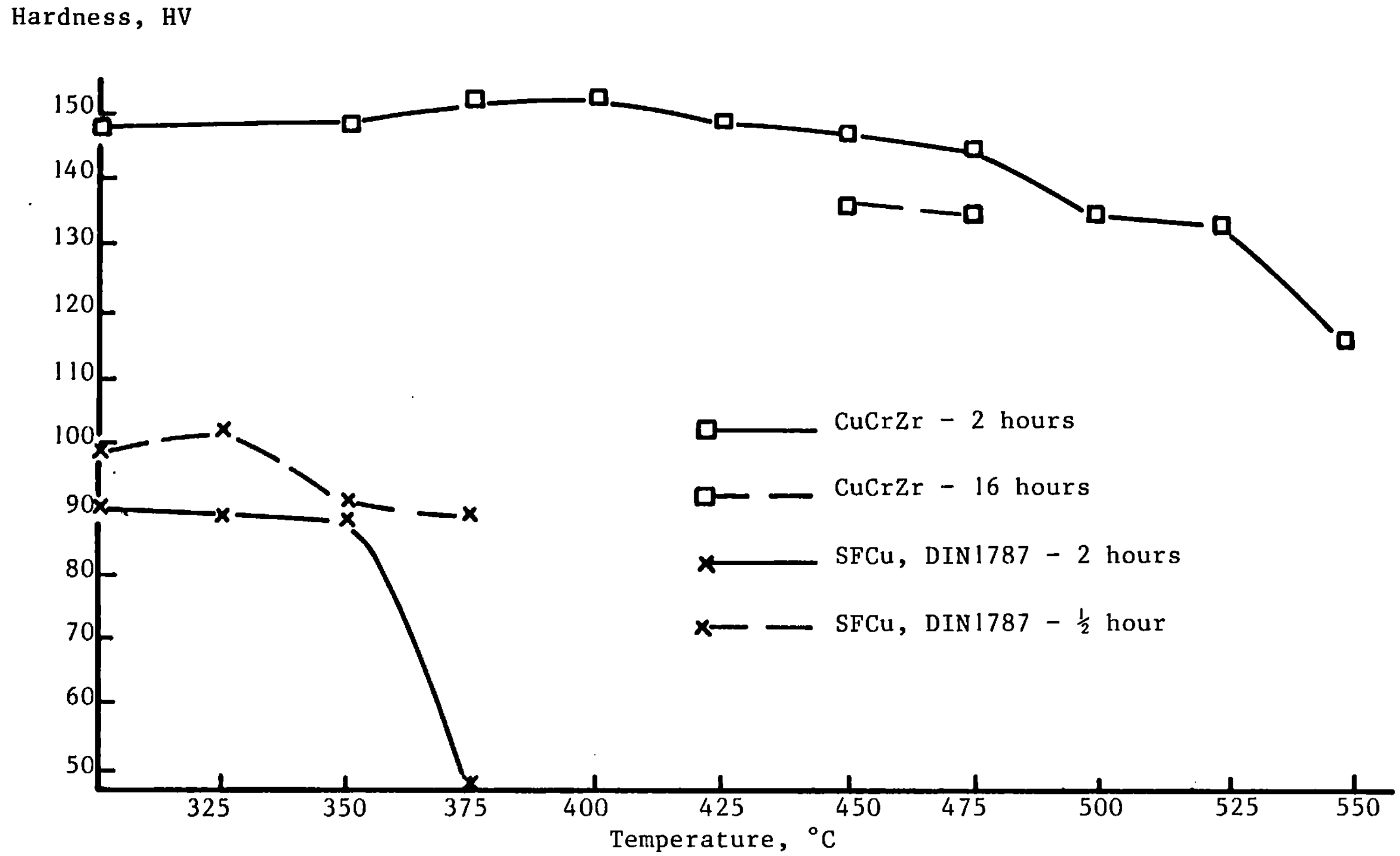
APPENDIX 1
SOFTENING CHARACTERISTICS OF COPPER

The thermal conditions employed during the surface coating of copper mould tubes have been shown to influence service performance during casting. Accordingly, to define limiting conditions in terms of the effect of thermal treatment on hardness, a study was made of the softening characteristics of two representative mould materials, phosphorised SF copper, DIN 1787 and a precipitation hardened, chromium-zirconium-containing copper.

The results of the work are presented in Fig. A1.1.

No significant change in hardness results from treatments up to 300°C.

As seen from the figure, coating temperatures in excess of 350°C, unless of very short duration are likely to produce significant softening in the standard copper. With the precipitation hardened copper a much higher temperature threshold appears feasible, with even prolonged exposure at up to 475°C producing little softening.



SOFTENING CHARACTERISTICS OF SFCu, DIN1787 AND CuCrZr MOULDS

FIG. A1.1
(R3/8891A)

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European Commission

EUR 15749 — Steelmaking
Mould coatings for continuously cast billet production

F. Faries, J. Rawson, A. Rose, M. Bugdol

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A study has been made of the use of coatings applied to the interior of continuous casting billet moulds, with the objective of improving billet surface quality, particularly for oil lubricated casts, and extending mould service life.

The range of coatings available was restricted by the need to avoid softening of the copper, precluding the use of a number of oxide and carbide deposition techniques. The constraint on internal accessibility imposed by the mould geometry further restricted the choice of possible coatings.

Coated 140 mm section moulds have been used in commercial trials to produce a range of carbon and low alloy steel billets. The mould coatings comprised Cr plating, Cr plating overlaid with TiN and CrTiN, and primary electroless Ni overlaid with ZrN and a series of proprietary low temperature deposits, including Ni/PTFE.

Comparisons have been made of the quality of billet surfaces produced with each coating and mould service performance has also been assessed in each case.

Only the nitrides on Cr plating and Ni/PTFE coatings on electroless Ni showed satisfactory resistance to damage in service, with the Ni/PTFE providing some evidence of advantages to both mould condition and billet surface quality.

Plant measurements have included mould friction and heat transfer. Metallographic assessment has been made both of billets produced during the trials and of moulds after service.

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