Thomas, B.G., "On-line Detection of Quality Problems in Continuous Casting of Steel", in Modeling, Control and Optimization in Ferrous and Nonferrous Industry, 2003 Materials Science & Technology Symposium, F. Kongoli, B.G. Thomas, and K. Sawamiphakdi eds., (Chicago, IL, Nov. 10-12, 2003), TMS, Warrendale, PA, 2003, pp. 29-45.

# On-line Detection of Quality Problems in Continuous Casting of Steel

Brian G. Thomas

University of Illinois at Urbana-Champaign,
Dept. of Mechanical & Industrial Engineering,
1206 West Green St., Urbana, IL, 61801, USA

Keywords: Continuous casting, defect detection, thermocouple signals, on-line control

## Abstract

Quality problems in continuous casting of steel can be identified as they occur by monitoring mold signals (level sensor, thermocouples in the mold walls, friction etc.) and taking appropriate action (such as slowing casting speed, changing taper, changing a clogged nozzle, or later visual inspection of the surface for possible downgrading. Surface depressions and groups of deep oscillation marks form at meniscus and reduce local heat transfer as they move down the mold at the casting speed. This slows shell growth, increases shell surface temperature, and causes characteristic dips in mold thermocouple signals. More importantly, they are also associated with longitudinal cracks. Characteristic thermocouple signatures have been identified for many defects, including sticker breakouts, transverse depressions and deep oscillation marks, narrow-face bleeds, transverse corner cracks, longitudinal cracks, mold level fluctuation defects, and other problems. With the help of computational models, these mold signals should be used to troubleshoot defects, and to take appropriate corrective action.

## Introduction

Defects in continuous casting have been studied for several decades, and understanding continues to increase. It is best to set standard operating conditions and control systems which avoid defects from ever forming. Because this is not always possible, it is also important to monitor the process to detect unexpected quality problems, and to take appropriate corrective action. To accomplish this, Brimacombe and others championed the "intelligent mold" [1], wherein signals from mold thermocouples, mold water temperature increase, mold level detection, tundish level, optical pyrometers in the spray chamber, and other measurements are continuously monitored. These signals are then continuously interpreted by mathematical models and expert systems, knowing conditions such as the steel composition and section size, and then used as part of a control strategy to control parameters such as casting speed, flow-control position (eg. slide gate), argon gas flow, electromagnetic forces, and nozzle submergence, and mold taper. Such systems have been partially implemented in a few plants [2, 3]. They are successful only to the extent that the relationship between the signals, the control measures, and the defects, is fully understood and included in the control software algorithms. Computational models are growing in importance as a tool to help find this quantitative understanding.

The continuous casting process is shown in Fig. 1. Steel from the ladle flows through the "tundish," and then it exits down through a ceramic Submerged Entry Nozzle (SEN) and into the mold. Here, the molten steel flows in the molten pool, where it carries superheat, inclusion particles, and turbulence, which can affect the level of the top surface [4]. The liquid then freezes against the water-cooled copper

walls to form a thin solid shell, which is continuously withdrawn from the bottom of the mold at a "casting speed" that matches the flow of the incoming metal. Flow through the SEN is gravity driven by the pressure difference between the liquid levels of the tundish and the mold top free surfaces. The flow rate is controlled (using feedback from a level sensor) to maintain the liquid level in the mold as constant as possible. Choices include either a "slide gate" or "stopper rod" flow control valve. Mold powder is added to the top surface, where it sinters and melts to form a liquid layer that insulates the molten steel both thermally and chemically from the environment above. The flux also infiltrates into the gap between the mold and shell, to act as a lubricant to prevent sticking, in addition to controlling heat transfer across the gap. The mold is oscillated to prevent sticking, which also forms "oscillation marks" on the surface. Solidification begins at the meniscus, where the molten steel, liquid flux, and mold wall meet. Surface defects in the shell initiate here, and affect heat transfer lower in the mold. In severe cases, a local thin spot may lead to a costly breakout, where the internal liquid pool escapes the shell below the mold to drain molten steel over the lower part of the casting machine.

This paper first discusses the relationship between mold sensor signals and their associated phenomena, exploiting knowledge gained from computational models. Next, the most successful application of this concept is reviewed: breakout detection. Further examples of the characteristic thermocouple signals produced by various quality problems are then shown. Finally, two successful implementations of online detection systems based on thermocouple measurements are discussed.

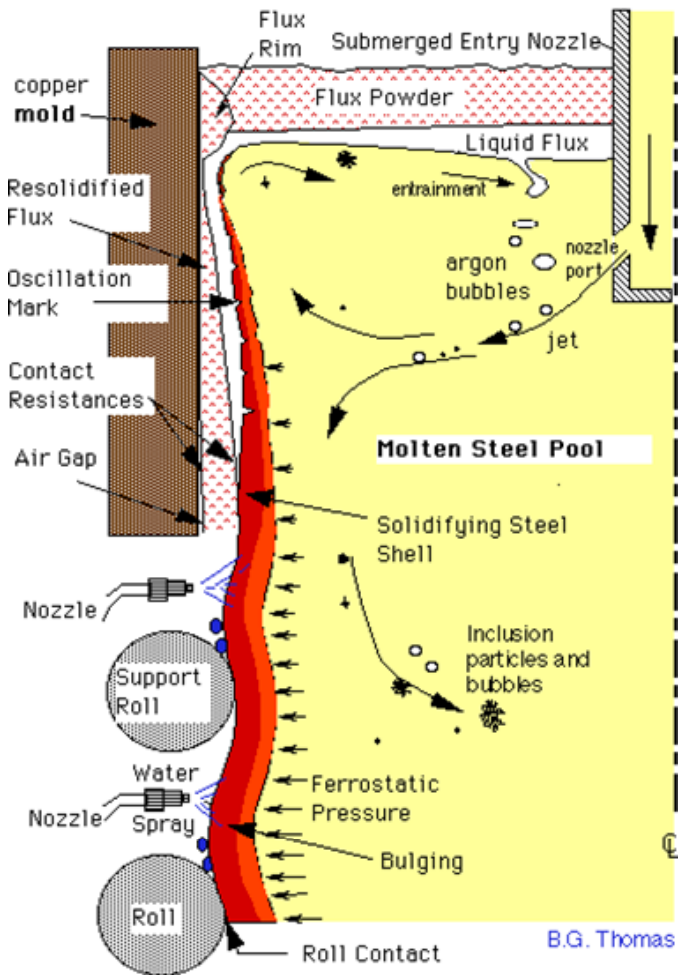


Fig. 1 Continuous casting process showing phenomena in the mold

## Surface Defects and Mold Sensor Signals

Mold defects can be inferred by examining signals from sensors in the mold. These routinely include heat-up of the mold cooling water, thermocouples embedded in the mold wall, and top surface level. Other signals may include argon gas injection rate and back pressure, mold friction (from accelerometers), the top surface liquid flux layer depth, velocity across the top surface, (indicated by MFC sensors or nailboards), and taper (from the angle of inclinometers).

### Strand Surface Appearance

Surface defects in the solidifying shell form at the meniscus and stay relatively unchanged as they move down the mold at the casting speed [5, 6]. Thus, the surface of the final solidified strand reveals important information about conditions at the meniscus when it was formed, and is important for post-mortem analysis of surface defects. For example, Fig. 2 a) shows oscillation marks on the surface of a continuous-cast bloom [7]. Ideally, the oscillation marks should be straight and regular with a spacing or "pitch" defined by the casting speed divided by the oscillation frequency. Overlapping or wiggly oscillation marks indicate a serious flow problem in the mold. The variable pitch of the distorted oscillation marks in Fig. 2 a), for example, shows evidence of time periods when the liquid level is generally rising (where the oscillation marks are deeper and spaced further apart) and falling (where they are shallow and closer together). In addition, the height of the standing wave is easily measured by variations in straightness. For example, the curved oscillation marks in Fig. 2 a) show evidence of a generally higher liquid level on the edge of the bloom, (right side) which is due in this case to mold electromagnetic stirring raising the liquid level in the corners. Although it serves as a crucial safeguard against manufacturing products from defective steel, surface inspection is obviously less desirable than online mold signals that could be used in automated quality analysis and control systems.

Surface depressions and groups of deep oscillation marks that form at meniscus will reduce local heat transfer as they move down the mold at the casting speed. This slows down solidification, leading to a thinner shell beneath the depression, as shown in Fig. 2 b) [7]. The segregation band in this figure was likely caused by fluid flow washing across the shell at a particular instant down the mold, so it indicates the shell thickness profile at that instant.

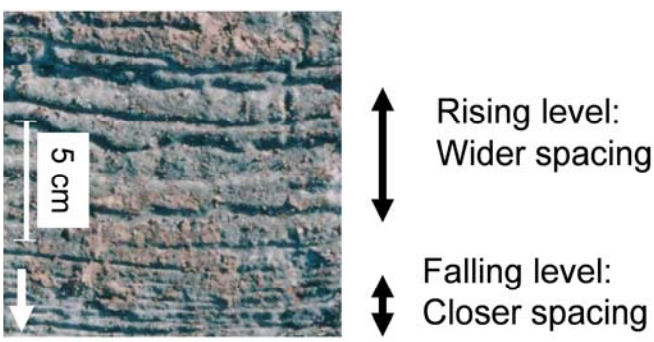


Fig. 2 a) Variation in oscillation mark spacing and depth caused by rising and falling liquid level [7].
(Vertical arrow indicates casting direction)

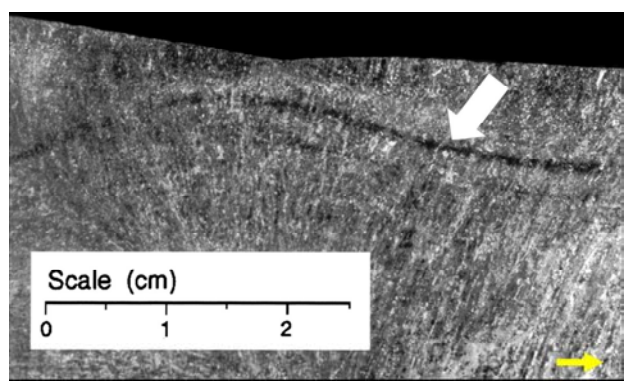


Fig. 2 b) Thin spot in shell beneath a transverse depression (indicated by discontinuous dark segregation band) [7].

### Mold Heat Flux

The total heat flux in the mold, based on a heat balance of the mold cooling water, is another important indicator of quality events in the mold. For example, Fig. 3 shows that a rougher strand surface (deeper

and / or wider oscillation marks) leads to lower overall heat flux [8]. It also causes a higher variability in heat flux [8].

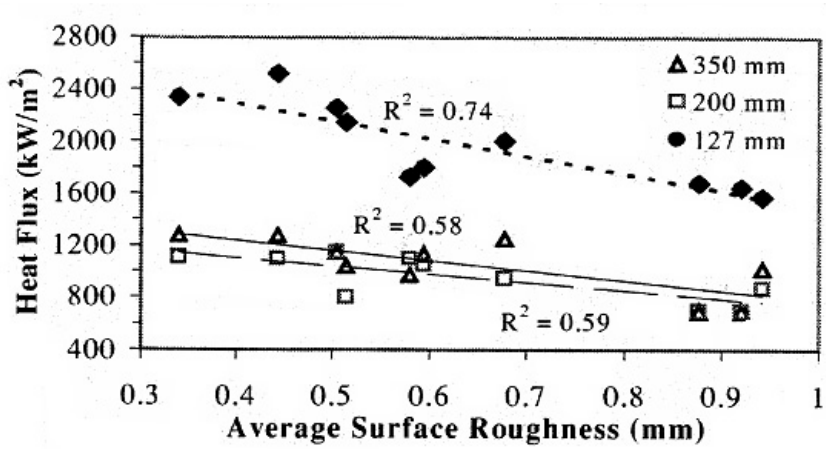


Fig. 3 Effect of oscillation mark size on total mold heat extraction [8].

**Mold Thermocouple Temperatures**

Surface depressions and oscillation marks cause the local heat transfer in the mold to drop severely beneath the depression. This in turn causes a local increase in shell surface temperature and a drop in the mold temperature. This is difficult to measure, but can be predicted with computational models. Figure 4 shows the computed effects of a particular group of deep oscillation marks on local shell growth and surface temperature rise using a 2-D longitudinal model, CON2D [6]. The shell thickness predictions are compared with measurements from a breakout shell, in addition to predictions if oscillation marks were not present. The heat flux profile was calibrated based on time-averaged measurements of total mold heat flux and thermocouple temperatures.

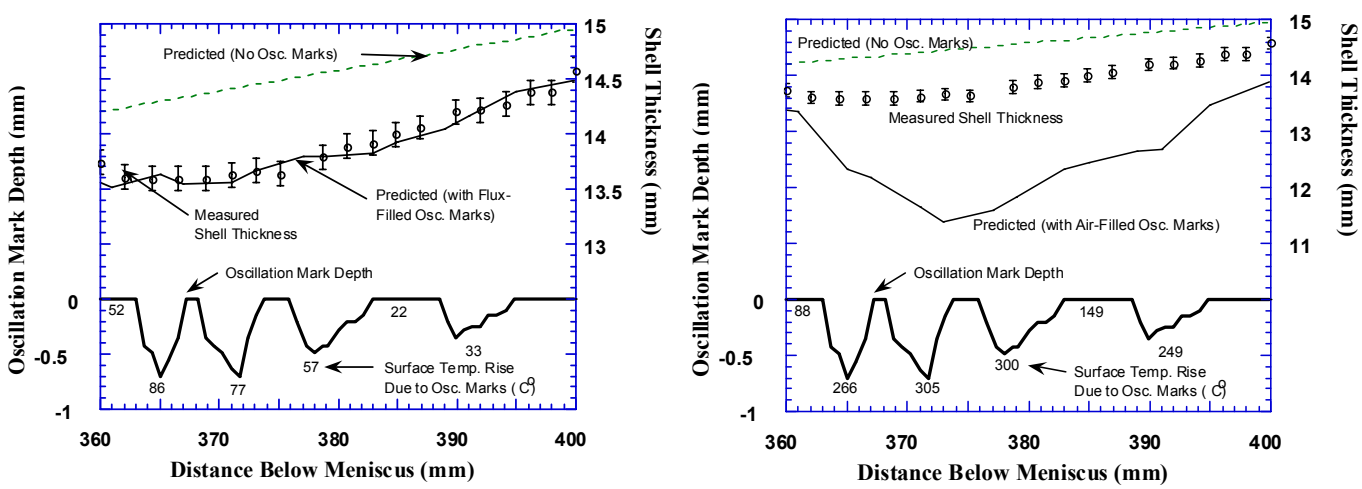


Fig. 4 Predicted and measured shell thickness with oscillation mark profile and surface temperature rises for large oscillation marks filled with mold flux (left) and air (right) [6].

Results in Fig. 4 (left) were based on assuming that gap made by the oscillation marks between the mold and shell was filled with mold flux, while Fig. 4 (right) assumed the gap was air. The flux filled marks are seen to match the measurement, which matches our expectations that liquid mold flux creates the oscillation marks at the meniscus and moves downward inside them. The air-filled oscillation marks show a very severe drop in shell growth and corresponding severe rise in local surface temperature (up to 300°C hotter than the adjacent shell with no oscillation marks). This indicates the severe

consequences of inadequate slag infiltration into the gap. It also reveals the value of computational models as an aid to process understanding.

Most importantly, a moving surface depression causes characteristic dips in the mold thermocouple signals. Figure 5 shows an example of the temperature histories recorded by three thermocouples shortly after formation of a surface depression [7]. The depression is observed to produce a temporary drop in mold temperature as it moves down the mold past each successive thermocouple. Furthermore, the time interval between the temperature valleys in adjacent thermocouple traces corresponds exactly to the casting speed. This is important, because appropriate signal processing could be used to detect such events.

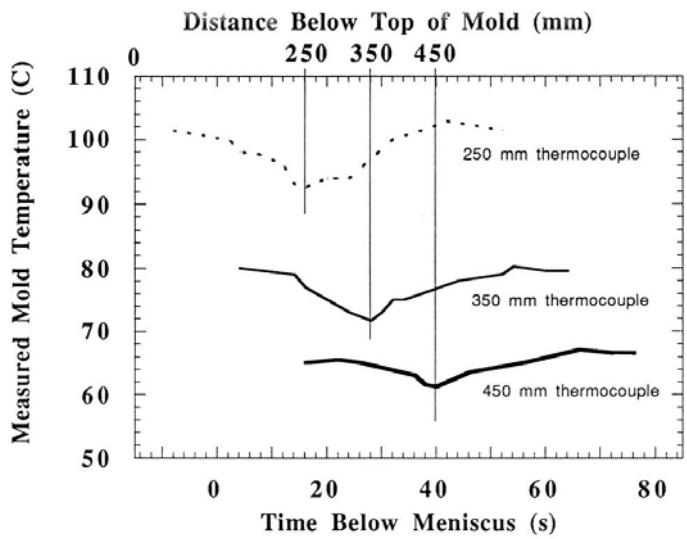


Fig. 5 Thermocouple signals measured while a transverse depression moves down the mold at the casting speed [7].

**Mold Friction Monitoring**

Mold friction can be measured using accelerometers attached to the mold surface. Figure 6 shows an example of the signals measured both in a "cold" mold, without steel, and during normal operation in a "casting" mold [9]. Subtracting the two signals yields a rough prediction of the effect of the friction between the steel shell and the mold. This produces total friction forces in the mold varying between about +10kN (upstroke) and -10kN (downstroke).

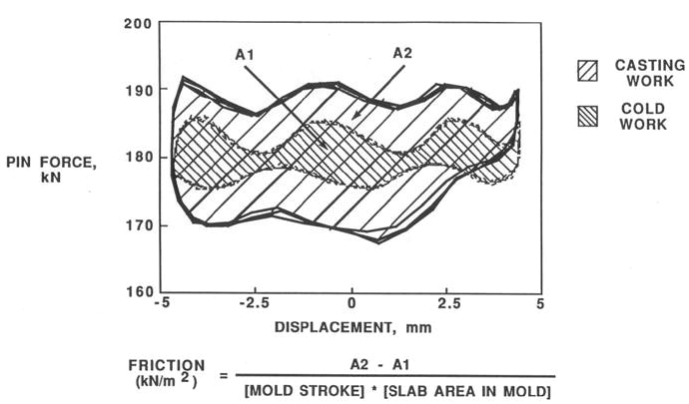


Fig. 6 Mold friction measured during an oscillation cycle in slab casting mold with and without steel [9].

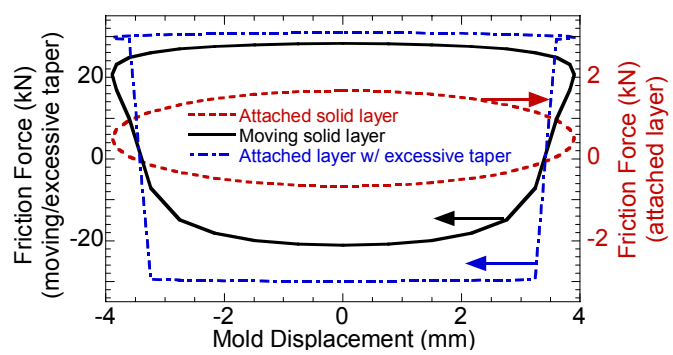


Fig. 7 Mold friction predicted during an oscillation cycle with and without an attached solid layer (with continuous liquid flux film) [10].

To understand the significance of these signals requires computational models. Figure 7 shows the results of a recent computation, based on heat, mass, and momentum balances in the interfacial flux layers coupled with heat flow calculations in the shell and mold [10]. When a stable solid layer is attached to the mold wall, so that a layer of liquid flux is able to flow between it and the steel shell, the friction forces drop to only a few kN. If the solid layer detaches and moves down the wall, a uniform liquid layer cannot persist, so solid – solid friction occurs. This raises the friction stress by an order of magnitude. The resulting prediction is on the same order as the measured mold friction forces (Fig. 6). Alternatively, if the mold taper is excessive, such as found for linear narrow face tapers at mold exit, then squeezing of the shell can increase the friction even further.

**Other Sensor Signals**

In addition to the signals discussed above, other sensors can reveal added insight into phenomena occurring in the mold. If argon gas is injected into the nozzle, it is important to measure both the flow rate and the back pressure. A sudden drop in back pressure may indicate a leak or other problem. Steel top surface velocity is important for predicting slag entrainment. Moreover, sudden changes in flow pattern correlate with strand defects [11] and is indicated by changes in top surface velocity. This velocity can be monitored using electromagnetic (MFC) sensors embedded in the mold wall [12], or other methods [13]. A spot check of mold velocity is possible using a simple nail board measurement [4]. This measurement is particularly important if electromagnetic break forces are used, as they can be adjusted accordingly to maintain a constant flow pattern. Taper can be measured online using inclinometers embedded in the mold, although they become less reliable at high oscillation frequency. Finally, surface quality itself can be measured by high-speed image analysis of the digital images of the strand or rolled sheet surface.

All of these signals should be interpreted with other known process parameters, such as steel grade, nozzle submergence, section size, casting speed, etc. in order to predict the quality condition of the cast product exiting the mold. When problems arise, they can be detected by noting characteristic patterns in the signals. The easiest signals to use for this purpose are thermocouple measurements, which are discussed in the next sections.

## Sticker Breakout Detection

Sticker breakouts initiate when molten steel at the meniscus sticks to the mold wall, instead of to the existing solidified shell. This has many possible causes, such as steel penetrating a gap between worn copper plates at the mold corner. The consequence is that an unwanted shell will grow against the mold wall, while the existing shell continues to be withdrawn from the mold bottom (Fig. 8). Each oscillation cycle, the two shells are pulled apart again. Their thin point of intersection then moves down the mold at some fraction of the casting speed, and eventually exits the mold. A breakout then occurs, as the pressure of the liquid contained inside the shell exceeds the strength of the thin spot in the shell, and ruptures an opening.

Fortunately, this disastrous sequence of events can be detected by its characteristic pattern of temperature profile development. As shown in Fig. 8 the point of highest heat flux is found where the shell is thinnest, which is usually at the meniscus. Temperatures decrease below this point. During a sticker event, this maximum point moves down the mold wall at 30-50% of the casting speed. Thermocouples in the mold wall will then detect a temperature inversion, where the lower thermocouples record higher temperatures than the upper ones for some time. Successful expert systems have been implemented using two rows of thermocouples spaced around the mold perimeter to identify these events. An alarm is triggered when the lower thermocouple is colder than the upper one for a

specified time period, and increases and / or decreases at a specified rate, especially if adjacent thermocouple pairs start to show the same behavior. Having identified the impending problem, the casting speed is dropped for some time, allowing the sticker to reattach or "heal" to the moving shell, and avoid a breakout. Three or more rows of thermocouples are even more reliable at detecting stickers with less chance for false alarms, although the analysis algorithms are more complex, and more thermocouples require more maintenance. Sticker breakout systems are routinely successful in almost all slab casters. Consequently, almost all molds contain embedded thermocouples, which could be exploited for other quality purposes.

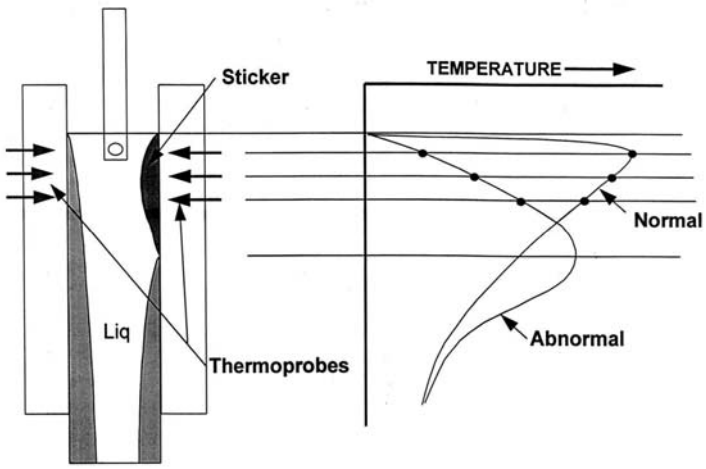


Fig. 8 Characteristic temperature profile history for sticker breakouts and their detection systems [14].

## Surface Defects and Characteristic Thermocouple Signals

Following the success of thermocouple signals at detecting sticker breakouts, this section explores the mold thermocouple "signatures" that have been found for other surface defects. In addition to the transverse depressions, narrow-face bleeds, longitudinal cracks, and mold level fluctuation defects discussed here, other surface defects, such as transverse corner cracks, have their own characteristic thermocouple signals, from which they can be identified and then controlled.

### Transverse Depression Defects from Gradual Level Fluctuations

Periodic transverse depressions have been observed on the surface of blooms subjected to low frequency level fluctuations [7]. In crack-sensitive steel grades, such as high carbon steels, these defects cause slivers in the rolled product. Fig. 9 shows a portion of the surface of a bloom cast at 0.5 m/min that contained severe intermittent depressions around its perimeter at various locations along its length (circled faintly and marked with vertical lines). This figure also shows that each defect formed at the peak of a very gradual level fluctuation, with a period of about 70s.

Figure 10 shows a close-up example of a single defect, that contains depressions over 2mm deep and extends 5-10cm along the bloom surface. The approximate profile of the maximum depth of the first 10 defects in the series is given in Fig. 11 (top). Each depression was generally accompanied by a region of deepening oscillation marks on its downstream side, and a region of shallow oscillation marks on its upstream side, often accompanied by longitudinal scraping marks [7].

The sequence of 4 steps that is believed to cause these defects is illustrated in Fig. 12.

1) The root cause of the defects is clearly the gradual level fluctuations. These were likely caused by the periodic squeezing and bulging of the shell as it moved between the support rolls below the mold during startup. This downstream source of level fluctuations presented a challenge to the mold level control system, which was not met by the standard Proportional-Derivative level controller. In fact, the problem was eventually alleviated by installing an improved level control system [7].
2) As the mold level slowly rose, the solidified flux rim at the meniscus moved closer to the newly solidified shell. This generated higher pressure in the liquid flux channel during each oscillation stroke, imposing bending forces on the shell. The result was deeper oscillation marks on the downstream side of the depression, similar to Fig. 2 a).

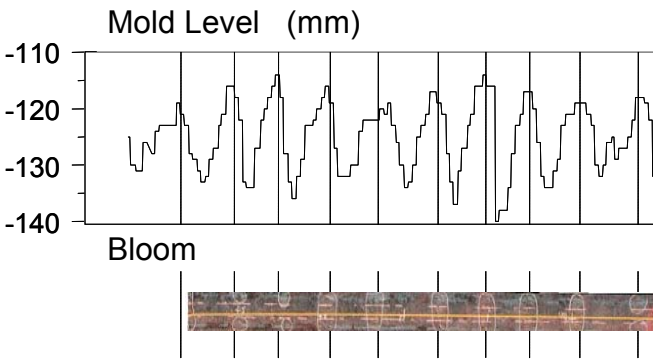


Fig. 9 Periodic bloom surface defects (below) and corresponding mold level signal (above), showing that defect forms at mold level peak [7].

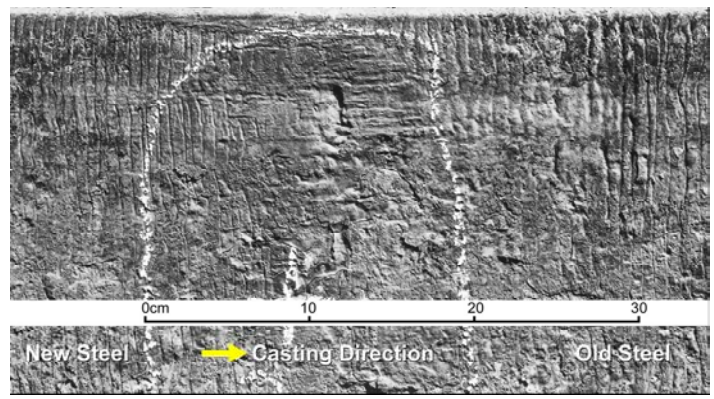


Fig. 10. Close-up of one of the bloom surface defects in Fig. 9 [7].

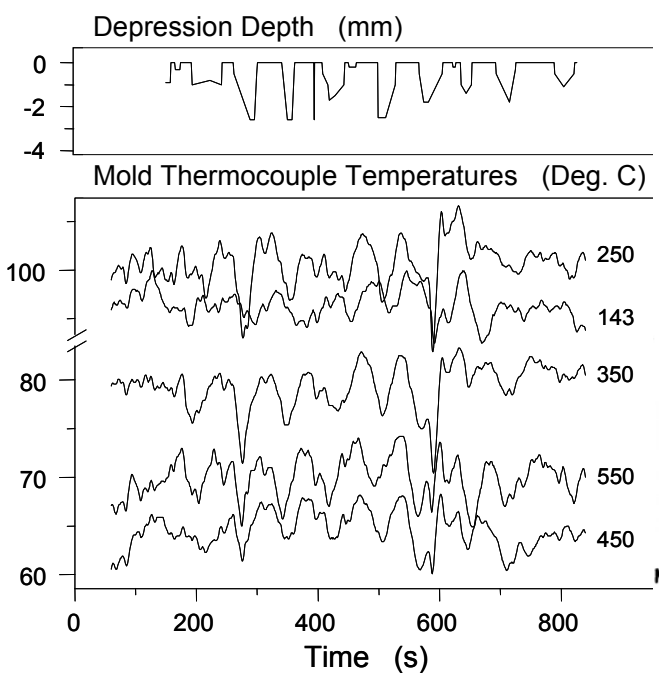


Fig. 11. Match-up of surface depressions (above) with mold temperatures (below), obtained by displacing the signals in time according to their distance below meniscus and the casting speed [7].

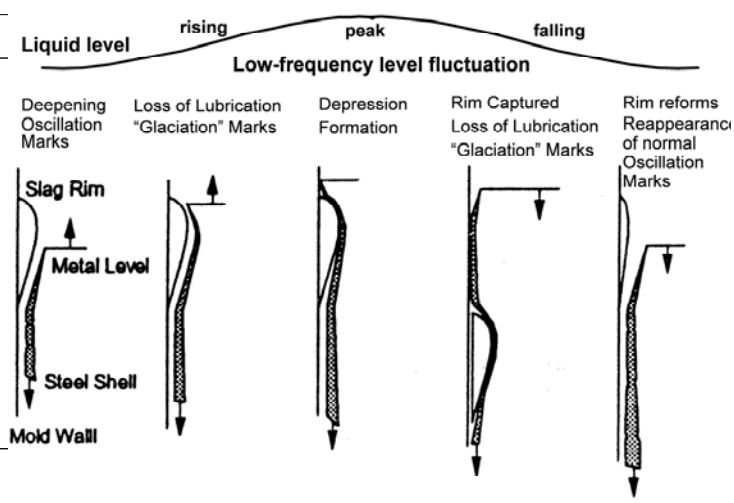


Fig. 12. Mechanism of surface depression formation via low-frequency level fluctuations [7].

3) At the peak of the mold level rise, the liquid level likely overflowed the solid mold flux rim at the meniscus. This interaction imprinted the flux rim on the new shell, and perhaps even captured the flux rim, to drag it downward. The lower heat transfer against the flux rim encouraged shallower oscillation marks.
4) During rolling, the depressed region would be subject to increased defects from two causes. Overflow and capture of mold flux at the meniscus might lead to oxide particles trapped just below the surface. The hotter, weaker shell beneath the depression would be more prone to stress concentration and cracks, which would later oxidize to form slivers.

The thermocouple signals for this defect align with the characteristic pattern expected for surface depressions that was previously discussed, as shown in the bottom of Fig. 11. This figure was constructed by displacing the signal of each thermocouple forward in time by its distance below meniscus divided by the casting speed. The time-dependent meniscus position is known from the mold level signal (Fig. 9). The striking feature of this figure is the close vertical alignment of each major drop in temperature of each thermocouple. It is interesting to note that the shape of some of the temperature "dips" changes slightly with distance down the mold, perhaps due to changes in the gap properties due to crystallization or loss of liquid flux in the local gap. Computer software that could recognize these patterns in the thermocouple signals would be able to detect the presence of these depressions.

## Narrow-face Bleed Defects

A "bleed" is a serious surface defect that can occur in molds with inadequate taper [15]. If the gap between the shell and mold becomes too great, heat transfer can drop to cause the shell to grow so thin that it cannot support the internal liquid steel pressure. Molten steel can then break through the shell inside the mold. Unlike a breakout below the mold, this liquid quickly spreads in the gap and freezes. Although this heals the shell, it leaves an ugly patch or scab on the steel surface that can delaminate during rolling.

The temperature history recorded for a narrow face bleed is shown in Fig. 13 [16]. The nearest thermocouple to the rupture location first records a sudden jump in temperature (300mm TC). As the hot escaped metal is dragged down the mold wall, the temperature increases in turn at lower thermocouples, with a time delay according to the casting speed. After reaching a peak, all of the mold temperatures drop, as the breech is sealed and the escaped steel continues to cool.

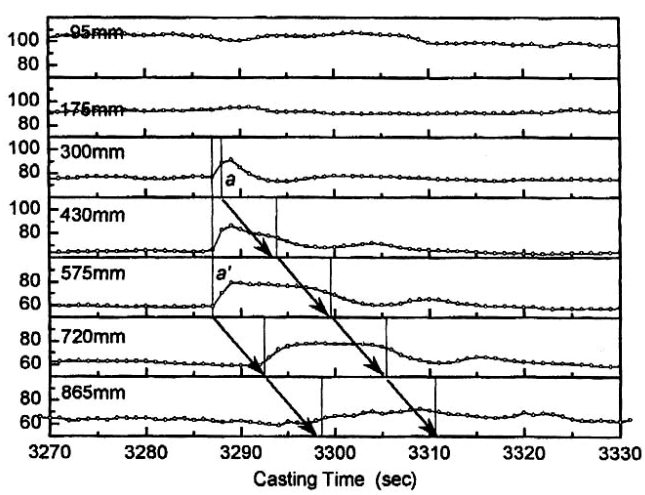


Fig. 13 Thermocouple signals recorded during a narrow face bleed [16].

A system detecting the thermocouple signal sequence in Fig. 13 could be used to flag that region of the final slab for careful inspection, and likely downgrading.

## Transverse Depressions from Sudden Level Fluctuations

Rapid fluctuations in the level of the top surface of the molten steel in the mold is responsible for many surface defects [17]. A sudden severe drop in liquid level exposes the inside of the solidifying shell to the mold slag, and also leads to surface depressions. Relaxing the temperature gradient causes cooling and bending of the top of the shell toward the liquid steel. When the liquid level rises back, the solidification of new hot solid against this cool solid surface layer leads to even more bending and stresses when the surface layer reheats [18]. This sequence of events is illustrated on a 20mm long section of shell in the calculation results in Fig. 14, for a 20-30mm level drop lasting 0.6s [18]. When liquid steel finally overflows the meniscus to continue with ordinary solidification, a surface depression is left behind.

In addition to the surface depression, a rapid level fluctuation can also initiate longitudinal cracks. As shown in Fig. 15, a severe tensile stress is predicted in the hoop direction around the shell surface when the level drops [18]. This is due to the shrinkage of the upper shell from rapid cooling, while it is constrained by the solid shell below it. This hoop stress may generate many fine cracks, or a single large crack, depending on whether there is a weak spot in the shell from some other cause. In either case, longitudinal cracks can be inferred indirectly by looking for temperature signals from transverse depressions associated with the rapid level fluctuations.

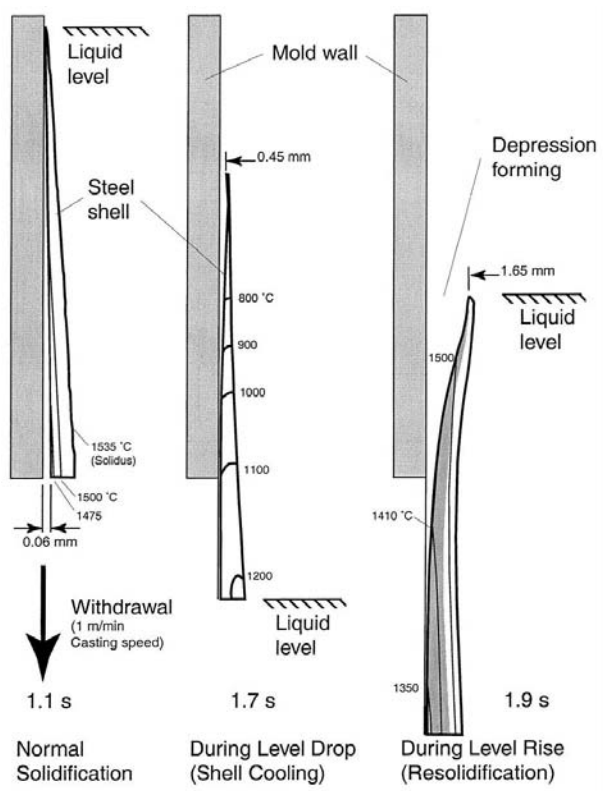


Fig. 14 Events causing a transverse depression from a high-frequency level fluctuation [18].

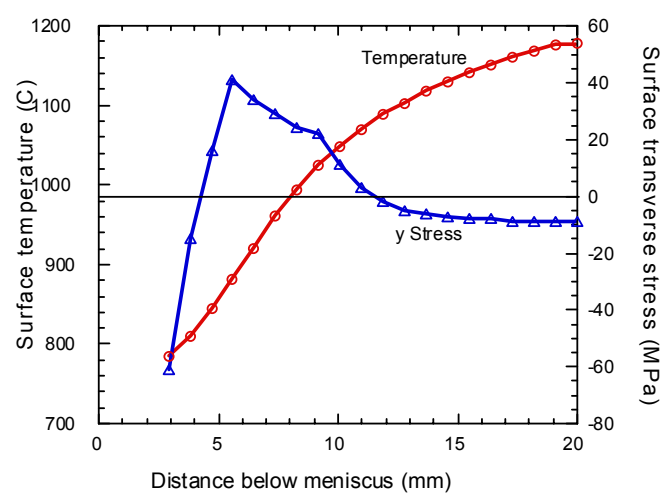


Fig. 15 High transverse stresses caused by a sudden level drop, which may start a longitudinal crack [18].

## Mold Level Fluctuation Control and Monitoring

Knowing that level fluctuations are detrimental to steel quality, mold level control systems are designed to keep such fluctuations to a minimum. Unfortunately, level control systems have only a single control actuator: the slide gate or stopper rod position. Thus, these systems at best can control only the average level. Accurate level sensors, such as the NKK eddy-current sensor, radioactive source detection, or EMLI detector, are expensive. Thus, to be most effective, the level sensor should be placed near the region of the liquid surface that is the least sensitive to level fluctuations: usually found midway between the nozzle and the narrow faces of a slab caster. Furthermore, the signal should be filtered (time-averaged) to avoid feedback problems due to the time delays in the system between changing the flow control and measuring the level changes. Thus, the level controller signal is not the best indicator for quality purposes.

For quality indication purposes, the unfiltered level sensor position is more useful. Even better would be to record level changes all around the mold perimeter. This might be done using mold thermocouples. Figure 16 shows the mold level position and the temperatures recorded in a slab caster by two nearby thermocouples, already present for breakout detection [19]. The temperatures clearly follow the large level fluctuation, although minor fluctuations can be different. This was investigated further using computational models [19]. Figure 17 shows results from a transient, 3-D finite-element computation in a segment of the upper region of the copper mold containing the meniscus, the two thermocouples, and a representative portion of the surrounding water slots. This was obtained by calibrating the mold heat flux to match both the time-averaged mold temperature and total cooling water heat balance. By then shifting the entire vertical heat flux profile up and down according to the fluctuating mold level signal, predictions of the mold thermocouple measurements were obtained. The predictions closely match the measurements in Fig. 16. They include their slight time delay, owing to the thermal capacity of the copper between the hotface and the thermocouple tips (located 20 mm beneath the hotface).

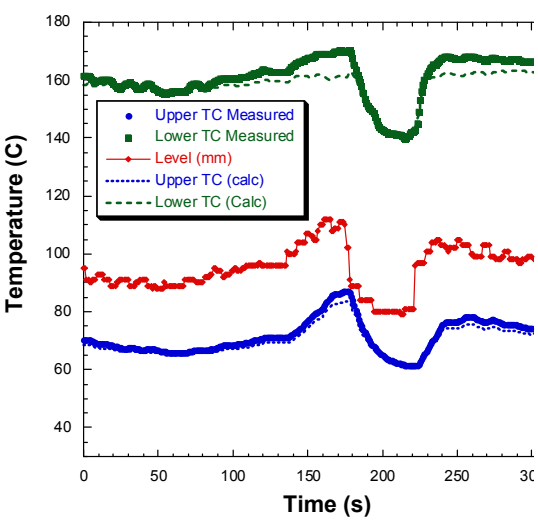


Fig. 16 Comparison of mold level signal with measured and predicted temperatures of two mold thermocouples [19].

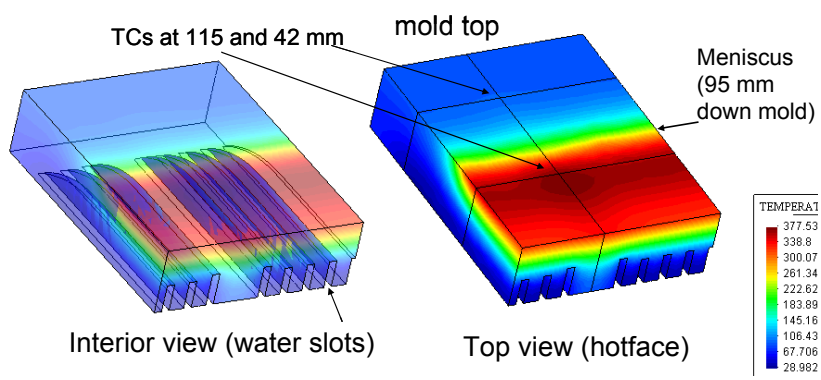


Fig. 17 Segment of copper mold showing water slots (left) and surface temperatures (right) computed by 3-D FEM model [19].

The model was next used to explore the ability of mold thermocouples to detect a single level drop of 10mm lasting 3s. Figure 18 (left) shows the predicted response of the upper thermocouple located at various distances beneath the hotface of the 43-mm thick copper mold plate. Naturally, the hotface itself responds the best, but it still records only a shallow drop of just a few degrees K, spread out in time over about 10s. The change in the deep thermocouples is almost imperceptible. The signals predicted for the lower thermocouple (Fig. 18 right) show a greater response, which initially increases, owing to the peak heat flux initially moving closer as the level falls. These results illustrate the great damping effect of the copper mold, which is affected by the entire heat flux profile, and not just the meniscus. Deriving accurate mold level predictions would require sophisticated analysis that took into account simultaneously signals from thermocouples both above and below the meniscus. The detection of small fluctuations does not appear to be feasible.

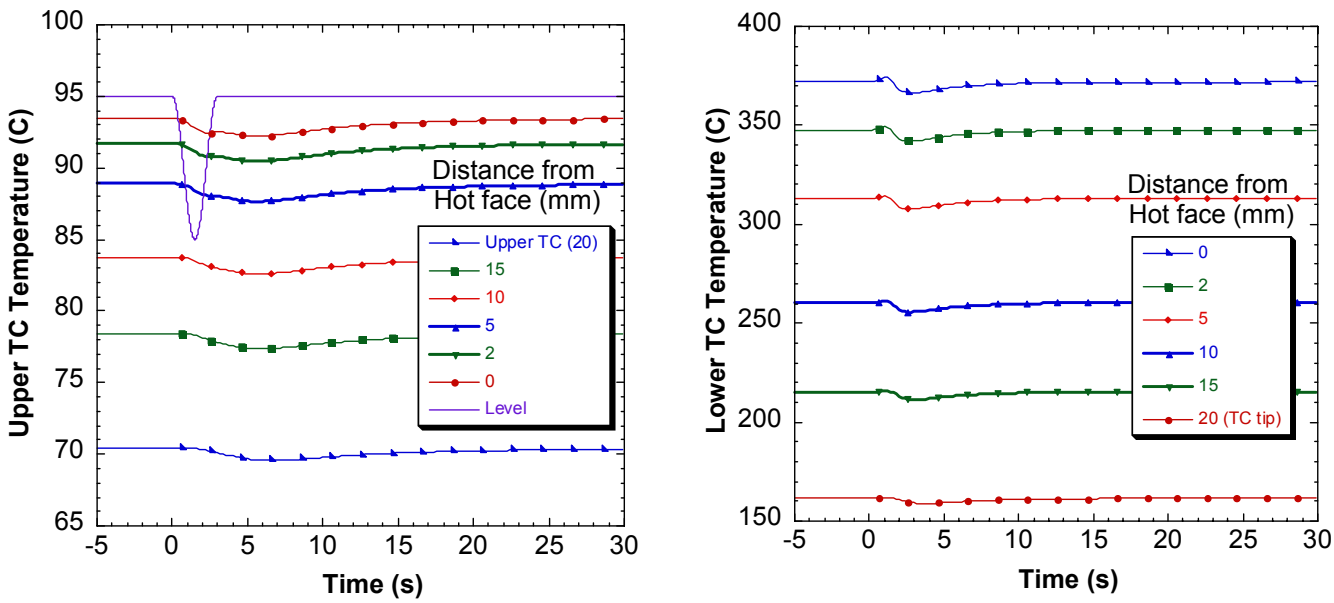


Fig. 18 Thermocouple signals predicted at various distances beneath copper hotface for a sinusoidal level drop of 10mm lasting 3s: at upper thermocouple location (left) and at lower TC location (right) [19].

## Online Quality Monitoring in the Steel Plant

The online models used to control the continuous casting process are steadily becoming more advanced. Spray water flow rates are routinely controlled dynamically using transient finite-difference models [20]as open-loop control models that update at least every minute [21]. The implementation of control systems based on the analysis of mold temperature signals that go beyond breakout detection is also underway. Two such examples are discussed here.

### Thermocouple Signal Expert System for Longitudinal Cracks

An expert system has been developed by British Steel, Sidmar, and CRM [2]to identify regions of the surface of cast slabs that are likely to contain longitudinal cracks. The system is based on interpreting thermocouple temperature fluctuations measured at many locations on the strand surface. Figure 19 shows the system setup. Large temperature fluctuations near the meniscus correlated well with longitudinal cracks, especially severe ones longer than 400mm. Maps were plotted over the strand surface of the magnitude of signal variations, quantified by the difference between the forecasted and measured temperatures. Where signal variations exceeded a critical value, those portions of the slab

surface were flagged for closer visual inspection. Correct crack prediction rates of almost 80% were reported, with less than 25% false alarms [2].

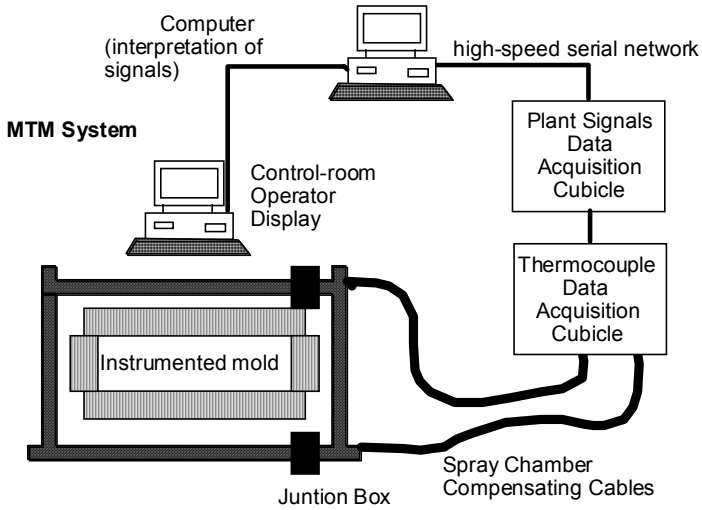


Fig. 19 Longitudinal crack identification system using expert system analysis of mold thermocouples [2].

## Visualization System for Surface Heat Transfer

Recently, Hemy et al [3] have developed an online visualization system using thermocouples to identify thermal events on the strand surface in the mold related to breakouts and quality problems. The system has been implemented at the Algoma Steel thin slab caster (72-90mm thick x 1100mm long x 800-1640mm width), containing 194 thermocouples (10 rows of 9 thermocouples on each wideface). The system records temperatures every 2s, and converts them into contour plots with a realistic color map, such as shown in Fig. 20.

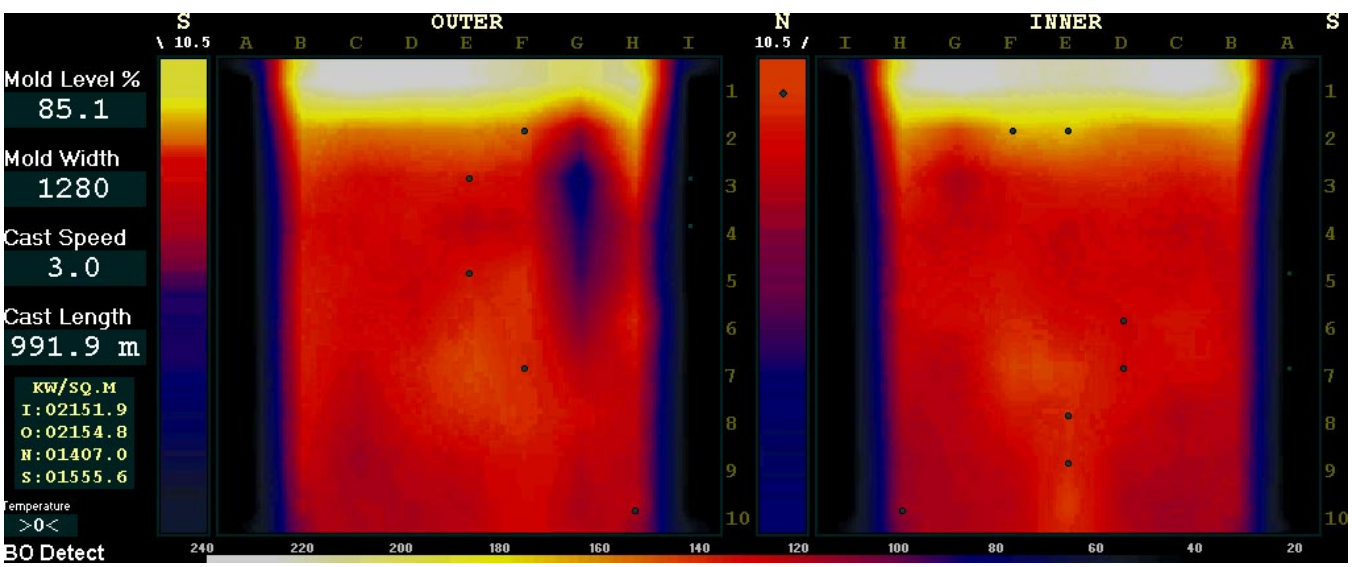


Fig. 20 "Hemy-vision" online visualization of off-corner crack from mold thermocouple contours [3].

This system has been used for post-mortem analysis of breakouts and other defects, or "forensic metallurgy". In addition, it has been used as online information for operators to take corrective action. For example, Fig. 20 shows a snapshot from the system of the temperature profiles visualized during a sudden drop in temperature along the off-corner region, due to loss of contact that caused local shell

thinning and an incipient longitudinal crack [3]. This event was identified in time to slow down and successfully avoid a breakout. Significant understanding such as this has been achieved, allowing operators to identify and avoid problems. Events that have been identified include breakouts, longitudinal broadface cracks, SEN rupture, meniscus tears, loss of taper, and shell detachment. However, automated computer control to take corrective action based on the signals awaits better quantitative human understanding of the signals, and software implementation of that understanding.

## The Future "Intelligent" Mold

Online monitoring in the future could simultaneously measure

- Metal level
- Mold heat transfer (from cooling water heat balance)
- Mold temperatures (using more than 100 thermocouples )
- Mold friction
- Fluid flow surface velocities, argon, taper, etc.
- Product surface quality (eg. Parsytec system)

After analysis by process models, online variables to control fluid flow include: casting speed (from flow control valve adjustment, such as the slide gate), dynamic spray cooling water flow rates, and electromagnetic breaking forces in the mold. Other adjustable parameters include mold taper and mold water flow rate. The ultimate measure of product quality lies with the customer, but every effort should be made to minimize this measure. Product inspection and downgrading of slabs according to quality monitoring criteria are better methods.

Although significant progress has been towards the understanding of characteristic thermocouple signals for various surface quality problems and its implementation into online control systems, much work remains to be done. Significant improvement in our understanding of defect mechanisms, the accuracy of sensor measurements, and the sophistication of control models is needed before the truly "intelligent mold" envisioned by Brimacombe [1]can become a reality.

## Conclusions

- Quality problems can be identified as they occur by monitoring mold signals (level sensor, mold water heatup, thermocouples in the mold walls, friction, etc.) and taking appropriate action (eg. slowing casting speed, changing taper, changing a clogged nozzle, later visual inspection of surface

- Surface depressions and groups of deep oscillation marks form at meniscus and reduce local heat transfer as they move down the mold at the casting speed, which
  - slows shell growth,
  - increases shell surface temperature, and causes characteristic dips in mold thermocouple signals.

- Characteristic thermocouple signatures have been identified for:
  - Sticker breakouts
  - Transverse depressions and deep oscillation marks
  - Narrow-face bleeds
  - Transverse corner cracks
  - Longitudinal cracks

- Mold level fluctuations

- Mold signals can be used to:
  - generate quality alarms when they deviate from a standard
  - troubleshoot defects (offline post mortem analysis)
  - visualize problems (e.g. online 2D thermal maps)
  - online prevention of defects (by recognizing characteristic patterns in the signals and taking corrective action)

## Acknowledgments

The author wishes to thank the National Science Foundation and the Continuous Casting Consortium at the University of Illinois for funding that made this work possible, and the National Center for Supercomputing Applications at UIUC for computer time and software. Thanks are also due to the many students and colleagues who helped perform the research summarized here.

## References

1. J.K. Brimacombe, "Empowerment with Knowledge - toward the Intelligent Mold for the Continuous Casting of Steel Billets," Metall. Trans., Vol. 24B, 1993, pp. 917-935.
2. D. Stewart, P.N. Hewitt and L. Peeters, "The Prediction of Longitudinal Cracking During Slab Casting," in Steelmaking Conf. Proc., Vol. 79, ISS, Warrendale, PA, (Pittsburgh, PA), 1996, pp. 207-214.
3. P. Hemy, R. Smylie and C. Srinivasan, "Analyzing Casting Problems by the On-line Monitoring of Continuous Casting Mold Temperatures," JOM-e, (Journal of Metals – electronic edition), http://www.tms.org/pubs/journals/JOM/0201/Hemy/Hemy-0201.html, 2002.
4. B.G. Thomas, "Continuous Casting Operation: Fluid Flow," in Making, Shaping and Treating of Steel: Continuous Casting, Vol. 5, A. Cramb, ed. AISE Steel Foundation, Pittsburgh, PA, 2003, pp. 14.1-14.41.
5. B.G. Thomas and J.T. Parkman, "Simulation of Thermal Distortion of a Steel Droplet Solidifying on a Copper Chill," in Solidification 98, S. Marsh, J. Dantzig, R. Trivedi, W. Hofmeister, M. Chu, E. Lavernia and J. Chun, eds., TMS, (Warrendale, PA), 1998, pp. 509-520.
6. B.G. Thomas, D. Lui and B. Ho, "Effect of Transverse and Oscillation Marks on Heat Transfer in the Continuous Casting Mold," in Sensors in Materials Processing: Techniques and Applications, V. Viswanathan, R.G. Reddy and J.C. Malas, eds., TMS, Warrendale, PA, (Orlando, FL), 1997, pp. 117-142.
7. M.S. Jenkins, B.G. Thomas, W.C. Chen, R.B. Mahapatra, "Investigation of Strand Surface Defects using Mold Instrumentation and Modelling," in Steelmaking Conf. Proc., Vol. 77, ISS, Warrendale, PA, (Chicago, IL), 1994, pp. 337-345.
8. W. Lai, M. Milone and I. Samarasekera, "Meniscus Thermal Analysis as a Tool for Evaluating Slab Surface Quality," in Steelmaking Conf. Proc., Vol. 83, ISS, Warrendale, PA, (Pittsburgh, PA), 2000, pp. 461-476.
9. M.R. Ozgu, D.N. Rego, B. Kocatulum, J.K. Simms, T.W. Fenicle, K.R. Burcaw, W.T. Bentley, D.J. Idstein, "Use of Instrumentation to Evaluate Mold Powders and Practices at the Burns Harbor No. 2 Slab Caster," 1st European Conference on Continuous Casting, (Florence, Italy), Vol. 1, 1991, pp. 1.73-1.82.

10. Y. Meng and B.G. Thomas, "Interfacial Friction-Related Phenomena in Continuous Casting with Mold Slags," in Steelmaking Conf. Proc., Vol. 86, ISS, Warrendale, PA, (Indianapolis, IN), 2003.
11. M.B. Assar, P.H. Dauby and G.D. Lawson, "Opening the Black Box: PIV and MFC Measurements in a Continuous Caster Mold," in Steelmaking Conf. Proc., Vol. 83, ISS, Warrendale, PA, (Pittsburgh, PA), 2000, pp. 397-411.
12. P. Andrzejewski, D. Gotthelf, E. Julius, H. Haubrich, "Mould Flow Monitoring at No. 3 Slab Caster, Krupp Hoesch Stahl AG," in Steelmaking Conf. Proc., Vol. 80, ISS, Warrendale, PA, 1997, (Chicago, IL), 1997, pp. 153-157.
13. B.G. Thomas, Q. Yuan, S. Sivaramakrishnan, T. Shi, S.P. Vanka, M.B. Assar, "Comparison of Four Methods to Evaluate Fluid Velocities in a Continuous Casting Mold," ISIJ Internat., Vol. 41 (10), 2001, pp. 1266-1276.
14. E. Szekeres, personal communication, Casting Consultants Inc, 1993.
15. S. Kumar, I.V. Samarasekera and J.K. Brimacombe, "Mold Thermal Response and Formation of Defects in the Continuous Casting of Steel Billets, Part 1: Laps and Bleeds," Iron and Steelmaker (ISS Transactions), Vol. 24 (June), 1997, pp. 53-69.
16. K.Y.M. Lai, M. Salcudean, S. Tanaka, R.I.L. Guthrie, "Mathematical Modeling of Flows in Large Tundish Systems in Steelmaking," Metall. Trans. B, Vol. 17B, 1986, pp. 449-59.
17. S. Kumar, B.N. Walker, I.V. Samarasekera, J.K. Brimacombe, "Chaos at the Meniscus - the Genesis of Defects in Continuously Cast Steel Billets," in PTD Conference Proceedings, Vol. 13, Iron and Steel Society, (Warrendale, PA), 1995, pp. 119-141.
18. B.G. Thomas and H. Zhu, "Thermal Distortion of Solidifying Shell in Continuous Casting of Steel," in Proceedings of Internat. Symposia on Advanced Materials & Tech. for 21st Century, I. Ohnaka and D. Stefanescu, eds., TMS, Warrendale, PA, (Honolulu, HI), 1996, pp. 197-208.
19. B.G. Thomas and T. Morthland, "3-D Heat Transfer Analysis of Columbus Slab Casting Mold," Report, Research Report to Columbus Steel, 2001.
20. R.A. Hardin, K. Liu and C. Beckermann, "Development of a Model for Transient Simulation and Control of a Continuous Steel Slab Caster," in Materials Processing in the Computer Age, Vol. 3, Minerals, Metals, & Materials Society, Warrendale, PA, 2000, pp. 61-74.
21. K. Dittenberger, K. Morwald, G. Hohenbichler, U. Feischl, "DYNACS Cooling Model - Features and Operational Results," VAI 7th International Continuous Casting Conference, (Linz, Austria), 1996, pp. 44.1-44.6.