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AN INVESTIGATION OF SOME MOLD POWDER RELATED STARTUP PROBLEMS

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ABSTRACT

This paper examines two mold powder related process problems experienced at BHP's Whyalla operations. Bands of deep transverse depressions extending about the perimeter of the strand in the first meter of cast product were identified as a potential cause of breakouts. These were associated with level drops in the mold during startup that allow sintered material to accumulate against the mold wall creating a template for depression formation. Extended delays in achieving steady state heat transfer conditions were observed on grades employing low basicity operating powders, and are ascribed to the retention of high basicity slag in the mold. Laboratory studies have identified a possible difficulty in replacing high basicity slags from the mold using low basicity slags due to their greater adhesion with the mold wall (as indicated by lower interfacial heat transfer resistance measurements). Mathematical modelling simulations indicated that higher slag consumption and a static solid slag layer both decrease mold temperature. Steady state conditions were achieved more rapidly by reducing the amount of mixing between startup and operating powders in the mold by delaying the addition of operating powder. This practice also reduced the severity of transverse depressions during startup.

INTRODUCTION

This paper investigates some mold powder related defects and thermal phenomena associated with startup based on data collected at BHP's Whyalla caster. The BHP Whyalla caster began operation in April 1992, and is capable of casting in single or twin slab, or triple bloom configurations. The plant has a capability of 1.15 mtpa and holds the Australian record for breakout free production.

Two years of unbroken production was interrupted by a sticker breakout in August 1996. This paper reports on the following investigation that examined the mold powder related issues that made the process susceptible to breakouts. Two related phenomena are identified and addressed in this paper. The first focuses on bands of deep depressions which extend around the perimeter of the mold in the first few meters of cast product. The second examines the cause of extended delays in reaching steady state thermal operation after startup. Both phenomena increase the susceptibility of the cast product to breakouts.

Transverse Depressions

Bands of deep transverse depressions extending around the entire perimeter of the strand are commonly observed on high carbon blooms. These can be up to 10 mm deep, and generally occur in either a single or double band in the first few meters of cast product as shown below in Fig. 1. Although sufficiently far removed from the tear in the shell not to be a cause in this breakout, these depressions were deep enough to be of concern. The generation of transverse depressions on startup was therefore included as a part of the investigation.

Fig. 1 **Deep depression extending around the perimeter of the mold occurring during startup.**

Steady State Delay

The investigation began with inspection of recorded plant data. Mold thermocouple data for both the breakout cast and several other steel products revealed unusual performance during the first heat of each sequence. Long delays in achieving steady state heat transfer conditions were observed on several grades, particularly high carbon rail grades where delays of up to an hour were experienced. Mold thermocouple response during these times revealed lower temperatures with fewer and less severe temperature fluctuations than encountered once "steady" thermal operation was achieved. Figure 2 shows a typical temperature history for this period. The temperature decreases progressively from the top of the mold down over a period of 5 to 10 minutes. The period of low temperature lasts for almost an hour whereupon temperatures rise rapidly. The period after this “recovery” point is denoted as “steady” operation as average thermocouple response remains effectively constant for several hours.

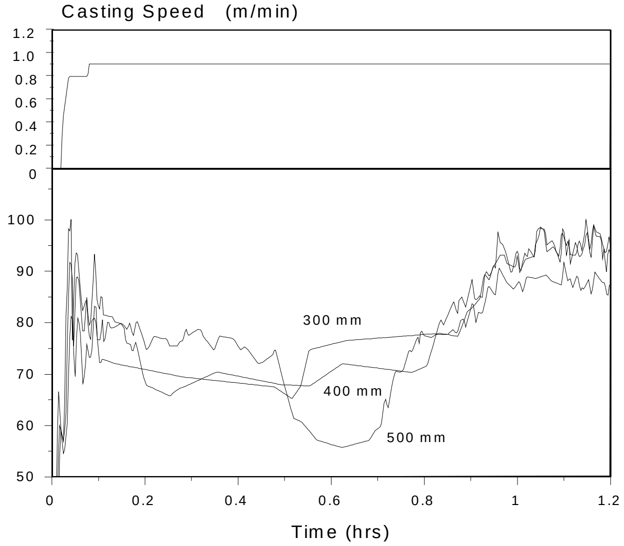

Fig. 2 **Mold temperature histories (as recorded by thermocouples located 300, 400 and 500 mm from the top of the mold) showing delay in achieving steady state.**

The decrease in mold thermocouple temperatures corresponds to a reduction in heat transfer. Low heat transfer reduces the solidified thickness of the steel shell. If general shell thinning is too severe, then a local thin region on the shell, such as under a depression, may breakout when the shell exits the mold. Heat transfer in the mold is primarily governed by the performance of the mold powder. Evidence for the loss of heat transfer during this transition period was therefore sought through the examination of solid slag shells recovered from the mold.

Slag Sample Analysis

Two slag samples were recovered after the breakout; one from immediately below the meniscus against the mold wall; the other from a deep depression in the first few meters of cast product. For comparison, a sample of slag shell recovered from the top of the mold during tailout of a successfully cast sequence of similar product and conditions was also obtained. Both breakout samples exhibited a porous crystalline structure, which contrasted markedly with the glassy structure observed from the tailout specimen (Fig. 3). The slag composition and structure were investigated using a JEOL JXA Scanning Electron Microscope with Energy Dispersive X-ray Analysis, which was calibrated using standard samples.

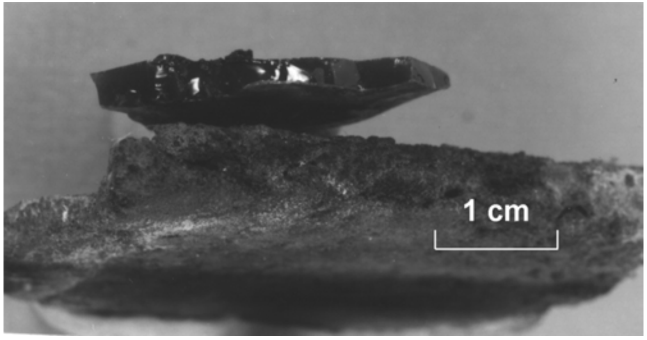

Fig. 3 **Samples of slag recovered from the mold after a breakout (lower) and tailout (upper).**

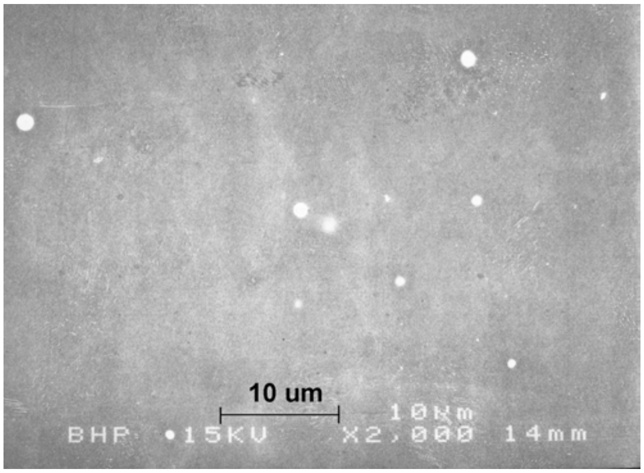

Fig. 4 **Micrograph of slag shell recovered from the mold wall during tailout after 6 hrs of casting revealing a glassy structure.**

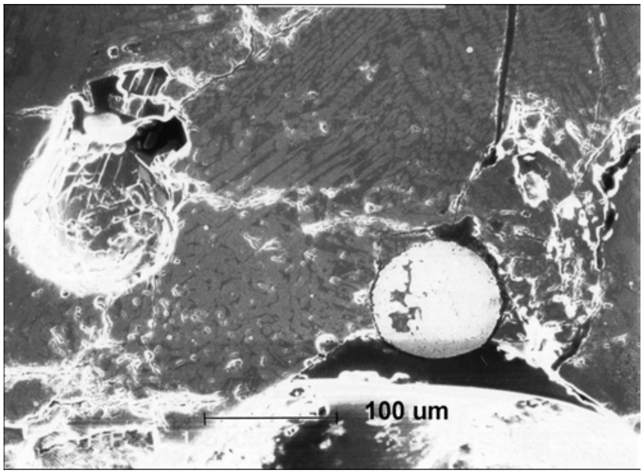

Fig. 5 **Micrograph of slag shell recovered from the mold after a breakout (10 min into cast) showing porous, crystalline structure.**

The tailout sample (Fig 4) exhibited a predominantly glassy structure containing a dispersion of very fine (< 1 µm) globular metallic droplets. Analysis of the base matrix reveals a composition consistent with the specifications of this glass forming operating powder. The tiny globules contained a mixture of iron and silicon and often included low levels of manganese.

Slag samples recovered during the transition to steady state (ie from startup depressions and breakout) revealed a significantly different structure (Fig. 5). Large (up to several hundred µm) iron-silicon based globules dispersed in a two phase matrix were observed. The predominant (dark) phase of the base matrix (dark) was CaO rich and exhibited a crystalline structure.

Laboratory Slag Analysis

Two different types of mold powders are used in the casting process. In addition to the powder normally used during casting (viz “operating powder”), a special exothermic slag or “startup powder” is added to the mold during the initial filling. Heat is released through the oxidation of silicon by iron oxide (itself reduced to iron) and atmospheric oxygen. The heat generated facilitates rapid melting which helps ensure lubrication during the first few minutes of casting.

Samples of startup and operating powder were melted and resolidified in the laboratory and their structure then analysed. Only startup powder samples were observed to exhibit a dispersed metallic droplet phase of silicon and iron. Its origin probably arises from incomplete oxidation of silicon. This silicon agglomerates with the iron formed by the reaction between silicon and iron oxide. Thus the presence of globular iron-silicon droplets in breakout slag samples (obtained during the period of low flat temperature 10 minutes after casting begins), provides direct evidence for the persistence of startup powder in the mold.

The addition of operating powder directly on top of a high basicity startup powder in the mold is likely to cause undesirable mixing of slags. Slag intermixing produces a larger quantity of slag with a basicity greater than that of the operating powder. This may be sufficient to prevent a glassy slag layer forming against the mold wall once casting begins. Breakout slag sample compositions may therefore reflect a mixture of startup and operating slags (cf Table 1). Tailout sample composition however, indicates essentially pure operating slag.

The solid slag layer high in the mold may persist for an extremely long time, especially that part which extends above the meniscus. The deposition of startup slag into such layers may permit its subsequent pickup by operating slag passing against it. This may contribute to contamination of the operating slag long after startup.

Effect of slag composition on heat transfer

Increasing the degree of crystallinity in the solidified slag layer is known to increase the total resistance to heat transfer between the shell and the mold [1]. This is because the slag becomes opaque to thermal radiation, which suppresses radiative transfer and effectively lowers its conductivity. Previous studies [1,2] have demonstrated the dependence of slag structure on basicity (Fig 6). As basicity increases, the tendency for a slag to crystallise also increases. The increase in operating powder basicity resulting from its contamination with startup powder will greatly facilitate crystallisation on solidification. In addition the mixing of slags may further retard heat transfer by permitting carbon (from the operating powder) to react with easily reducible oxides in the startup slag (ie iron oxide) producing porosity in the slag. Both crystallisation and porosity would contribute significantly to the observed drop in mold heat transfer during the low-flat period of temperature response after startup.

Table 1 Composition Analyses Mold Powders and Slag Shell Samples

Component	Startup Powder	Breakout Slag Shell			Tailout Shell		Operating Powder
		Dark Phase	Light Phase	Dispersed Phase (10-100 µm)	Dispersed Phase (1-2 µm)	Light Phase	
CaO	36.5	10.2	56.5	Fe 68.1	Fe 54.1	24.0	22.5
SiO_2/SiC/Si	37.1	51.0	52.4	Si 18.4	Si 25.3	47	33.5
Al_2O_3	1.5	13.0	-	Mn 12.3	Mn 20.5	10.5	5
Na_2O	7	16.0	-			12.3	11
F	10.5	-	-			trace	5
Fe_2O_3	18	-	-			-	2
C	-	-	-			-	18.5
Melting Point	1170 °C						1050 °C
V Ratio	0.98	0.2	1.08	Metal	Metal	0.51	0.65
BO/NBO	1.5						0.97

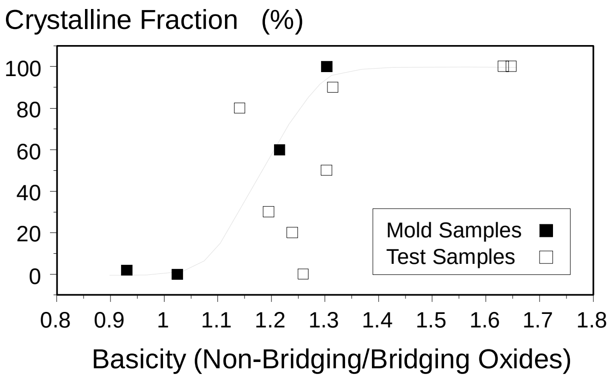

Fig. 6 **Effect of basicity on the degree of crystallinity in the slag layer**

The extent to which other products were affected by a slow transition to steady thermal conditions was investigated using historic thermocouple data from the caster. Figure 7 shows the maximum recorded delay for each operating powder used. It is evident from this data that only low basicity operating powders appear to experience a delay in achieving steady state. High basicity slags may be unaffected by startup powder contamination as their structure is already crystalline. Increasing basicity further will not promote additional crystallisation, and heat transfer to the mold will remain largely unchanged.

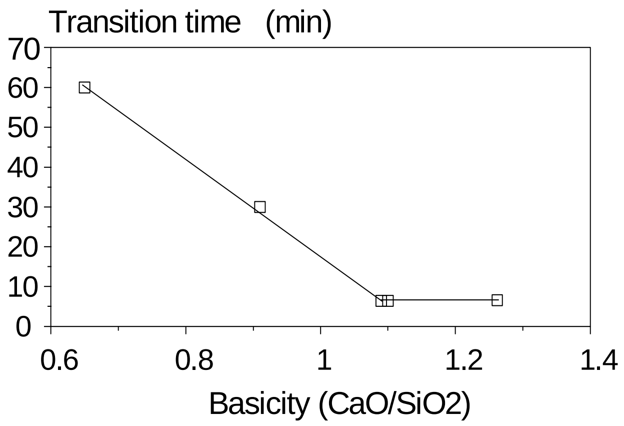

Fig. 7 **Effect of operating powder basicity (lime:silica ratio) on maximum recorded time required to reach steady state.**

Interfacial Heat Transfer Measurement

The influence of slag basicity on the nature of slag-mold contact was first conjectured by the observed variation in the degree of difficulty in removing slag from a copper substrate dipped in molten slag [3]. These early observations suggested that high basicity slags exhibited strong adhesion with the mold wall. A series of experiments were conducted to quantify the relationship between slag basicity and slag contact with a metal substrate by measuring the interfacial contact resistance using the "copper finger" technique, which has been described previously [4].

The experiment consists of immersing a water cooled copper tube into a graphite crucible of liquid slag (cf. Fig. 8) forming a solid slag shell. Monitoring the temperature rise and flowrate of the cooling water allows the rate of heat extraction through the slag layer to be calculated. Thermocouples positioned both within the slag medium and the wall of the copper "finger" define the steady-state temperature gradient through the solidified slag shell and across the interface. This information enables both the conductivity of the slag and its contact resistance with the wall to be evaluated using Fourier's law for steady heat conduction across concentric cylinder conductors. Liquid slag conductivity can also be measured using this device in addition to the temperature dependency of all measured properties. Fig. 8 shows the equipment configuration during a test.

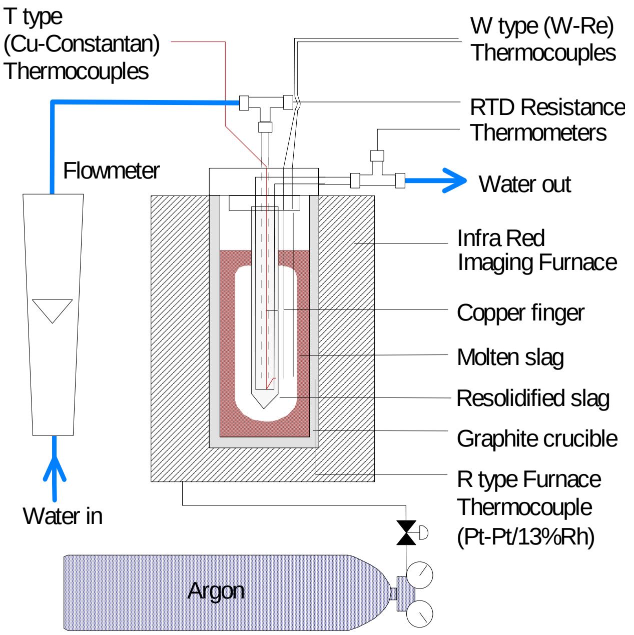

Fig. 8 **Schematic of experimental apparatus used to measure both slag conduction (phonon and radiative) and contact resistance.**

Test pieces were immersed at 1300 °C in the sample slag which was then cooled to 800 °C where steady state conditions were measured. Testing of these slags produced results which were consistent with the previous observations as shown in Fig. 9. In this graph, basicity is expressed by the mole ratio of non-bridging oxides to bridging oxides. The term bridging oxides (network formers) denotes SiO_2, Al_2O_3 and B_2O_3. Non-bridging oxides (network breakers) included all other oxides. Note that this measure of basicity does not incorporate the fluorine content of the slag. This limitation likely contributes to the scatter in the data.

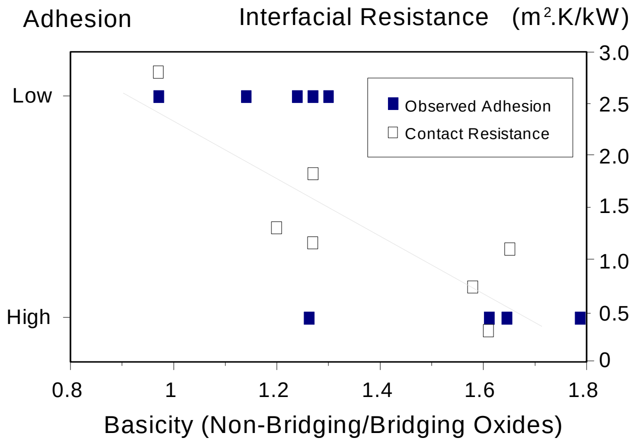

Fig. 9 **Effect of basicity on slag-substrate contact showing observed slag performance together with measured slag-substrate interfacial contact resistances.**

Increasing the basicity of mold powders increases their adhesion with the mold wall. Laboratory testing of startup powder exhibited strong adhesion, even to traditionally not wetting surfaces such as graphite. The superior adhesive properties demonstrated by this slag may contribute to its persistence in the mold, by making the slag layer more difficult to remove from the mold wall.

Mold Level Fluctuations

Previous studies have demonstrated the link between mold level fluctuations and the creation of both transverse [5] and longitudinal [6] depressions. The process of filling the mold and increasing casting speed causes severe perturbations in mold level. Mold level variation was therefore investigated as a possible cause of depressions during startup.

Direct comparison of recorded data with bloom surface measurements is complicated by mold filling and variations in casting speed. Strand distances were related to time by integrating the casting speed history and adjusting for mold level changes. Figure 10 presents the results of such an analysis for the breakout strand. The strand studied exhibited depressions in three transverse bands. Their separation is indicated by the series of three crosses in Fig. 10. The earliest (first) depression was most severe (over 5 mm deep) and the middle band the shallowest. The identical separation between level fluctuation events and surface depressions offers strong evidence for their association. It is interesting to note that the large cast length over which the final level fluctuation occurred indicates that the depression is introduced into the strand surface during a period of rising mold level.

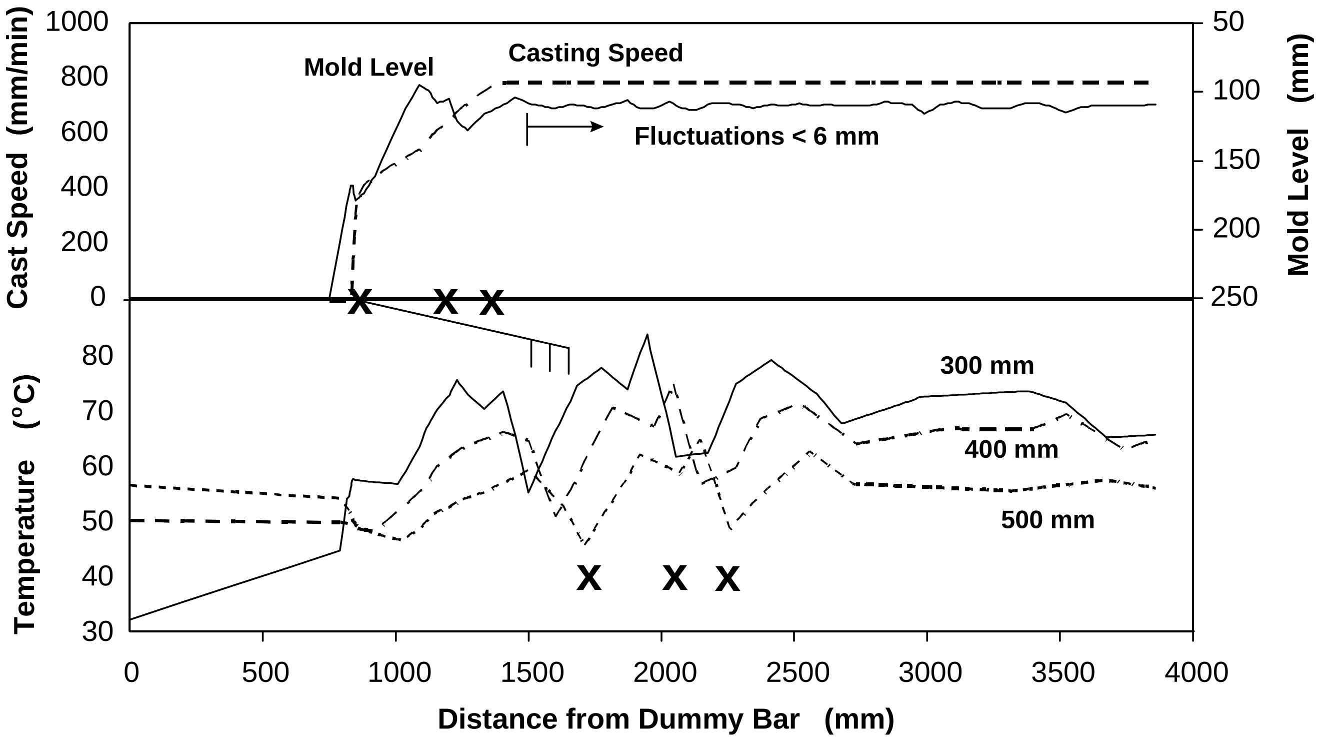

Fig. 10 **Depression and temperature fluctuations as a function of cast distance measured from the dummy bar compared with measured startup depression separations (as represented by the series of crosses).**

Inspection of mold thermocouple data during the first few minutes of startup revealed three drops in temperature (Fig. 10). These temperature troughs propagate down the mold at the casting speed which associates their origin with strand related surface features. The distance between these features corresponds well with the measured distance between the bands of startup depressions. This is illustrated in Fig. 10 by comparison of the lowest series of crosses with the temperature trace from the thermocouple located 500 mm from the top of the mold. These temperature troughs therefore mark the passage of these depressions down the mold.

The time between each mold level fluctuation and when a depression is observed to pass a particular thermocouple appears to be significantly longer than can be explained by the time the steel shell takes to travel the intervening distance from the meniscus. This observation is reflected in the large cast length between level and thermocouple fluctuations in Fig. 10. This implies that the level fluctuation does not create the depression immediately [5,6] (as can happen if the level drops more rapidly than the casting speed during otherwise "steady" operation [7]) Instead each fluctuation creates a feature which can persist in the mold and later generate a depression.

Evidence identifying the nature of these depression generating features may be seen in the thermocouple traces in Fig. 10. The thermocouple traces indicate that the depressions retain the same separation after a delay as is observed between level fluctuations. This is despite the fact that the first mold level fluctuation occurred 75 mm below the final level of the meniscus and the second 10 mm above it. The simultaneous movement of these depression generating features suggests that they may be physically connected.

The most realistic means of connecting these features is through the solid slag layer. This means that when the features giving rise to the depressions are captured by the strand, the entire solid slag layer (at least in the top half of the mold where the thermocouples are located) moves as a single sheet. Inspection of other plant data shows that movement of the slag sheet need not occur simultaneously on all mold faces. This was confirmed through visual observation of occasional discontinuity between transverse depressions on different faces. These were sometimes linked by a severely angled depression band probably indicating an unevenly removed slag layer.

Physical simulation of mold level fluctuations

To understand how falling mold level can produce a feature capable of generating a depression, a simple simulation was constructed. Mold level fluctuations were simulated through immersion and removal of a 10 mm diameter steel bar into a crucible of molten slag at 1300 °C (130 °C above its melting point). The sinter and powder layers were simulated by the addition of a thick layer of mold powder immediately prior to immersion. Two scenarios were examined; immersion into an entirely molten slag, and into a molten slag supporting a powder layer.

Figure 11 below compares the nature of the shells formed in each case. It was observed that immersion of the steel rod through a powder layer produced a thicker and generally lumpier slag shell. This was measured to be at least twofold greater than immersion into slag only. Although this simulation is unable to accurately reproduce and control key process variables, it does provide a qualitative demonstration of how severe level fluctuations may create significant localised slag buildup against the mold wall. This mechanism is consistent with the work of Kim et al [6] who observed that the severity of observed depressions increased with increasing level fluctuation.

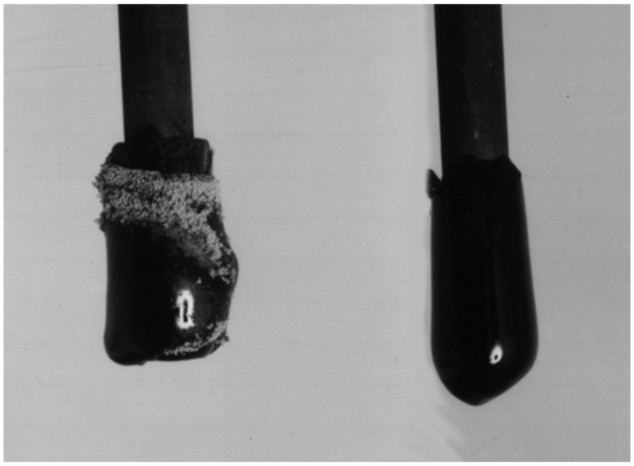

Fig. 11 Simulation of the effect of sinter layer contact with the mould wall. Twofold increase in deposited material was observed when powder material could accumulate on the slag layer.

Examination of recovered shells revealed an internal structure exhibiting well defined layers. Samples recovered from the molten slag incorporating a powder layer revealed large pockets of embedded sinter. This material resembled (in cross-section) samples of accumulated slag and sinter recovered from above the meniscus. Mold level fluctuations thus appear to be a likely mechanism for the accumulation of slag and sinter such as found above the meniscus (and sometimes referred to as "slag ropes" when detached).

This simple simulation indicates that mold level fluctuations produce a localised accumulation of slag on the mold wall. When the level drop is sufficiently large (eg of the order of slag pool depth), significant quantities of sinter will also accumulate. The build up of both slag and sinter during large level drops produces a significant slag bulge around the perimeter of the mold wall. This bulge may serve as a template for the formation of transverse depressions and then may be captured by the strand and carried down the mold in the depression.

The slag bulge generated during a period of falling mold level may be left isolated above the meniscus if the mold level does not return to its previous level. This is observed with the overshoot in mold level on startup. The depression will only form when some event allows the slag bulge to be overrun by the meniscus. In this case, a delay will exist between the mold level fluctuation and the depression it creates.

Mathematical modelling study

Insight into the behavior of the interfacial slag layers was sought using a steady state heat transfer model of the continuous casting mold, interface, and shell (CON1D) which was developed in previous work [8]. This model features a detailed analysis of the interfacial gap between the mold and shell, and includes both a mass and momentum balance on the solid and liquid slag layers.

Slag consumption is input to the model and carried downward in three ways: 1) by the solid (which moves with a specified velocity between zero and the casting speed, which may vary with distance down the mold), 2) by the liquid (which moves with a velocity profile that depends on the temperature-dependent viscosity function of the liquid) and 3) in the oscillation marks (moving at the casting speed). Previous coupled modeling and experimental studies have provided evidence that oscillation marks [8] and depressions [5] are filled with slag as they move down the mold. The oscillation mark shape is input to the model for this calculation, which also contributes an extra contact resistance to the heat transfer equation. Thus, the gap is modeled as a series of four resistances for the solid slag, liquid slag, oscillation marks, and air gap/contact resistance.

Model parameters (solid slag velocity profile and contact resistances) were adjusted in order to match the total heat flux from both the mold water temperature rise and the average mold thermocouple temperatures under roughly steady-state conditions. Even considering that enhanced consumption of slag is expected down the shrunken corners of the initial bloom, it is likely that the true consumption rate during startup is higher than steady state. A second simulation was performed by tripling the total slag consumption (from 0.4 to 1.2 kg/t), to explore conditions possibly experienced during startup.

Results in Figures 12 and 13 predict that a thick liquid slag layer exists over the entire length of the mold for the high slag consumption experienced during startup. The thick lubricating layer may protect the solid layer, including any slag bulges, from the frictional shear forces of the moving strand. This enables these features to persist for significant times. If the solid sticks to the mold wall (zero solid velocity), other simulations predict that the total slag layer will grow even thicker. A stationary solid slag layer with a thick liquid layer would both drop the heat transfer rate and minimize heat transfer variations with time. These predictions are consistent with the flat temperature profiles observed during the long periods of low heat transfer period after startup.

As consumption drops, the slag layer becomes thinner and heat transfer increases. This increases steel solidification and decreases the surface temperature of the steel shell. Fig. 13 shows that this surface temperature falls below the solidification temperature of the mold slag (1060 deg C) roughly midway down the mold. From at least this point down the mold, the solid slag layer must move if slag is to be consumed. The time-average velocity of this slag was calibrated in this work to be 13% of the casting speed, which is similar to the 10-20% values suggested in previous work [3].

At the top of the mold, the solid slag might remain adhered, as it is still protected by a liquid film. However, as the steel shell moves against the solid slag layer lower in the mold, it drags it downward. The strength and adherence of the slag layer is important to its behavior. A soft glassy slag might fragment due to friction against the steel. Alternatively, the strong crystalline basic startup slag is more likely to persist longer, but then detach in large portions and move as a sheet. This would explain the relatively sudden, non-uniform recovery observed from the low heat transfer period to steady casting. If the operating slag is contaminated with some startup slag, it might be induced to crystallize, lowering its conductivity and increasing its adherence to the mold wall. Both effects would tend to decrease heat transfer and help to explain the period of low heat transfer after startup.

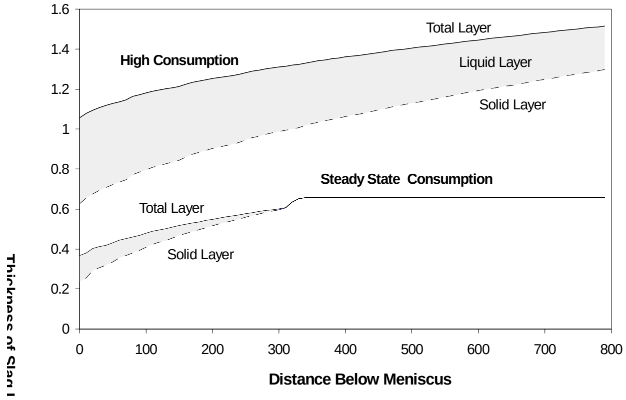

Fig. 12 Comparison of predicted slag layer thicknesses for startup and steady state casting.

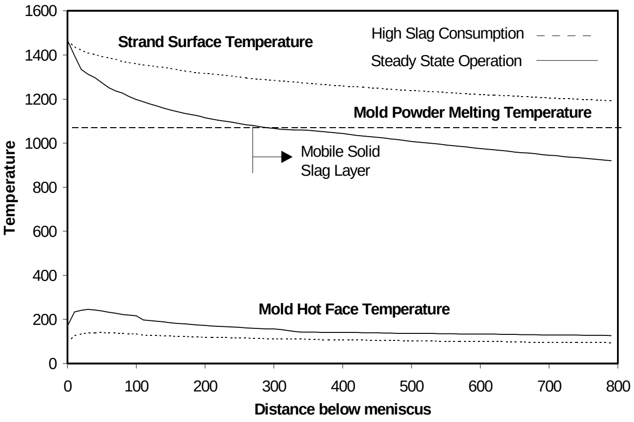

Fig. 13 Comparison of predicted strand surface and slag solidification temperatures. As consumption is increased, the point of complete slag solidification moves down the mold.

Proposed Mechanism of Depression Formation and Steady State Delay

Based on the combined insights from the appearance of the defects, analysis of slag samples, recorded mold level and temperature data and the mathematical and physical modelling studies, it is possible to suggest how the startup depressions and long transitions to steady casting conditions occur. The proposed sequence of events occurring in the mold are as follows:

- Operating powder is added directly over startup powder allowing intermixing.
- The strand is withdrawn once the SEN is covered causing a drop in mold level and the accumulation of slag and sinter against the mold wall. This process repeats when mold filling is complete as the level overshoots.
- Accumulated slag below the meniscus is protected from immediate removal by the large liquid slag layer present in the first few minutes of casting as evidenced by the high slag consumption rate. Under “steady state” casting conditions, any bands of accumulated slag below the meniscus would be removed immediately (as had been previously observed).
- This build-up of material can become a template for depression formation when overrun by a rising meniscus (cf Fig. 14). It may then be captured by the strand and move down the mold at the casting speed leaving characteristic drops in mold temperature as the depression passes each thermocouple.
- As slag consumption decreases, the depletion of the liquid slag layer begins to bring the bands of accumulated slag below the meniscus into contact with the strand. This provides a “handhold” for the removal of the solid slag layer. The persistence of temperature drop spacings as they move down the mold suggest that large portions of the slag layer may be dragged out as a single sheet. Even accumulated material above the meniscus could be dragged below the meniscus due to the thickness and strength of this solid slag layer.
- The original sheet of startup slag is replaced by operating slag contaminated by high basicity slag. This causes the solid slag layer to crystallise, retarding heat transfer to the mold. The absence of variation in the temperature traces is indicative of a thick slag layer in both producing smaller surface defects and insulating the mold from the effects of any defects which are present.
- The strong adhesion of this layer makes it more difficult to be removed from the mold. Recovery is a statistical process which likely relies upon some process disturbance to allow capture of the slag layer. For example, in one instance a drop in casting speed was observed to precede recovery.

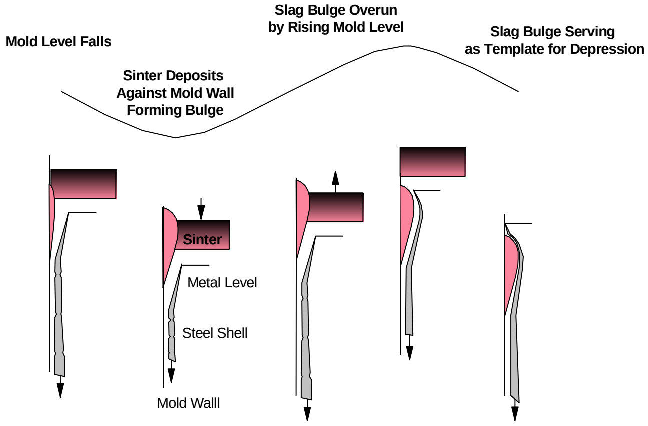

Fig. 14 Schematic representation of depression formation during a mold level fluctuation. Filling the mold deposits a thin layer of solidified slag against the mold wall. A large level drop deposits sintered slag against the mold wall forming a large bulge around the perimeter of the mold. This build-up of material can become a template for depression formation when overrun by a rising meniscus and then may be captured by the strand.

Improvement Strategies

Several strategies for eliminating depressions and steady state delay were considered. One successful strategy involved delaying the addition of operating powder to the mold. Using reduced quantities of start-up powder, and allowing this material to be consumed before the addition of operating powder both eliminated delays in reaching steady state (cf Fig 15) and dramatically reduced depression severity. Delayed addition (approx 30 s) reduces the amount of sinter material present during the startup level variations producing smaller slag bulges. This strategy also ensures the formation of a glassy slag layer against the mold wall by minimising the contact and subsequent mixing of startup and operating slags in the mold. Preliminary trials using low basicity startup slags have also indicated improved performance.

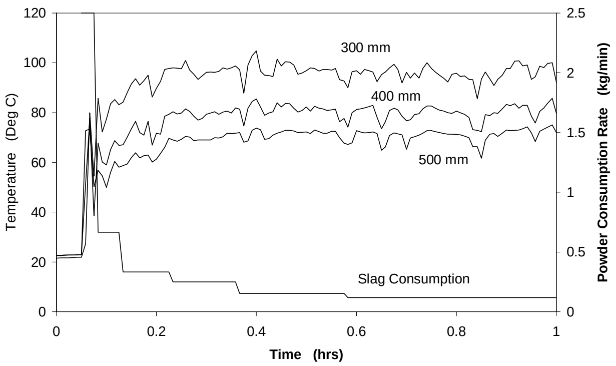

Fig 15 Rapid achievement of steady state thermal response and reduced depression severity was achieved through delay in feeding operating powder to the mold.

Conclusions

1) Depression defects on the surface of the strand during startup originate at the meniscus during filling of the mold due to the build up sintered material against the mold wall during episodes of appreciable level drop.
2) Long delays in achieving steady state mold heat transfer are ascribed to the persistence of high basicity startup powders in the mold when used in conjunction with low basicity operating powders. This situation is compounded by the superior contact exhibited by high basicity slags.
3) Surface quality improvement during startup and more rapid achievement of steady state is obtained by reducing the quantity of startup powder remaining in the mold before the operating powder is added.

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