Influence of Mold Flux Crystallite Film Fracture on Thermal Fluctuations in a Thin-Slab Funnel Mold






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Mold thermal data was investigated from two thin-slab casting facilities that employed funnel molds instrumented with thermocouples that extended into the lower part of the mold. Under specific operating conditions, regular "sawtooth-like" temperature fluctuations were observed in the lower part of the funnel area. Analysis of cap-off flux film samples and mold temperature data suggests that the temperature fluctuations are caused by the fracture, withdrawal and regrowth of the crystalline layer of the flux film. The effects of this flux film fracture and reformation on the heat flux profile in the mold are investigated.

The magnitude, stability and uniformity of heat extraction in the mold of the continuous casting process are influenced markedly by the properties of continuous casting mold flux and the conditions within the mold gap.[1–4] Large local variations in heat removal in the mold can induce stresses in the solidifying steel shell that can lead to defects such as longitudinal cracks, shell buckling and shell thinning. The crystallization behavior of the mold flux plays an important role in the control of the process by slowing the rate of heat extraction and reducing heat removal variability.[5,6] It has been shown that the stability of the crystalline layer that resides against the mold within the mold gap has a strong effect on the variability in mold temperature and heat removal during casting.[2,7] Weak crystallites can fracture easily, leading to large variations in heat transfer with time, while excessively strong crystallite layers can cause a steady drop in heat removal over time.[2,8]

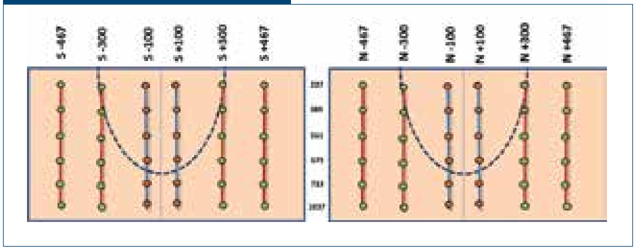
In high-speed thin-slab casting, the shear stresses in the mold gap are often higher than the stresses observed in the conventional continuous casting process, in part because higher casting speeds and oscillation frequencies are employed in the process. In thin-slab casters that employ funnel mold designs, additional shear stresses can be generated in the lower area of the funnel as the solidifying steel shell is formed in the mold to achieve a rectangular slab shape at mold exit.[9,10] If the shear stresses in this region of the mold exceed the shear strength of the crystalline layer in the flux film, the film can fracture locally in the region of high shear stress.[11–13]

In this paper, the authors present some examples of localized thermal instabilities that were observed in the mold funnel area on two thin-slab casters along with evidence for the source of these instabilities. It should be noted that sawtooth-like mold temperature fluctuations have been observed in many studies.[2,7,8,12] What is of interest here is the relatively small localized area within which these fluctuations occur, and the difficulty in detecting them without employing enhanced mold instrumentation.

Data Collection and Sampling Procedure

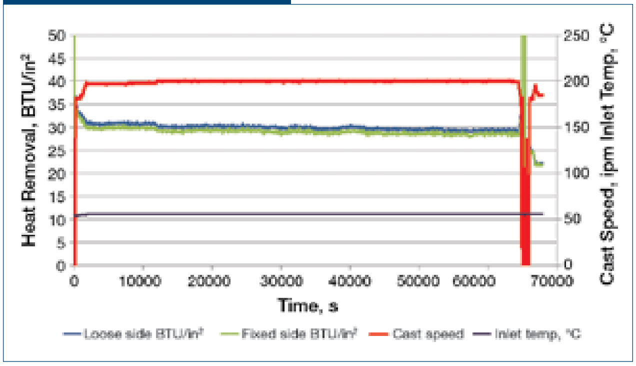
Process data (cast speed, mold broad face heat removal, etc.) was collected along with mold temperature

Figure 1



Thermocouple locations in funnel mold at Company G. Numbers shown are in mm from center or top of mold.

Figure 2

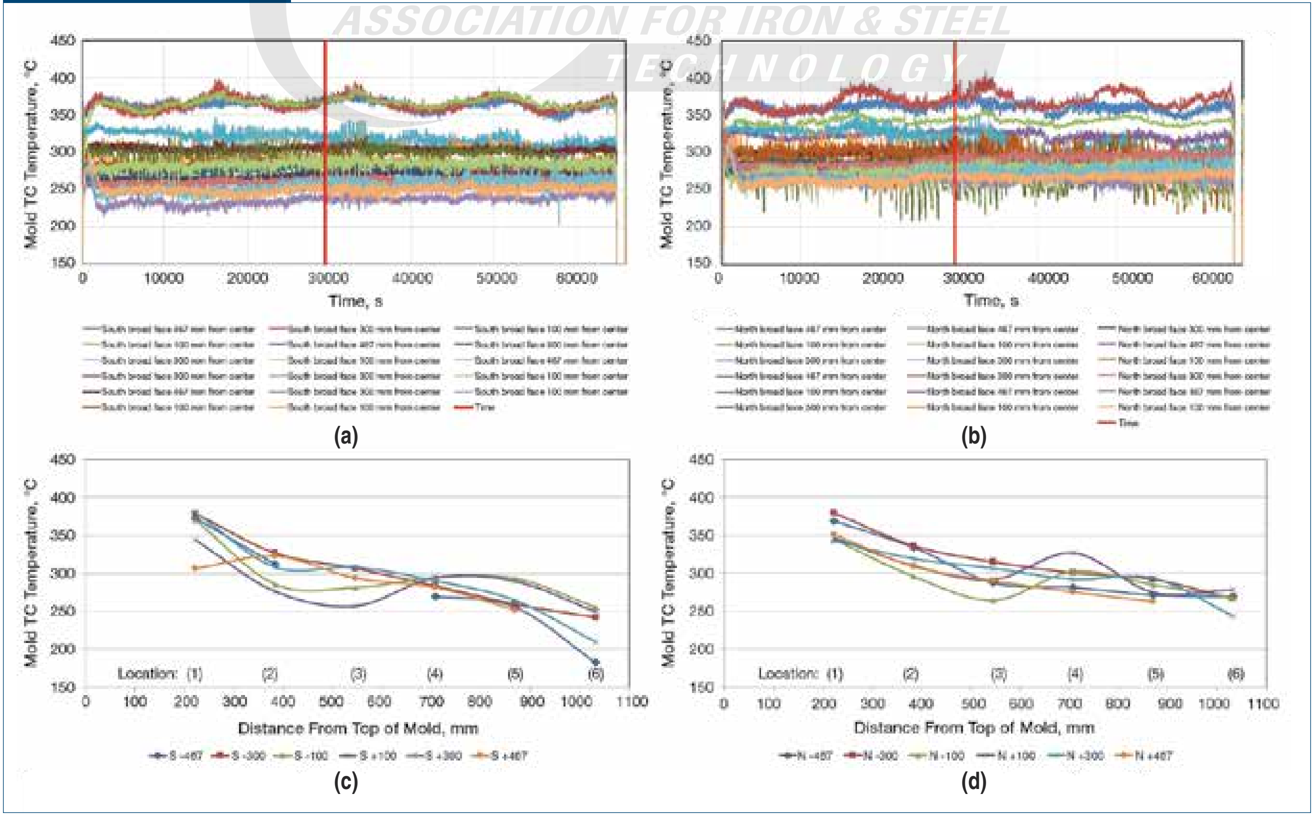


Mold heat removal for 1026 steel cast with Flux G2 at Company G.

data during casting from two thin-slab casters that employed funnel molds. The molds were both instrumented with thermocouples over a large area of the mold to examine the mold temperatures during casting. At Caster G, mold flux films were also extracted at cap-off to examine the structures of the flux films in different areas of the mold. A map of the thermocouple positions in the mold at Company G is shown in Fig. 1. The mold at Company D had a similar thermocouple layout.

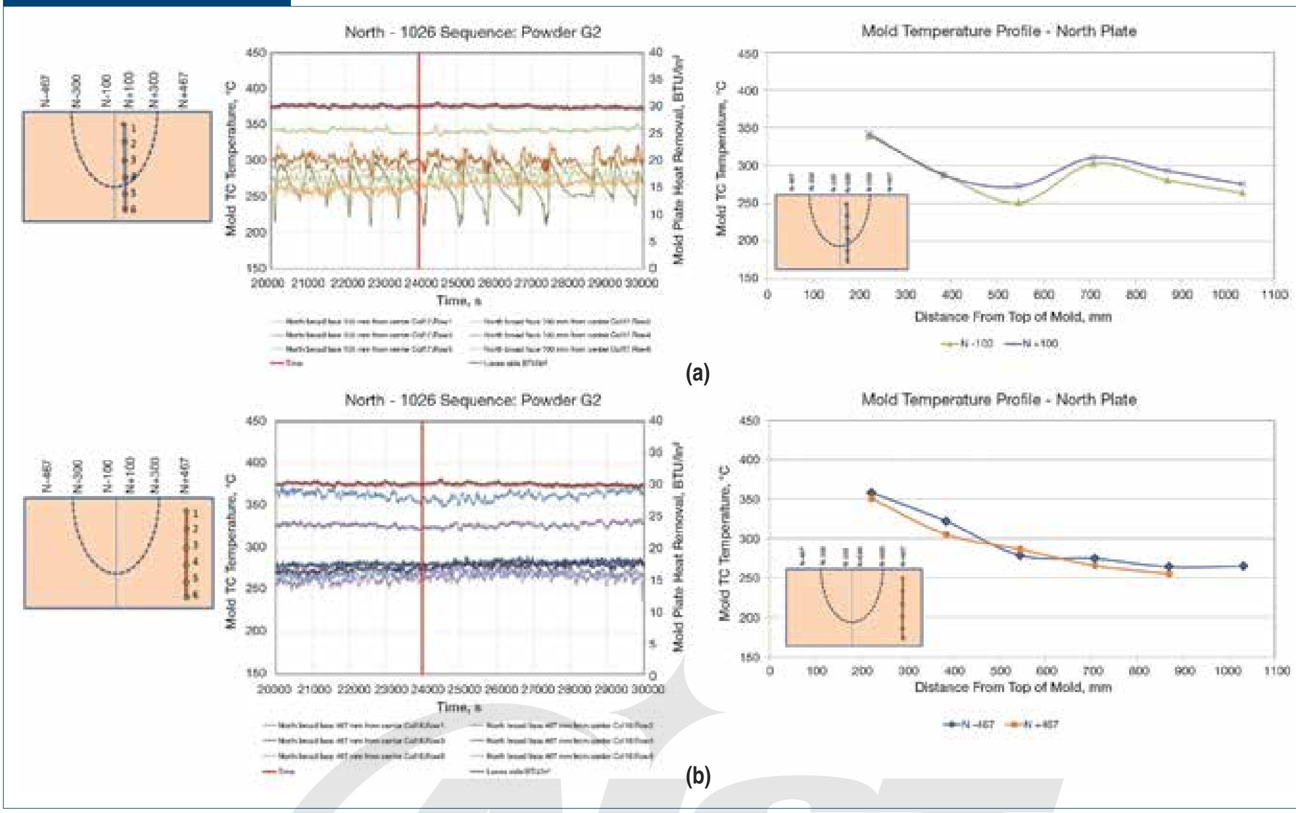
The data collected at Company G was from an 18-hour cast sequence of 1026 steel shown in Fig. 2. The corresponding thermocouple traces from each broad face plate for this cast sequence are shown in Fig. 3. The red vertical lines in Figs. 3a and 3b mark the time for the temperature profile snapshot plotted in Figs. 3c and 3d. These profiles were also reviewed

Figure 3



Thermocouple mold broad face temperatures for 1026 with Flux G2 at Company G (a and b) and snapshot of temperature profile on north and south broad face plates at 31,000 seconds (c and d) at red vertical line in upper figures.

Figure 4



Comparison of individual thermocouple array temperatures located inside and outside of the funnel area for 2.8 hours of steady state operation (left) and corresponding thermocouple temperature profile snapshot at 24,000 seconds (right) (a) within the mold funnel area and (b) outside the mold funnel area.

as a function of time to observe the dynamic behavior of the mold temperature profiles.

Observations and Discussion

The sequence presented in Figs. 2 and 3 was selected because the caster operated at steady-state conditions for most of the operating time and exhibited stable mold broad face heat removal levels during the cast. The overall heat flux and mold temperatures appear to be stable at first glance, but they do exhibit some thermal instabilities that were only evident after reviewing the animated temperature profiles of specific thermocouple arrays and examining the data on an expanded time scale.

Fig. 4 shows data for two specific thermocouple arrays on the north broad face over a period of 2.7 hours in the middle of the cast sequence. Fig. 4a shows the data from a thermocouple array that is within the funnel region of the mold, while Fig. 4b shows the data from a thermocouple array that is outside of the funnel region of the mold. It is evident that some specific thermocouple positions within the lower funnel area show strong periodic sawtooth-like temperature fluctuations, every 600 to 1,000 seconds of cast time. It is also interesting to note that while the temperature fluctuations are large (on the order of 50 to 80°C), the observed overall heat removal fluctuations on the broad face plate are barely evident in the heat removal trace, also plotted in Fig. 4. This suggests that the thermal disturbance is localized to the funnel area and is not large enough to be detected in the overall broad face heat removal measurement. Outside of the funnel area (Fig. 4b), the mold temperatures do not exhibit the large sawtooth-like fluctuations.

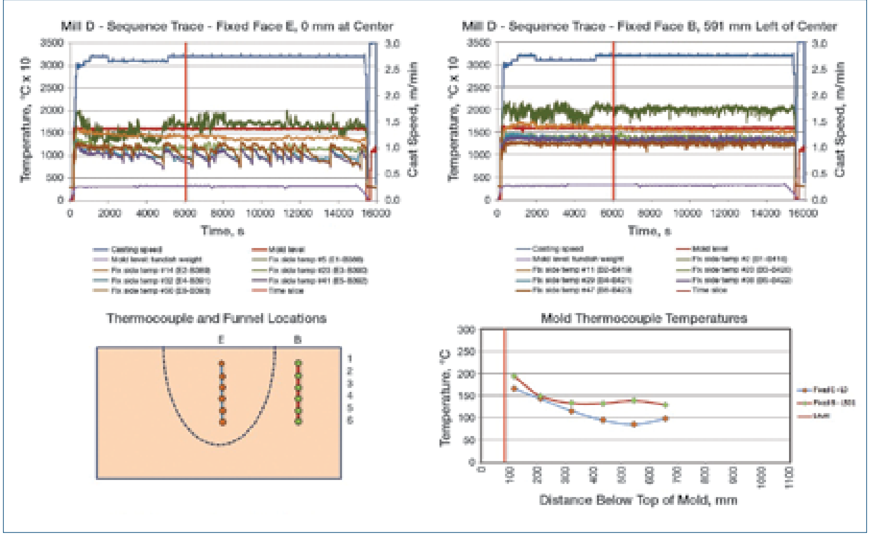
A snapshot of the corresponding temperature profiles is shown on the right side of Fig. 4 at 24,000 seconds (6.7 hours) into the cast sequence. Outside of the funnel area (Fig. 4b right), the mold temperature decreases uniformly down the length of the mold. However, within the funnel area (Fig. 4a right), the temperature decreases down the length of the funnel area but then increases at the base of the funnel and decreases again toward the bottom of the mold. Similar mold thermal behavior was observed in temperature measurements at Company D. Fig. 5 shows the mold temperature trends from thermocouple arrays within (a) and outside (b) of the funnel area during the casting of a 0.25% carbon steel. As observed previously, sawtooth-like fluctuations are evident in the root area of the funnel and the region outside of the funnel the periodic fluctuations are absent.

The sawtooth thermal behavior is remarkably similar at both mills, despite significant differences in the two thin-slab caster designs and the differences in the mold powders employed to produce similar grades of steel. A comparison of the two mold fluxes used in these studies is shown in Table 1. Note that the sawtooth-like thermal behavior is observed despite the fluxes having very different chemistries and basicity.

An estimate of the rate of propagation of the thermal disturbance was made at Company D by timing a single temperature-rise event as it passed successive thermocouples in the funnel area. Data from Caster D was used because it had a lower casting speed (2.7 m/minute) and a faster (0.5 second) data logging rate. The results, shown in Fig. 6, suggest that the thermal disturbance travels down the mold at about 70% of the casting speed. A similar analysis performed at Company G showed a thermal disturbance propagation rate of about 88% of the cast speed at 5 m/minute.

The sawtooth-like temperature fluctuations do appear to be associated with conditions that exist exclusively within the lower funnel area. Fig. 7a shows that the timing of the fluctuations is highly correlated within the funnel on the north mold plate at +100 mm and –100 mm from the center of the mold. This suggests that the disturbances within the funnel on an individual mold plate have a common cause. On the other hand, Fig. 7b shows that the disturbances within the funnel areas on the north and south face mold plates are out of sync.

Figure 5



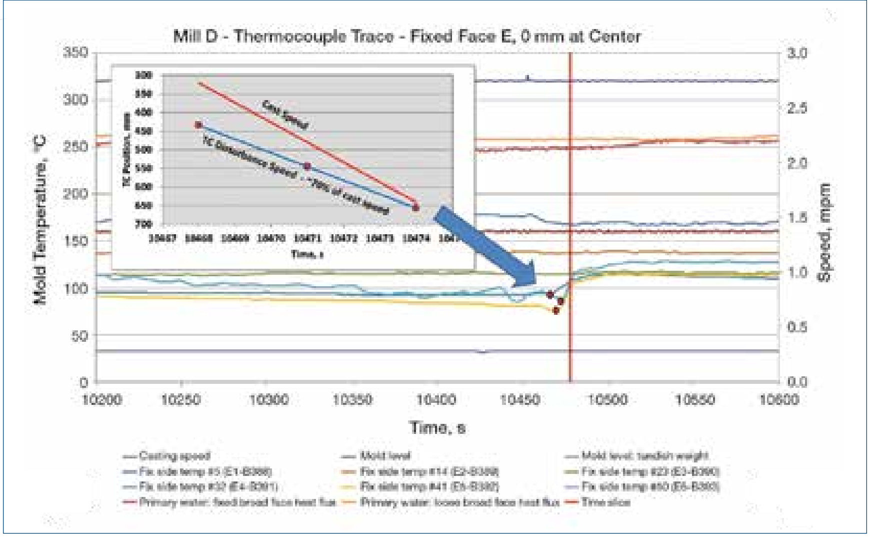
Temperature trends inside and outside of the mold funnel area over 4.5 hours of operation with flux D2 at Company D casting a 0.25 carbon steel.

Table 1

Composition of Mold Fluxes Used – wt.% (R = Na, K, Li)

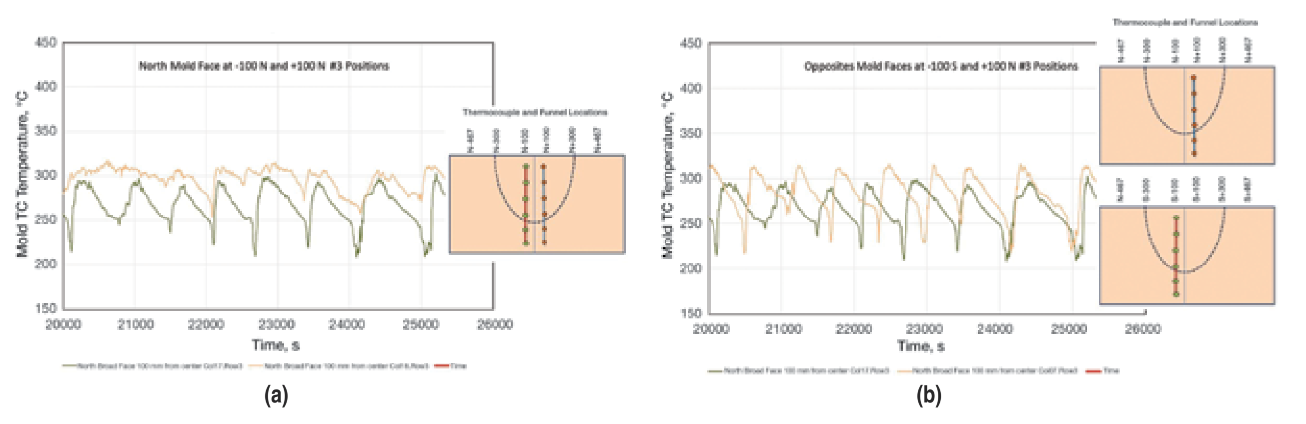
Flux	Basicity	MgO	Al_2O_3	R_2O	F
G2	0.80	2.6	5.9	16.5	8.6
D2	1.18	1.2	3.5	10.9	8.7

Figure 6



Rate of propagation of thermal disturbance past successive thermocouples in funnel area at Company D compared to casting speed.

Figure 7



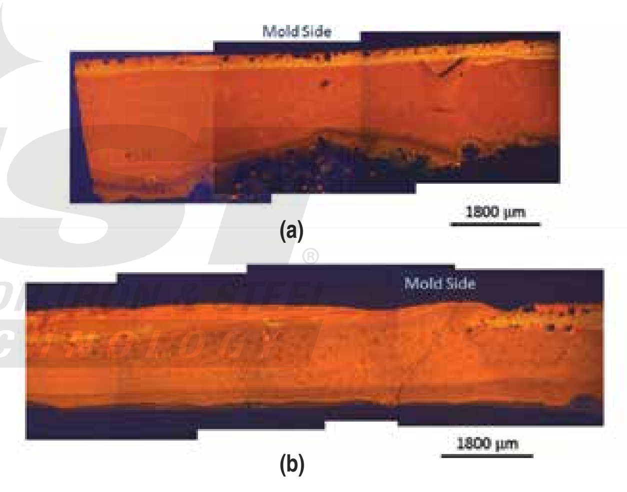
Sawtooth temperature fluctuations: (a) on north broad face plate at opposite sides of the mold center within the funnel, and (b) on north and south broad face plates within the funnel.

The thermal disturbances on opposing mold plates were not correlated, despite having very similar average cycle times. This suggests that the disturbances on the loose and fixed-side mold plates are not initiated simultaneously by a single event, but instead are initiated within each funnel area separately, likely due to the local friction conditions on each mold plate. It should also be noted that no catastrophic shell sticking events, severely degraded oscillation marks or other degraded surface conditions on the slab were observed during these sequences at either facility during these tests. This suggests that the disturbance is occurring within the mold gap and not on or in the solidifying shell.

A G2 mold flux film sample was collected at the end of the cast sequence to investigate the possible cause of these thermal fluctuations in the funnel area. The flux film was sampled at the end of the cast sequence during cap-off and handled carefully to preserve the approximate position of the flux film within the funnel area. An evaluation of this flux film has been reported on in a previous publication.[11] This work showed that the flux film sample from the upper position in the funnel where the temperature trace was stable shows a continuous, well-formed, crystalline layer (Fig. 8a). However, the investigation also showed that the flux film sample taken from lower in the funnel area showed evidence of crystalline film fracture and flow lines in the glass that suggest that the observed free-floating crystallites originated by fracture and removal of the crystallites from the mold wall (Fig. 8b).

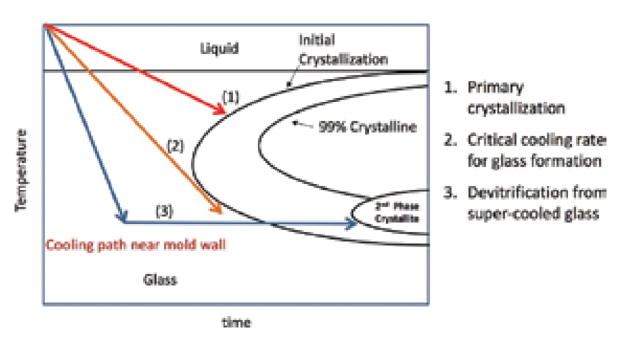
The flux film sample, shown in Fig. 8b, suggests that fracture and withdrawal of the crystalline film on the mold wall is the primary cause of the observed thermal fluctuations in the root area of the funnel. The timing of the observed thermal fluctuations in the funnel area is of considerable interest. Even

Figure 8



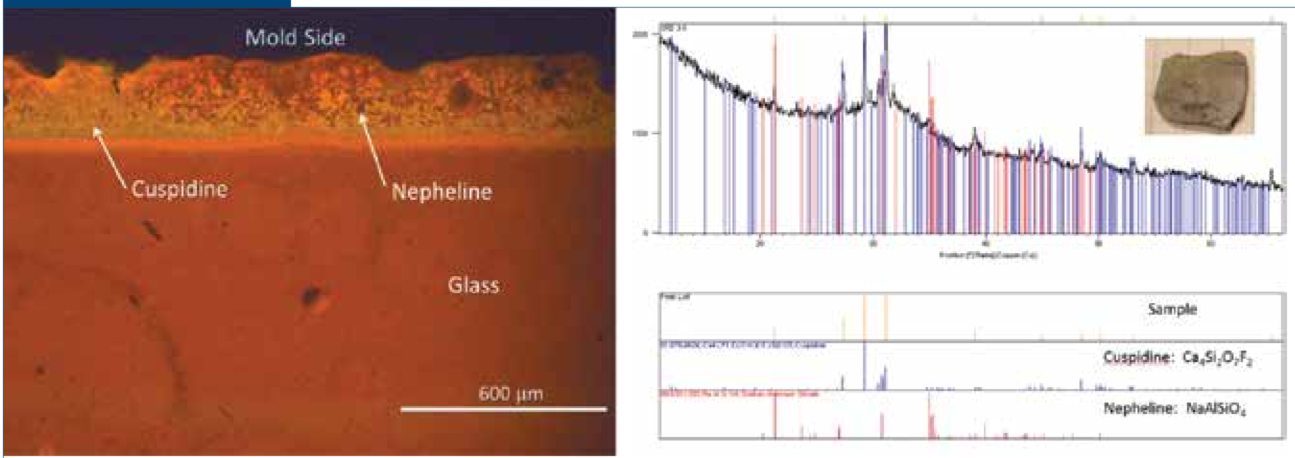
Cathodoluminescence (CL) images of flux film sample G2 taken at cap-off from: stable temperature region (a) and region with sawtooth temperature fluctuations in lower funnel area (b).[11]

Figure 9



Typical continuous cooling transformation diagram showing alternate paths for crystallization.

Figure 10



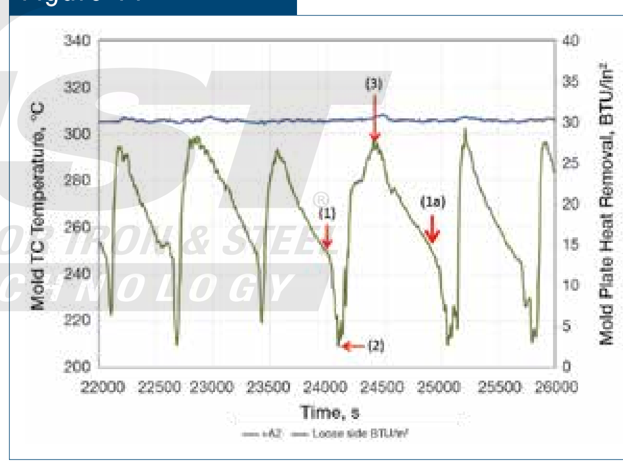
(a) (b)

CL image of crystalline layer in G2 flux film sample showing evidence of Cuspidine and Nepheline phases (a).[11] Phases confirmed by x-ray diffraction analysis (b).

though the solidifying steel shell residence time in the mold is only about 12 seconds on Caster G, it was observed in this investigation that a complete thermal disturbance cycle takes roughly 10–20 minutes to complete, with the temperature rise occurring relatively quickly (1–3 minutes) and the temperature decrease occurring very slowly during the remainder of the cycle (7–19 minutes). This slow decrease in temperature is consistent with the time required to form a crystalline layer on the mold wall from a super-cooled glass. Measurements performed by Cramb and others[14–17] have observed comparable crystallization rates when the glass is super-cooled below the nose of the time temperature transformation curve. The authors' laboratory work on flux G2 that has been melted, quenched to 500–800°C and aged shows a similar incubation time for crystal nucleation and growth.[18] In addition, it was also observed that flux G2 only forms Nepheline crystals when the glass is super-cooled below the nose of the primary Cuspidine crystallization curve and aged, as shown in Fig. 9, path 3. The presence of Nepheline in the G2 flux films extracted from the mold at cap-off (Fig. 10) supports the claim that the crystallites observed in the mold gap form by devitrification of a super-cooled glass.

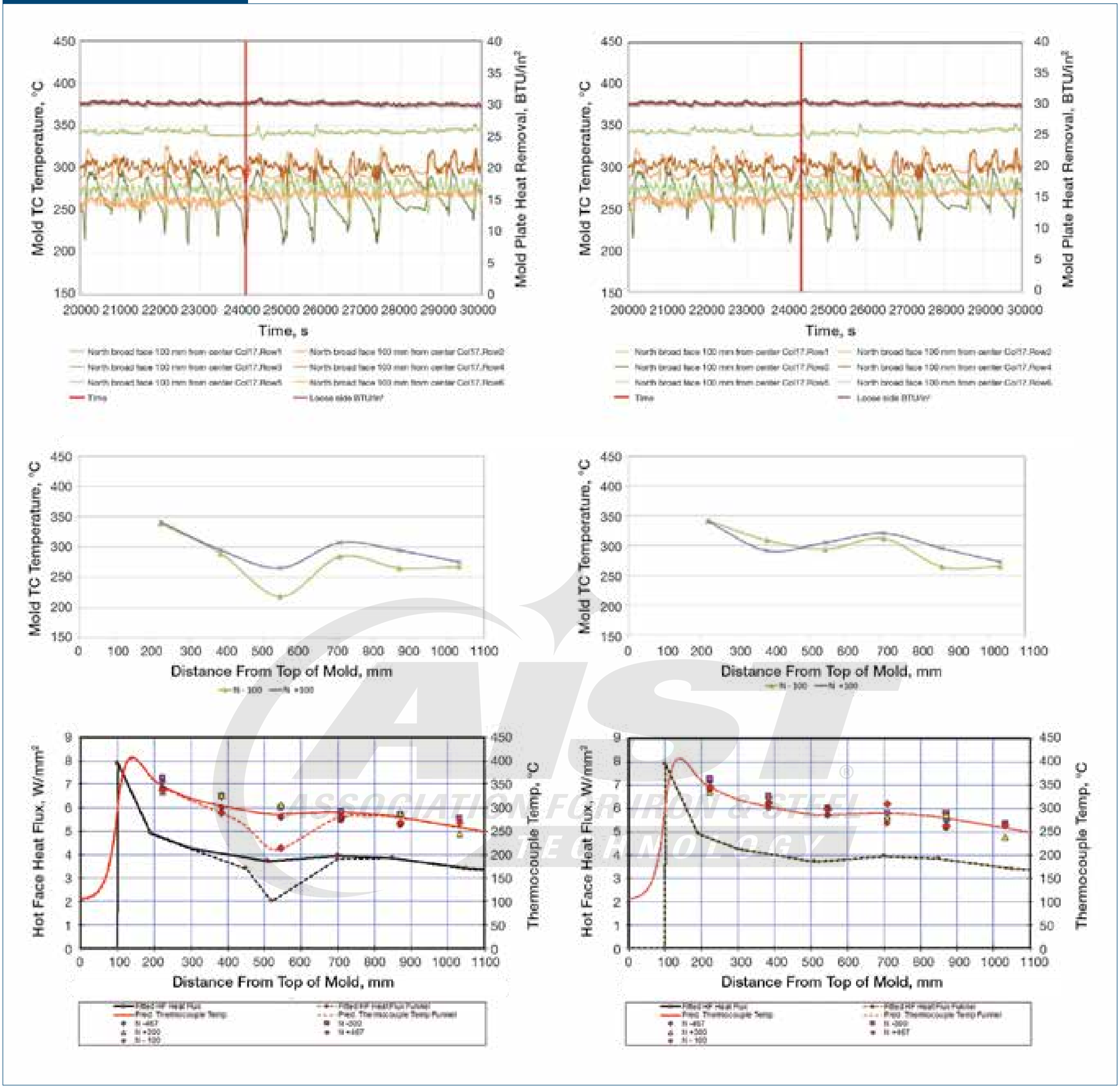
Based on evidence from the flux film petrography and analysis of the mold thermal data from the two casters investigated, the following mechanism for the occurrence of sawtooth-like temperature fluctuations in the lower part of a funnel mold is proposed: A crystalline film forms by infiltration of molten flux and aging of the glass that resides on the mold wall. As this crystalline layer slowly forms, the rate of heat removal slowly decreases. In regions of higher shear stress local stresses acting on the crystalline film cause it to fracture and detach from the mold wall. In some cases, the withdrawal of the crystalline layer creates an air gap that causes a sudden additional drop in heat removal. This air gap is rapidly back-filled with molten glass, causing the heat removal rate to rise sharply. At this point, the glass begins to age to form a new crystalline layer, repeating the cycle. These steps are summarized in Fig. 11. Note that not all thermal fluctuations exhibit air gap formation (steps 1–2, for example).

Figure 11



Proposed origin of sawtooth temperature fluctuations at TC#3 in funnel: (1) fracture of flux crystalline film, (1→2) withdraw of flux crystalline film and air gap formation, (2→3) inflow of glass, (3) complete glass infiltration, (3→1a) aging and crystallization of glass.[11]

Figure 12



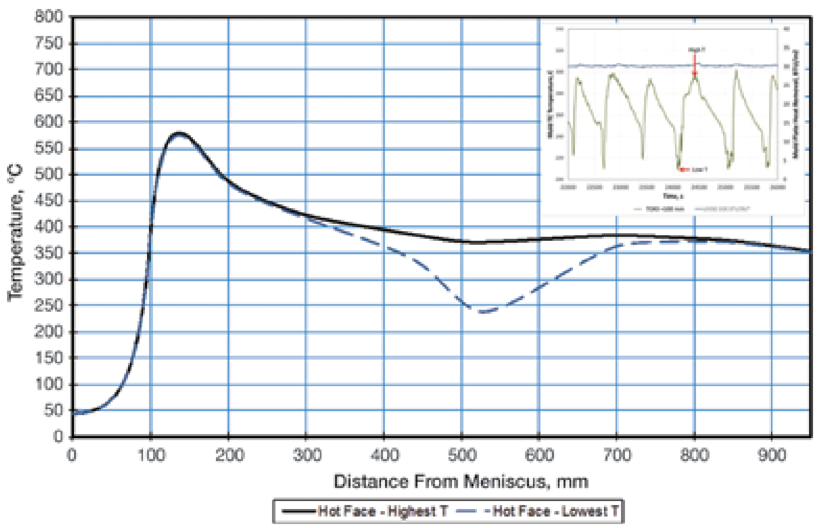
Thermocouple temperature profile snapshot at 24,105 seconds (minimum temperature) and at 24,405 seconds (maximum temperature) and predicted heat flux profiles.

Mold Heat Flux Model

A mold heat flux model was employed to attempt to estimate the magnitude of the local changes in the heat flux profile in the funnel area compared to the body of the mold under the localized crystalline film sheeting conditions. This model was adapted to the operating conditions employed at Company G during the time of the casting trial. The details of the model formulation and data fitting procedures are reported elsewhere.[7,19,20]

The temperatures and predicted heat flux profiles for two of the three steps in the thermal cycle of a single sawtooth-like temperature fluctuation event shown in Fig. 11 are summarized in Fig. 12. The predictions suggest that the local heat flux varied by approximately 47% locally (1.8 MW/m^2) in the funnel root area when fluctuations were present. Furthermore, the predictions suggest that the local heat flux dropped by about 21% (0.8 MW/m^2) as the infiltrated glass crystallized, with the remaining 26% drop (1.0 MW/m^2) resulting from local flux starvation and

Figure 13



Predicted mold plate surface temperature profiles for high- and low temperature conditions shown in Fig. 12.

air gap formation. The mold model predictions for the two extreme heat flux conditions presented in Fig. 12 suggest that the mold hot face temperature can fluctuate by more than 160°C during a flux film shearing event as shown in Fig. 13.

It is interesting to note that an animated view of the temperature profiles shown in Fig. 12 shows evidence that the thermal disturbance induced by the flux film fracture and withdrawal initiates at or before the TC#2 position (384 mm from the top of the mold), propagates through to the exit of the mold on Caster G and exits at about 88% of the shell withdrawal speed. The largest temperature disturbance is observed at TC#3 (546 mm below the top of the mold). The thermocouples below position #3 show smaller temperature disturbances. The temperature decrease from (1) to (2) in Fig. 11 appears to be the result of an air gap that formed by local liquid flux starvation immediately after the withdrawal of the crystalline layer. This sharp drop is not seen at other thermocouple positions, suggesting that the proposed intermittent flux starvation event is localized to the region in the lower funnel area.

Ultimately, the crystal structures and phases that form in the mold gap have a strong influence on the strength of the crystallite film and its ability to resist fracture. The crystallite morphology is a strong function of temperature and the cooling path that the molten flux experiences in the mold gap. Conditions of high localized stresses found within the funnel area of a thin-slab mold can lead to localized flux film fracture where, elsewhere in the mold, the flux film can have sufficient strength to resist fracture. Currently, the authors are able to reproduce the phases and structures observed in extracted flux films using commercial mold fluxes in the laboratory.[18] However, a method for testing their strength in the lab has yet to be developed. More work is still needed to realize the goal of laboratory testing of mold fluxes to confirm how they function in the mold gap of the continuous casting process.

Conclusions

Localized periodic thermal fluctuations observed in the lower funnel region of the mold on two thin-slab casters were investigated using mold thermocouple array data, flux film sampling and laboratory crystallization studies. Analysis of the thermal data and analysis of extracted flux films indicate that the thermal fluctuations are the result of flux film fracture and withdrawal in the funnel area, followed by a brief period of air gap formation at some locations, glass infiltration into the gap and crystallization of the infiltrated glass. The withdrawal rate of the fractured crystalline layer was observed to be between 70% and 88% of the strand withdrawal speed.

The slow drop in heat removal following glass infiltration was found to be consistent with crystallization rates reported in literature and with those measured in the lab for the G2 mold flux. The presence of Nepheline in crystalline phases observed in the extracted flux films was also consistent with a cooling path that produces a super-cooled glass that remains in contact with the mold wall for an extended period of time and slowly ages and devitrifies.

Thermal disturbances appeared to be caused by a single sheeting event within the funnel of an individual broad face plate. The cycles of the thermal disturbances within the funnel on a single mold plate were well correlated. Thermal disturbances in the funnel region on opposing broad face plates were not correlated but did have similar cycle times. Sheeting events appear to be associated with local conditions on each broad face plate. Conditions of high localized stresses found within the funnel area of a thin-slab mold appears to promote localized flux crystalline film fracture, where elsewhere in the mold, the same crystalline film may have sufficient strength to resist the fracture because of lower shear stresses in these areas. However, additional work is still needed to characterize the relationship between flux film structures and their resistance to crystalline film fracture.

This investigation also highlights the importance of mold temperature mapping in the development of fluxes for continuous casting. The temperature disturbances observed at both casting operations would likely never have been identified by conventional mold heat removal and breakout detection thermocouple measurements, but they are sufficiently large in localized regions to increase the probability of casting defects.

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