Investigation of strand surface defects using mould instrumentation and modelling

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The surfaces of continuously cast steel blooms exhibit a variety of surface features and defects, which were investigated to reveal the interactions at the meniscus between the steel shell and interfacial flux layers that caused them. One such defect formed at periodic intervals along the surface of first and second blooms in a sequence. It was characterised by gradually deepening oscillation marks, followed immediately by longitudinal striations or 'glaciation marks'. In severe cases, deep depressions were clearly visible within the glaciated region. These defects were investigated through plant trials and both physical and mathematical modelling. The defects were found to exhibit a characteristic temperature history: temperature troughs that move down the mould at the casting speed. These defects may be monitored in much the same way as sticker breakouts, thereby allowing existing thermocouple based breakout detection systems to be modified to include a quality alarm. This study attributes these defects to high amplitude, low frequency, mould level fluctuations. A mechanism is proposed which ascribes the generation of these defects to the interaction of the meniscus with the slag rim at peaks in the mould level cycle. Installing an improved mould level control system eliminated the defects.

Keywords: Continuous casting, Billet casting, Casting defects, Instrumentation, Modelling

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Introduction

The surface condition of the strand is an important aspect of continuous cast steel quality and is controlled mainly by the initial stages of solidification in the mould. Undetected surface defects can cause serious quality problems that may persist into the final steel product, and in severe cases, may cause breakouts during the continuous casting process. To avoid these problems, it is useful to understand how each different type of defect forms, so that its presence may be detected by inexpensive monitoring of process sensor signals rather than full inspection of the final product.

This study was undertaken to investigate surface defects in continuous cast steel, based on blooms cast at the Rod and Bar Products Division of BHP Steel, Newcastle, Australia. This large four strand caster produced 630 × 400 mm blooms that were hot charged to a reheating furnace and then hot rolled into a variety of steel products, including semi-finished 89–158 mm square billets. The billets occasionally suffered a range of surface defects, needing expensive, time consuming surface grinding, and in severe cases, even downgrading or rejection. The reconditioning yard was often a bottleneck in the process, and the cost associated with removing these defects was about $3 500 000 per year. Surface quality problems persisted despite changes in rolling practice, demonstrating that at least some of the defects originated in the mould.

After introducing a variety of different surface defects, this paper focuses on a particular surface defect of periodic surface depressions. A plant trial was conducted to simultaneously monitor mould variables (mould level and thermocouple temperatures) and examine the associated bloom and billet surfaces. Metallurgical investigations studied the sub-surface structure of bloom samples through depressions and oscillation marks. With the assistance of mathematical and physical modelling, the findings were interpreted to understand how the defects arise. It was envisioned that by linking events in the mould instrumentation data to specific bloom and billet surface features, a means of predicting surface quality problems could be devised. Finally, changes were made to minimise the occurrence of these defects and improve both bloom and billet quality. It is hoped that insights gained from this study will help to understand and avoid future surface defects.

Surface defects

Surface features on the strand reveal a great deal about events at the meniscus during their formation. To save energy via hot charging, however, careful inspection of the cooled bloom surface rarely occurred. This section presents some example bloom surface imperfections observed in this study. The inspection revealed a wide variety of features including oscillation mark problems

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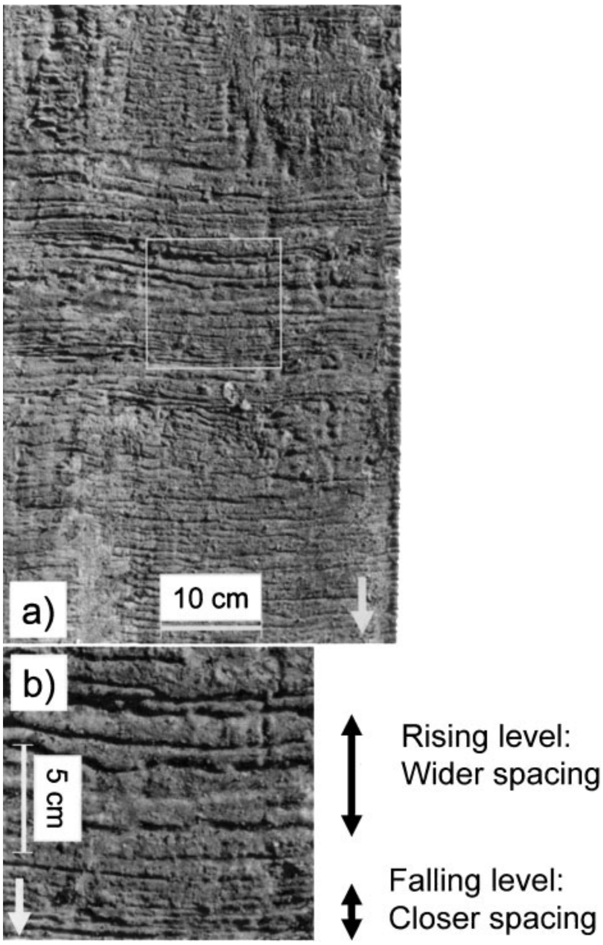
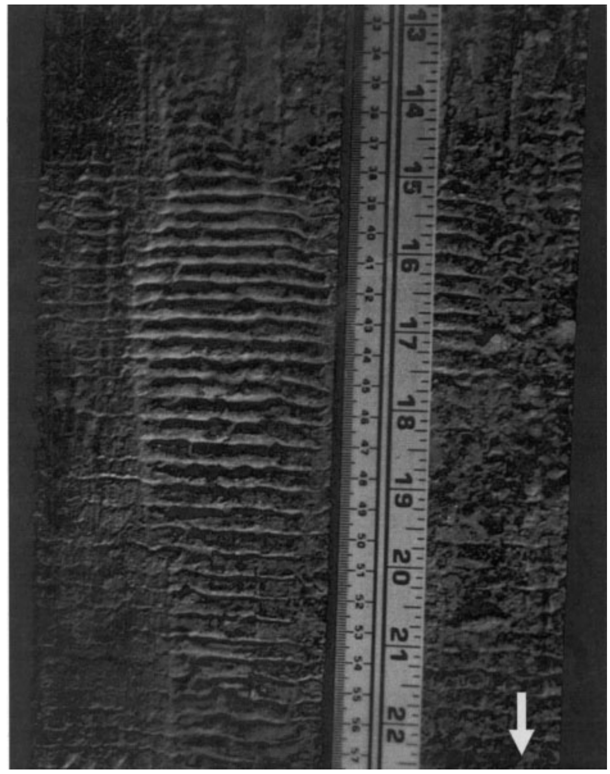


1 ***a*** **variation in oscillation mark profile and pitch caused by gradual meniscus level variations and** ***b*** **close-up: arrow indicates casting direction**



2 Region of bloom surface exhibiting oscillation marks with regular spacing but variable depth across the strand

(shape, pitch, and depth variations), and both transverse and longitudinal surface depressions.

The shape of the oscillation marks indicates the shape of the liquid metal/molten flux interface when it solidified at the meniscus. Ideal oscillation marks are horizontal with a spacing (pitch) equal to the casting speed divided by the oscillation frequency. Radical variations in oscillation mark shape and pitch are a clear indication of level fluctuations caused by a turbulent meniscus, and often are accompanied by quality problems.[1] Figure 1*a* shows a gradual curvature of the oscillation marks across the bloom that rises towards the edges. The arrow on this and subsequent figures indicates the casting direction. This mark shape indicates that a standing wave existed in the mould that was higher near the corners. This was caused by the momentum of the flow circulating around the vertical axis in the mould as a result of the electromagnetic stirring forces used in this caster, and is well understood.[2]

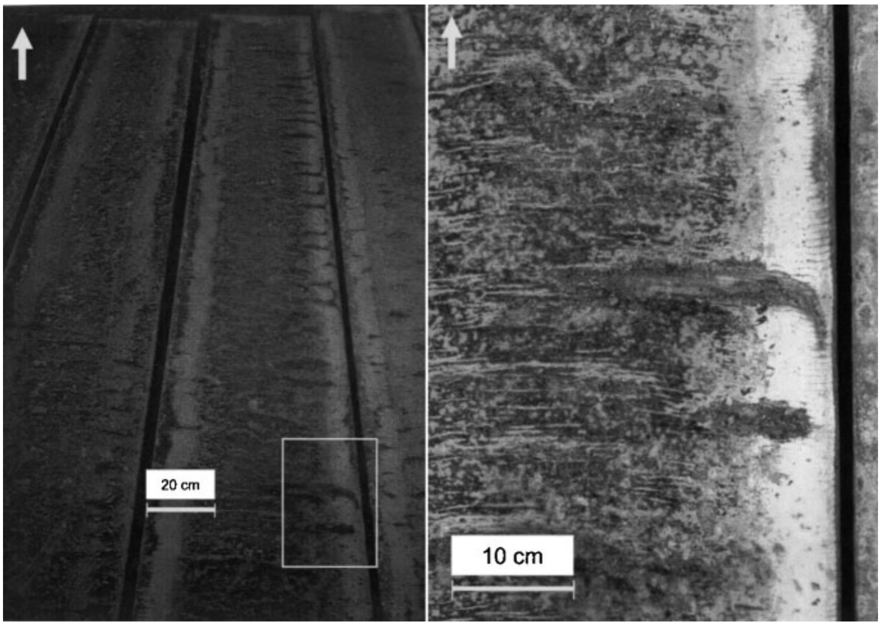
Figure 1*b* shows how the oscillation mark pitch sometimes deviates from its average value ($P_{avg}=7{\cdot}8$ mm). This indicates gradual changes in meniscus level. A steadily falling level leads to a closer oscillation mark spacing ($P\approx3$ mm), while a rising level causes increased spacing ($P\approx10$ mm). The meniscus level rising velocity, V_L, can be estimated from this variable pitch, P, by

$$V_L=(P-P_{avg})f, \quad \text{where } P_{avg}=V_c/f \qquad (1)$$

The oscillation mark depth also changes, according to the pitch and the liquid level changes. Specifically, the rising level (rate=2 mm s^{-1} here) produces deeper oscillation marks while the falling level (rate=-5 mm s^{-1} here) produces shallower marks. This is likely to be caused by increased interaction of the meniscus with the resolidified flux rim, as discussed in depth in this paper.

Figure 2 shows that oscillation mark depth can suddenly change across the strand width, even though their shape and spacing remains quite regular. Wolf has shown that flux casting produces deeper but more regular oscillation marks than oil casting,[2] owing to the pressure variations in the flux channel during the oscillation cycle.[3] The deep oscillation marks are consistent with the presence of a thick liquid mould flux layer experiencing large pressure fluctuations from a large flux rim. The adjacent regions with very shallow marks, suggest a lack of liquid flux infiltration. This is consistent with the flat region (shallow marks) being a plateau that is raised slightly above the bloom surface, meaning that the molten steel was able to touch the mould wall locally, while the adjacent region (deep marks) contained mould flux that kept the steel further away. These variations are important because the accompanying variations in thermal resistance of the shell/mould gap are likely to lead to significant transverse variations in heat transfer, which may produce subsurface cracks.

Figure 3 shows typical transverse depressions on the wideface surface of a peritectic steel bloom, cast at low speed (0·5 m min^{-1}). The close-up of Fig. 3 (*right*) shows that depressions near the edge are readily visible against the off-corner region of the bloom that has been flattened somewhat by the support rolls. The depressions form at the meniscus, owing to the large thermal



3 Depression defects on peritectic bloom surface (*left*) and close-up (*right*)

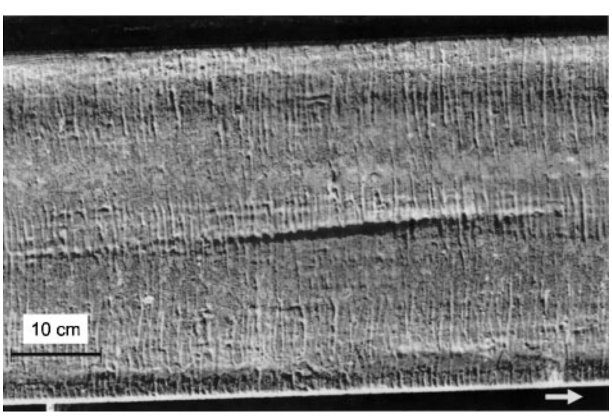
contraction that accompanies the phase transformation from delta-ferrite to austenite. They are associated with rippling of the shell[4] and various quality problems, such as transverse cracks and slivers. Figure 4 shows a long longitudinal surface depression running down the centre of the bloom narrow face. By lowering heat transfer locally, this depression may cause a longitudinal facial crack, and even initiate a breakout in severe cases.

These and many other surface defects were observed at the Newcastle bloom caster. Although surface defects have been studied in past work, each can be manifested in different ways from different causes, and there is still much to understand about the details of their formation mechanisms. The remainder of this paper focuses on a particular periodic surface depression defect, which was subjected to an intense, multifaceted investigation in order to fully understand its formation mechanism.

Periodic defect investigation

Strand surface inspection

The commonly observed surface defect studied in this paper is pictured in Fig. 5. This region of surface depressions is believed to affect the initial one or two



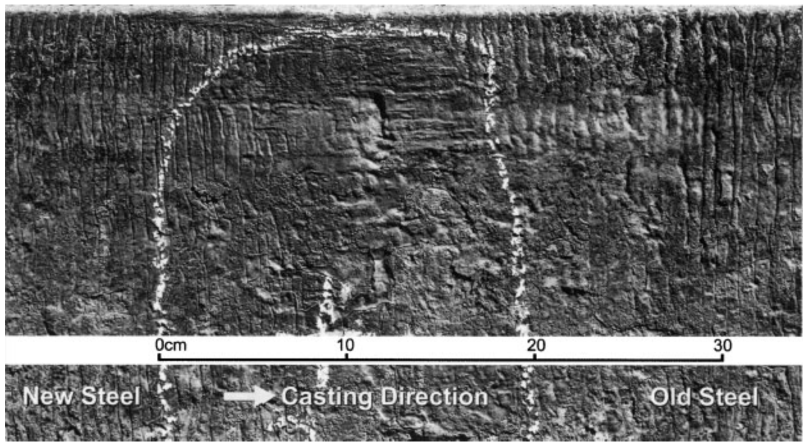
4 Longitudinal depression along narrow face of bloom surface

blooms cast of most steel grades, although the bloom shown here contained 0·055%C (*see* Table 1). Attention was focussed upon this particular defect owing to its distinctive periodic appearance along the bloom surface, occurring at semi-regular intervals of between 500 and 1000 mm. The defect was most obvious on the narrow faces, which are not flattened by the rolling action of support rolls. The defect was found on all four faces of the bloom, extending around the entire perimeter.

The defect assumes a characteristic form with a commonly recurring sequence of features. Describing these features from right to left in Fig. 5, in the order in which they were created, the defect begins with a region of gradually deepening oscillation marks. This region extends over 5–10 cm of bloom length, where the oscillation mark depth increases from a standard depth of between 0·2 and 0·4 mm to a maximum depth of over 2 mm. This region then evolves into a 10–20 cm long region of longitudinal scrape marks or striations: 'glaciation marks'. The glaciated regions are almost completely devoid of oscillation marks, and those that are visible are very faint. The glaciation marks are often interrupted by severe depressions of random orientation and shape, extending from 1 to 4 mm in depth. In severely affected blooms, every incidence of glaciation has these depressions, which intermittently traverse the entire perimeter of the bloom. Following the depressions, the glaciation region becomes most pronounced, particularly in the off-corner region of the narrow face. Following the last of the glaciation marks is a return to relatively uniform, regular oscillation marks of standard depth and average pitch.

Metallurgical investigation

Sections through depressions and oscillation marks were cut and examined metallographically to reveal sub-surface structures. The oscillation marks and depressions examined rarely exhibited any distinguishing microstructural features such as sub-surface hooks or cracks. In other grades, some depressions exhibited fine cracks with random orientation while other specimens



5 Close-up of a representative periodic bloom surface defect exhibiting deep oscillation marks, depressions and glaciation

displayed faint 'dark' and 'light' bands of segregation. These bands are believed to be caused by fluid flow against the growing shell, and indicate the position of the solidification front at some time in the mould. A photograph of such a depression is given in Fig. 6. The faint bands in this figure imply that the shell is significantly thinner beneath the depression. This is consistent with the lower heat transfer expected beneath a depression while it moves down the mould.[5,6]

Table 1 Casting conditions and mould details

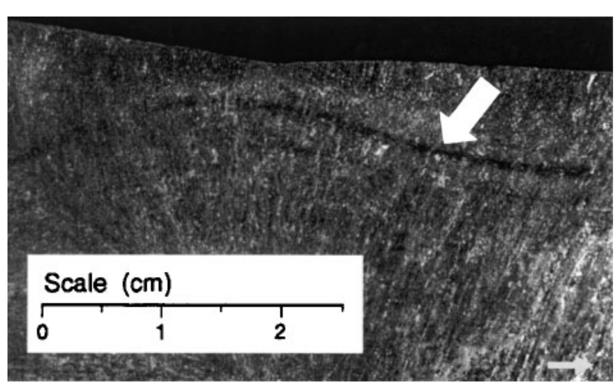
Mould specifications		
Width (top)	650 mm	
Width (bottom)	634 mm	
Depth (top)	413 mm	
Depth (bottom)	410 mm	
Length	900 mm	
Working length	775 mm	
Plate thickness	15 mm	
Ni–Fe coating	0·5 mm	
Mould water velocity	7·8 m s^{-1}	
Mould stirring	On	
Casting speed	0·5 m min^{-1}	
Thermocouple specifications		
Type	K	
Column of 5 thermocouples (position as a distance from the top of the mould)	143, 250, 350, 450, 550 mm	
Distance from thermocouple tip to hot face	11 mm	
Mould oscillation		
Stroke	6 mm	
Frequency f	64 cpm	
Mould powder details		
Viscosity (at 1300°C) μ_{1300}	0·31 Pa s^{-1}	
Solidification temperature T_s	1130°C	
Exponent* n	1·682	
Conductivity	4 W m^{-1} K	
Powder Consumption	0·4 kg m^{-2}	
Contact resistance	8·8 cm^2 K W^{-1}	
Steel grade (AISI 1006)		
0·055%C	0·019%O	0·33%Mn
0·011%Si	0·012%S	0·01%Ni
0·03%Cr	0·01%Mo	0·04%Al
Mould flux composition (CNS-LC)		
5·7%C	40·4%CaO	35·8%SiO_2
6%Na_2O	4·6%Al_2O_3	<3%MgO
<3%Fe_2O_3	<3%MnO	<3%TiO_2
<3%K_2O	3·3%F	

*The exponent n was fitted from measurements for use in the following equation in CON1D[8] for the variation of viscosity μ with temperature T (°C): $\mu=\mu_{1300}\times[(1300-T_s)/(T-T_s)]^n$.

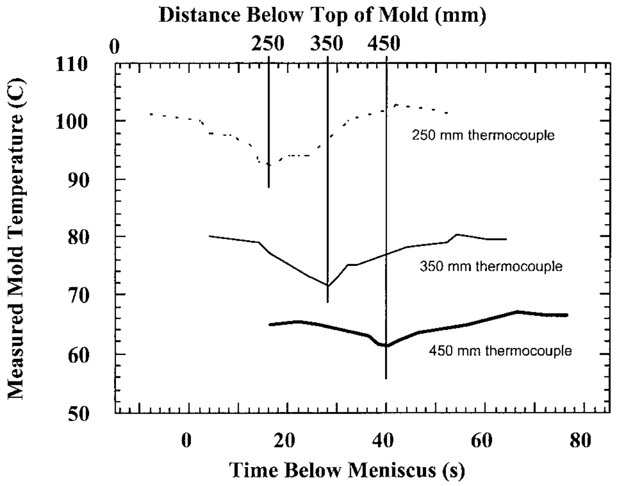
Mould level and thermocouple data analysis

Based on the defect observations made in the previous sections, it was evident that this problem originated in the mould, and probably at the meniscus. Having noted the periodic nature of the depressions, mould thermocouple data was inspected for events of similar frequency. Two columns of K-type thermocouples were embedded into each mould face, as part of a breakout detection system. It was expected that each depression should produce a temporary drop in mould temperature as it moved down the mould past each successive thermocouple, owing to the reduced heat flow associated with the larger interfacial gap between the strand and the mould.[5] The time interval between these temperature valleys in adjacent thermocouple traces was also expected to correspond exactly to the casting speed. A typical example of the raw thermocouple data is presented in Fig. 7, which clearly shows these expected effects.

Two consecutive blooms that together exhibited a sequence of 18 major defects were obtained; comprising a representative 12 m length of low carbon steel strand cast under the conditions listed in Table 1. Thermocouple data were obtained for the casting period of these blooms. The bloom surface profile was measured along the lines corresponding to the mould thermocouple



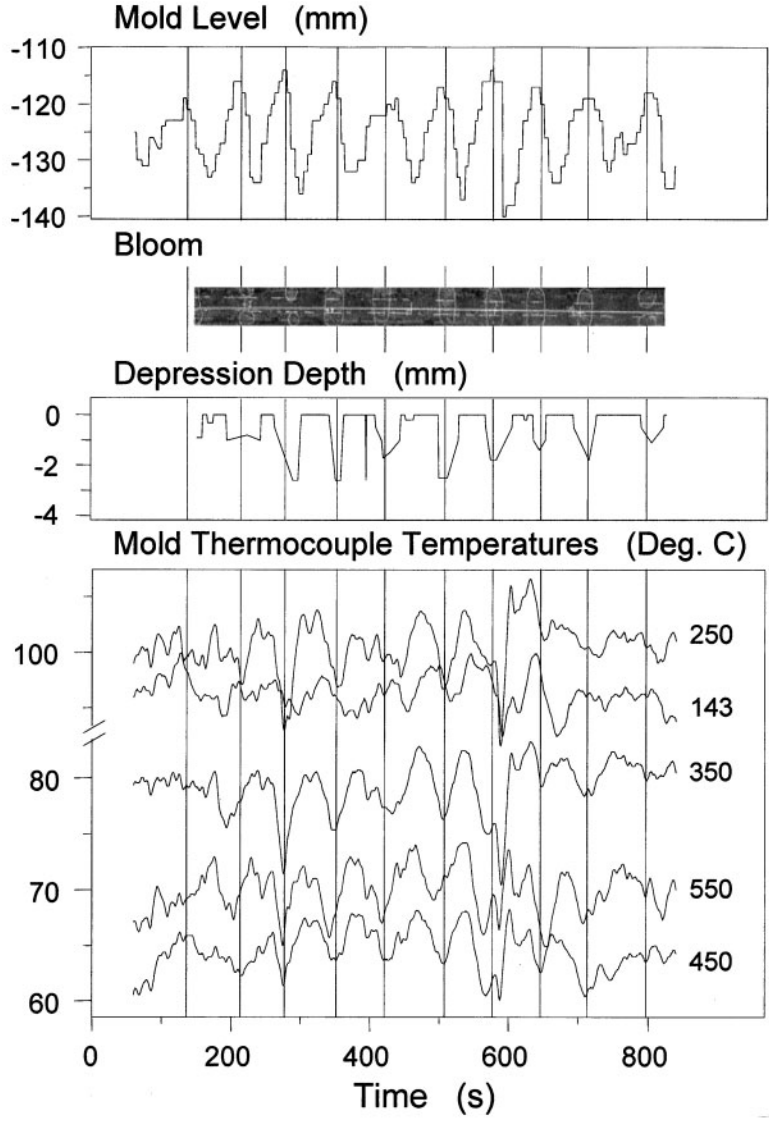
6 Sub-surface structure beneath a bloom depression: note the faint dark bands that indicate shell thinning as a result of the local reduction in cooling rate caused by the depression



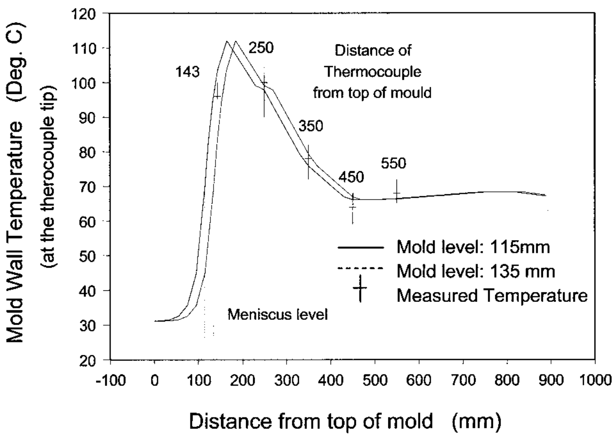
7 Thermocouple measurements showing effect of a transverse depression on temperature drops at successive distances down the mould

positions, and the approximate location and depth of each depressed region were recorded (*see* Fig. 8).

To dispel any uncertainty regarding the correspondence between the logged data and position along the bloom surface, the measured temperatures were replotted as follows. The mould level set point was chosen as the reference position. Each of the lower four thermocouple signals was shifted backward in time by the distance separating it from the reference point divided by the casting speed. This is the time taken by a point on the strand surface to travel to that thermocouple from the reference position. After this correction, all of the temperature valleys that move down the mould at the casting speed and correspond to the same surface depression will align. Temperature valleys that do not align are also observed. The latter are assumed to have a different origin, such as the drop in heat transfer occurring when the continuous solid mould flux film is broken, as suggested by Ozgu and Kocatulum.[7]



8 Photo of a bloom showing defects highlighted by chalked circles (*centre*) matched with the corresponding mould level history (*top*) and the thermocouple temperature profiles (*bottom*): the latter data has been shifted in time, according to casting speed and distance from the top of the mould, to the same reference point; the measured surface profile is also given (*centre*)



9 Predicted mould temperature profiles for a 20 mm change in mould level

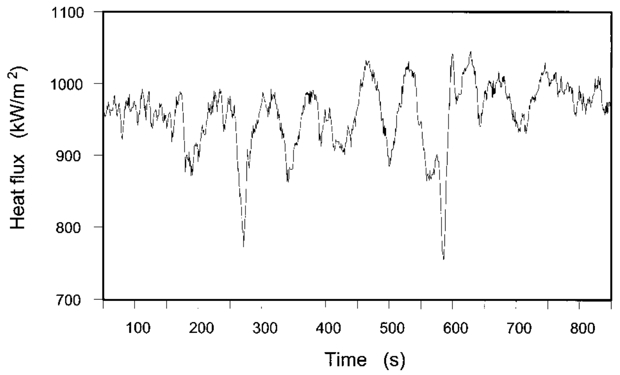
By shifting the entire data set in this way, it was possible to find an exact match between the drops in the temperature data and the 18 depression defects on the bloom surface. Variations in the periodicity of the defect spacings permitted a unique match to be obtained. The first 10 defects are presented in Fig. 8, along with the corresponding mould temperature and level histories. The scale of the photograph of the bloom in this figure was chosen to match that of the data.

The match seen in these results clearly shows that each defect is created during a peak in the mould level. These mould level fluctuations are seen to have a period of roughly 70 s, which corresponds to a very low frequency component of the level variation.

Mathematical modelling study

To obtain further insight into the nature of the observed temperature valleys, mathematical models were applied. First, a two-dimensional heat conduction model of the mould was coupled with a one-dimensional, transient model of the solidifying shell.[8] Interface conditions input to this program, CON1D, were adjusted until the average mould wall temperatures were matched, for the casting conditions given in Table 1. The resulting temperature profile down the mould is shown in Fig. 9. The effect of the changes in mould level on mould wall temperatures was determined by shifting this curve down the mould by 20 mm. Figure 9 shows that only the top thermocouple located near the meniscus, (143 mm from the top of the mould), is significantly affected by this change. Lowering the mould level decreases the temperature at the thermocouple tip by 15°C. This is because the hottest spot on the mould (found just below the meniscus) moves downward (away from it), and the temperature changes sharply with distance in this region. All of the lower thermocouples are essentially unaffected by the change, as the measured temperatures increase by less than 3°C.

The results from this model explain the behaviour of the thermocouples. The temperatures of the top thermocouple found near the meniscus tend to increase owing to of the rise in mould level, but decrease because of a depression. The net result is erratic behaviour. The lower thermocouples consistently drop only when a depression passes by, as the mould level has no direct effect on them.

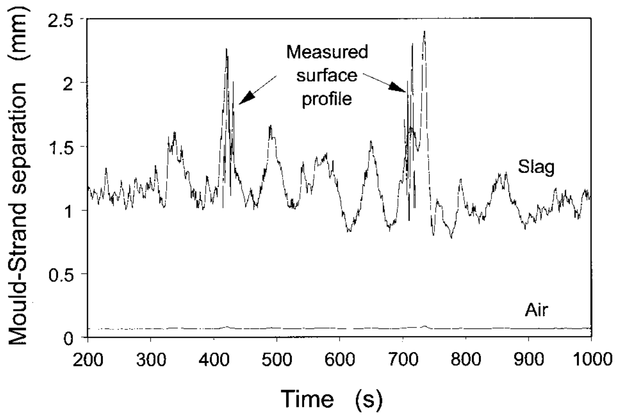


10 Predicted heat flux history 350 mm below top of the mould

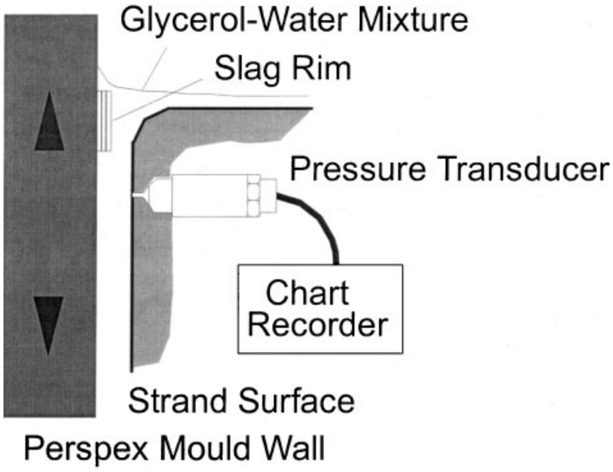
Next, a one-dimensional, inverse, transient heat conduction model was used to calculate the heat flux history at particular locations down the mould from the measured thermocouple traces. A plot of the heat flux curve based on a portion of the temperature history at 350 mm below the meniscus is given in Fig. 10. This figure shows that the heat flux drops significantly for time intervals of 10–30 s, corresponding to the passage of 80–250 mm long depressed regions in the shell moving down the mould at the casting speed.

The heat flux histories from this model were further used to calculate the expected thickness of the interfacial gap between the steel shell and the mould, based on different assumptions for the material filling the gap. Figure 11 compares the depth profile measured along two particular depressions with the gap thickness calculated at these locations of the extreme assumptions of 100% air and 100% mould flux filling the gap. The results clearly show that the observed temperature changes are consistent with depressions that are filled almost completely with mould flux.

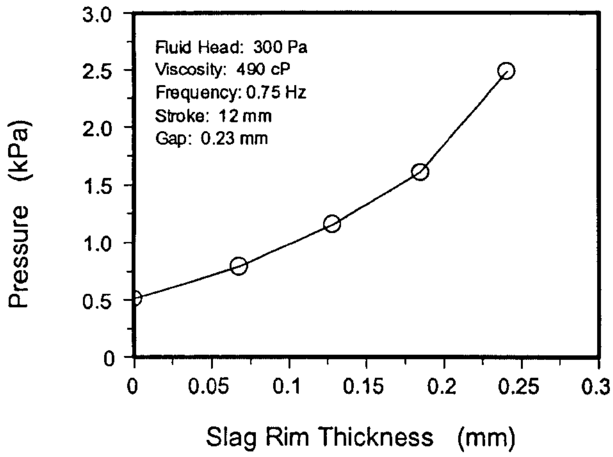
Further model calculations showed that the growth of the steel shell in the upper region of the mould is much slower when there is a thicker layer of mould flux filling the interfacial gap. This condition arises, as expected, beneath a depression, and explains the banding described previously. Shell thinning is also expected to



11 Predicted surface profiles for extreme cases of a completely slag and air filled mould-strand gap: a detailed measurement of the matching depressions has been shown for comparison; it is apparent the depressed regions must be almost entirely slag filled



12 Schematic of physical model used to simulate meniscus region

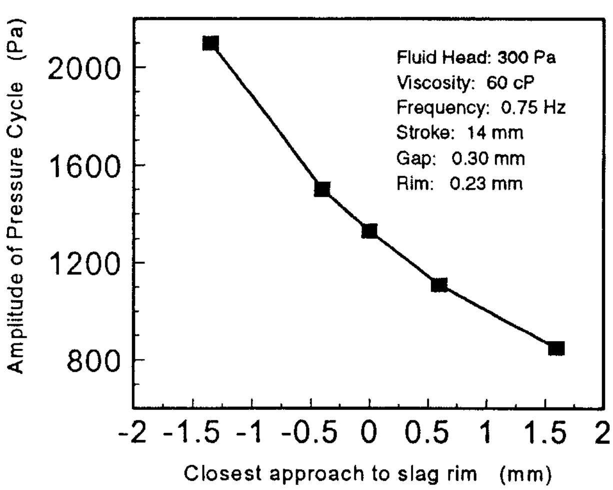


14 Effect of slag rim thickness on magnitude of pressure oscillation

occur at the meniscus, if solidification occurs against the solidified flux rim.

Physical modelling study

In order to examine the possible effect of rising steel level in the mould, the meniscus region was modelled physically. Oscillation mark formation has been attributed to changing pressure levels in the slag.[9] When this exceeds a critical value (slightly greater than the local ferrostatic pressure), the meniscus is pushed inward. When the slag pressure falls below this value, the meniscus is pushed back, leaving a permanent crease in the shell, or oscillation mark. The greater the magnitude of this pressure variation, the deeper will be the resulting oscillation marks. The pressure in the flux channel was modelled by simulating the meniscus region as shown in Fig. 12. Using glycerol-water mixtures to simulate the slag, a pressure transducer embedded in the simulated shell wall recorded the pressure fluctuations in the channel at various distances from the mean slag rim position. The pressure in the gap was found to increase as the meniscus, and attached pressure transducer, were raised towards the slag rim (*see* Fig. 13). This is consistent with the numerical modelling study performed by Tada.[10] This suggests that gradually deepening oscillation marks may be a feature of regions of rising mould level, consistent with the plant observations in Fig. 1*b*. It was also observed that as the slag rim penetrated the gap, the fluid flow was choked off. In the mould this would result in a loss of lubrication, possibly explaining both the loss of oscillation marks and the evidence of surface friction in the glaciated region.



13 Effect of distance from mean slag rim position on slag pressure: slag consumption was reduced to zero as the rim entered the gap (closest approach to slag rim <0)

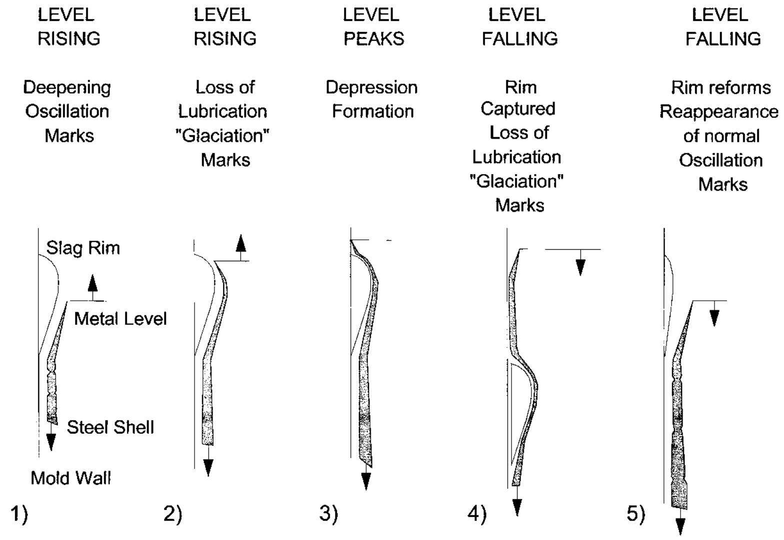
Figure 14 demonstrates the strong dependence of slag pressure on the thickness of the slag rim.[11] In his numerical modelling studies, Tada also determined that decreasing slag rim thickness reduced the pressure in the molten flux until the thin shell at the meniscus could no longer bend. Because the slag rim plays such an important role in the infiltration of slag into the mould-stand gap, its loss would also be likely to cause a loss of both oscillation marks and lubrication until a new rim could be established.

Mechanism of defect formation

Based on the combined insights from the appearance of the defects, the mould level and temperature data, and the mathematical and physical modelling studies, it is possible to suggest how the different regions of surface imperfections were formed and how they may affect bloom and billet quality. The stages are illustrated in Fig. 15 and discussed below.

Periodic level fluctuations

The root cause of the defects appears to be large fluctuations of liquid level in the mould, with an amplitude of about ± 10 mm with a low frequency of only about 0·01 s^{-1}. One possible source of these level fluctuations is the periodic squeezing and bulging of the initial strand attached to the dummy bar as it moved through the rolls supporting the shell below the mould. The BHP Newcastle bloom caster was particularly susceptible to this problem, owing to large roll spacings (>0·7 m) lower in the caster, especially between segments 10–12 m below the meniscus. Bent rolls are another potential source. Unsteady alternating between contraction and expansion of the shell causes the internal volume of liquid metal in the strand to decrease and increase. This in turn pushes molten steel upward



15 Schematic diagram proposing the sequence of events that gives rise to the observed defect: rising mould level first causes gradually deepening oscillation marks, followed by a loss of lubrication as the slag rim is over-run, the rim is then captured by the steel, which carries it with the shell when the mould level falls, thereby creating a depression in the steel surface, lubrication is lost until the time a new slag rim can form (in the case of rim capture shown) resulting in a severely glaciated region

and then draws it downward. The frequency could not be predicted in this paper, but other work has suggested correspondence with the casting speed divided by the roll pitch or the roll perimeter.[12] This phenomenon is often worse just after startup, as confirmed in this paper. The periodic changes in strand thickness also cause periodic variations in roll force and accompanying tiny periodic variations in casting speed.[12] This downstream source of level fluctuations presents a challenge to the mould level control system, which was not met by the standard proportional-derivative level controller. Regardless of the cause of the high amplitude, low frequency level fluctuations, they led to surface imperfections via the following steps.

Deep oscillation marks

The results of this paper clearly show that deepening oscillation marks are created when there is a general trend of rising mould level. As the mould level rises, the solidified flux rim at the meniscus moves closer to the newly solidified shell. This increases the pressure generated in the liquid flux channel during each oscillation stroke. This, in turn, increases the bending forces imposed on the shell. In addition, the low solidification rate against the flux rim produces a thinner steel shell, which is easier to bend. Other work suggests that the flux rim itself could even interact mechanically with the shell.[13,14] In either case, oscillation marks logically deepen as the forces imposed on the thin shell increase.

Deep depressions

As the mould level reaches its peak, this paper has found that deep depressions can form in the thin shell. The rate of level increase probably exceeds the ability of the slag rim to melt and maintain a uniform shape with respect to the meniscus. This could cause depressions in several ways. First, flooding the slag rim to solidify steel directly against the solid slag would produce an imprint of the slag rim in the newly solidified steel. This imprint would naturally be deepest where the solid slag rim at the meniscus is thickest. Second, the slag rim is often only weakly attached to the mould wall,[15] so could be captured by the solidifying steel shell. Third, it has been suggested that the slag rim may be buoyed upward by a rising mould level. If the upward movement of the slag rim along the mould wall is stopped at some maximum upper height by sintered powder build up, then the rising mould level would overflow it immediately thereafter. In each case, the result is a thin steel shell with a depressed region filled with solidified mould slag, which moves down the mould. Later removal of the slag reveals the permanent depression in the bloom surface.

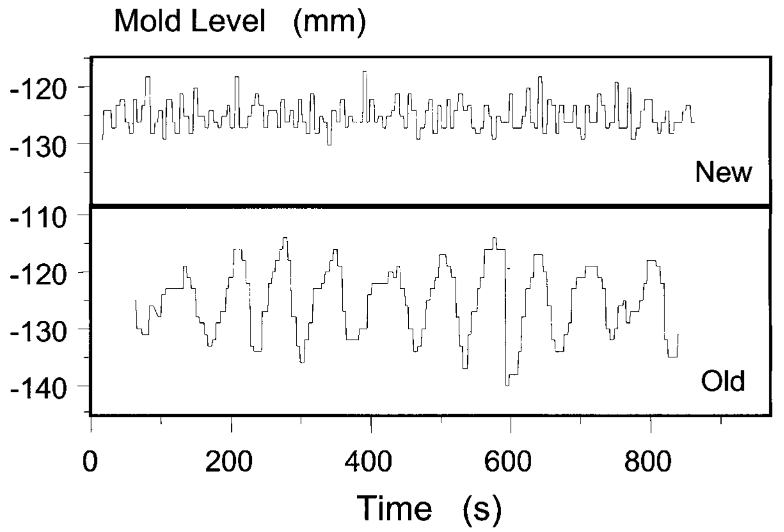
Glaciated regions

These regions begin near the peak in mould level, and are associated with both rising and falling mould level. The absence or weakness of oscillation marks in this region suggests a lack of liquid slag and pressure. This could be caused by difficulties in slag infiltration as the slag rim is over-run or removed. This is consistent with the observed longitudinal striations, which are presumably caused by friction against the mould wall, when the soft, weak shell is dragged downward.

The very low heat transfer rate that accompanies solidification against the slag rim prevents solidification of the meniscus. Oscillation marks with sub-surface hooks[13] are therefore unlikely. This is consistent with the almost complete absence of sub-surface hooks found associated with the oscillation marks near the glaciation.

Billet defects

After they have formed at the meniscus region, the depressions in the steel shell, which are filled with mould flux, move down the mould at the casting speed. These depressions have been shown to sustain a reduced rate of cooling for the entire time the shell is in the mould. Reduced cooling is a concern as it may give rise to a coarser grain structure, making the region more susceptible to localised segregation, leading to cracks in alloy steels, and pinholes in oxygen rich steels[16] The



16 Comparison of mould level fluctuations obtained with the old and new control systems for strands C and A respectively

cracks and pinholes near the surface then appear as seams on the surface of the rolled billet product. It therefore seems plausible that billet seams, a major plant concern, may be associated with the depression defect studied in this paper.

Implementation of new mould level control system

This paper has shown that large changes in mould level were responsible for surface quality problems, despite the slow rate at which they occurred. Therefore, a new mould level control system was implemented.[17]

The mould level variations (approximately ± 10 mm) depicted in Fig. 3 were representative of the control that was achieved with the old system that caused the surface defects in Figs. 1–5. The low-frequency level control problems likely arose from the downstream disturbances because the controller had been 'detuned'. Specifically, the mould level signal had been filtered (smoothed by a moving time average) in order to prevent over-sensitivity to sudden small changes in level, such as caused by sticking of the slide gate, which had the tendency of freezing in place during periods of inactivity.

A new system was installed that overcame the problem of slide gate sticking through the use of dithering.[17] This removed the need to detune the control system and eliminated the low frequency fluctuations. Figure 16 compares mould level signals of both the new and the old control systems. With the new system, the average amplitude of the fluctuations was reduced from around ± 10 mm to ± 3 mm. The average instantaneous rate of level fluctuation was unaffected by the change however, remaining at about 0·5 mm s^{-1}.

Improved level control and billet quality

Further trials were conducted to evaluate the effect of the new mould level control system on both the bloom defects and the surface quality of billets rolled from them. Preliminary observations of the blooms revealed substantial improvement in the bloom surface, independent of grade. The periodic deep depressions pictured in Fig. 1 were completely absent from the two adjacent strands that were cast at the same time and under the same casting conditions but with the new level control system.

Temperature signals from the two strands with the new level control system exhibited fluctuations of the same magnitude as with the old system. However, none of the valleys consistently aligned when the thermocouple data was shifted. This indicates that the temperature fluctuations were not caused by depressed regions moving down the mould at the casting speed, and is consistent with the visual inspection of the bloom surfaces. The temperature signals can therefore be used in this way to detect the presence of this type of depression defect. In the future, it may be possible to install 'quality alarms' to detect the thermal events in the mould that are known to lead to this defect. The system could function in a similar manner to a breakout detection system and be used to designate surface grinding.

A statistical study was conducted to quantify the influence of the improved level control system (and improved bloom surface) on billet quality. Each billet was assigned an overall surface quality rating using a Therm-o-Matic 300080. By first passing billets through an intense magnetic field, cracks and depressions on the billet surface were preferentially heated by the induced currents generated and stood out clearly to IR detection. This system did not distinguish between different types of surface defects. Significant improvement in surface quality was attained for grades with high carbon content that were susceptible to seams from the rolling out of sub-surface pinholes. Specifically, a study of 415 billets containing 0·40–0·59%C found that the total number of surface defects dropped roughly in half, and severe surface defects decreased by an order of magnitude.[18]

This quality improvement is believed to be a result of the removal of sub-surface cracks and/or pinholes associated with the depressions described in this paper. This is consistent with many previous studies that correlate a reduction in the magnitude of level fluctuations with a reduction in a variety of surface defects.[19,20] The lack of improvement in the instantaneous rate of level change is consistent with the mechanism presented in this paper. Because the data in Fig. 16 were logged only every 6 s and the mould level signal from the old system was filtered, the instantaneous rates of mould level change are not completely certain. It does appear however, that the quality problems addressed in this paper are not associated with rapid level fluctuations. This contrasts with previous work, where surface defects have been attributed primarily to rapid level fluctuations (greater than 2 mm s^{-1}). It therefore appears that different surface defects are affected differently by changing mould level because they form in different ways.

A bloom cast using the old level control system (shown in Fig. 3 from strand C) together with one cast at the same time and under identical conditions with the new system (strand A) were followed through rolling into billets. Although the bloom surface qualities differed greatly, billets from both blooms had only minor surface blemishes, which furthermore did not correlate with the location of depressions on the parent bloom. This confirms that the low carbon steel grade examined in this trial was not particularly prone to cracks or pinholes. Therefore, although the severe glaciation/depression 'defects' were observed on the surface of all bloom grades, they only lead to quality problems in grades prone to surface cracking or subsurface blow holes.

Conclusions

1. Depression defects on the strand surface originate at the meniscus and can be caused by low frequency mould level fluctuations.

2. Rising liquid level or thicker slag rims both increase pressure fluctuations in the flux channel near the meniscus, which likely causes deeper oscillation marks. Falling liquid level causes shallower oscillation marks with closer spacing.

3. Thicker slag rims increase pressure fluctuations in the flux channel near the meniscus, which likely causes deeper oscillation marks. Rising liquid level causes the same thing and also increases pitch.

4. A mechanism for the formation of these defects has been proposed, based on gradual rising and falling of the liquid level at the meniscus, with possible overflow of the slag rim at the peaks of the level fluctuations.

5. The depressions are shown to be filled with mould flux and cause temporary drops in heat flux and mould temperature as they move down the mould at the casting speed.

6. Surface quality in both the as-cast strand and billet product can be improved through better mould level control.

7. Severe depressions on the strand surface can be detected by examining the thermocouple traces for temperature valleys that are displaced in time according to the casting speed. Inspection of the as-cast surface is an important research tool to understand meniscus events in addition to confirming defects.

8. Mould thermocouple and mould level signals should be used as part of a quality monitoring system to produce 'quality alarms' for surface defects in a similar manner to the way breakout detection systems are used to detect and prevent breakouts.

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