Thermal mold monitoring using fiber optics: Getting better insights with Data Analytics.

Alma Olivos[1], Stephen Carless[1], Dirk van der Plas[1], Martin Schuster[2], Oliver Lang[2], Sonja Strasser[2]

[1]Tata Steel IJmuiden B.V., Wenckebachstraat 1, 1951 JZ Velsen-Noord, The Netherlands
[2] Primetals Technologies Austria GmbH, Turmstrasse 44, 4031 Linz, Austria

Abstract

Mold thermal monitoring in continuous casting is essential for breakout prevention and process monitoring. Whilst useful, the number of thermocouples and coverage has been limited. Owing to these limitations, a mold containing Fiber Bragg Gratings (FBG) was developed to increase measurement resolution.

This high-resolution grid provides the basis for various data analytics approaches to get a clear heat transfer picture and to characterize casting mold phenomena that until now have remained only accessible through modelling. Firstly, an accurate temperature-based mold level measurement along the entire mold width has allowed to link mold flow with meniscus shape. Describing the meniscus shape has proven central to relate process parameters such as argon, throughput, and electromagnetic flow control to surface quality. Secondly, the information on heat transfer along the slag pool and meniscus area has allowed to observe localized performance of the melting powder behavior. This has served as an accelerator to evaluate mold powder performance. Thirdly, having the full heat transfer picture has enabled the observation in a very early-stage of other features related to mold powder infiltration. Among the advantages of using FBGs as thermal monitoring tool is the ability to collect the process status in real-time. This enables the analysis of the process with statistical and other data analytics methods in a shorter amount of time. For this we have developed an interactive app where the results of the analysis are summarized and visualized. This allows faster and better-informed decision making for process optimization and incident prevention.

Key Words: FBG mold level, slag pool, meniscus shape, mold flow control, (ir)regular solidification shell, data analytics, mold powder performance.

Introduction

To meet quality demands of continuously cast products it is needed to have good operational practices. Specifically for surface quality it is essential to have a very good control in the mold where the steel shell is born. Real time mold monitoring is invaluable to follow, quantify and improve process performance. In Tata Steel IJmuiden, BOS 2, we operate 3 slab casters to produce over 6 million tons of slabs. We have targeted a good control and understanding of real time temperature monitoring via implementation of FBG technology as temperature measurement in the mold.

In the first stage we have used a FBG test installation in CC21 in addition to the existing thermocouples-based system for breakout prevention. In the recently commissioned CC23 the FBG system is equipped as the main mold temperature measurement covering the entire area of the mold plates.

In the test installation in CC21, we focused on continuing the strategy to use temperature measurements to achieve process stability[1]. A series of measurement campaigns opened the door to follow in real time the behavior of key process parameters, for example the meniscus shape[2] under different casting conditions. Through monitoring of the meniscus level across the entire mold width, it was possible to define a relationship between meniscus shape and meniscus velocity. At first, we looked into meniscus wave height[3]. We established a clear correlation between meniscus height and the meniscus speed measured from nail board experiments. Ultimately, the ability to estimate meniscus speed gave us a very good tool to link our process practices to our product quality.

Exploring meniscus shape relationship to mold flow

Mold flow in continuous casting has been typically optimized targeting a “double roll”. The ultimate goal is to achieve stable heat transfer, a good lubrication and an adequate temperature at the meniscus whilst avoiding high mold level disturbances to lower the probability of mold slag entrapment. Typical process variables that have an effect on mold flow are mold geometry (mold width), steel throughput (including casting speed) and SEN submergence depth. In IJmuiden, all our casters are equipped with electromagnetic flow control to achieve better control over meniscus stability.

To continue exploring the capabilities of the FBG system, we performed a series of trials to screen these process variables. The aim was to picture the meniscus shape while varying process setting in ranges within and beyond the boundaries of our operational window. To facilitate the trials, we integrated the recording of the measured FBG temperatures in the Mold Expert system and computed in real time the calculation for, among others, meniscus level from the FBG system.

In figure 1A, we can observe the various meniscus shapes for three different applied magnetic fields for two different throughputs. In all 6 cases shown in figure 1 other variables such as argon and nozzle submergence depth were kept constant. One can observe that meniscus waviness can be modified when varying the strength of the applied magnetic field. The effect of increasing the magnetic field is clearly visible in the shape of the meniscus, having a flatter shape with the high setting. This effect is fully reproducible and reversible. The three top cases in contrast with those at the bottom of figure 1A show the difference in meniscus waviness when varying the steel throughput. This is expected since the velocity of the steel jet coming out from the SEN port will be higher to achieve the higher throughput. A consequence of this velocity difference is that the total force from the applied magnetic field will be different and thus will have a different braking effect. This in turn has an impact on the resulting meniscus waviness. Moreover, we can also observe that those different settings create different patterns in heat distribution just below the meniscus.

In figure 1B six cases are shown where the total argon flow rate in the mold was screened. From left to right one can see the effect while increasing total argon. In the top three cases the magnetic field applied at the meniscus region was kept in the low setting. In these 3 cases one can see that upon an increase of argon, the meniscus waviness can be modified, having the flattest profile for an intermediate setting. In the three bottom cases, the applied magnetic field was kept at medium setting since the throughput was also increased. In contrast to the low throughput examples, the effect of argon on the meniscus waviness for the high throughput examples was negligible. Presumably, the effect that argon has on meniscus waviness is somewhat less strong than that of the magnetic field applied.

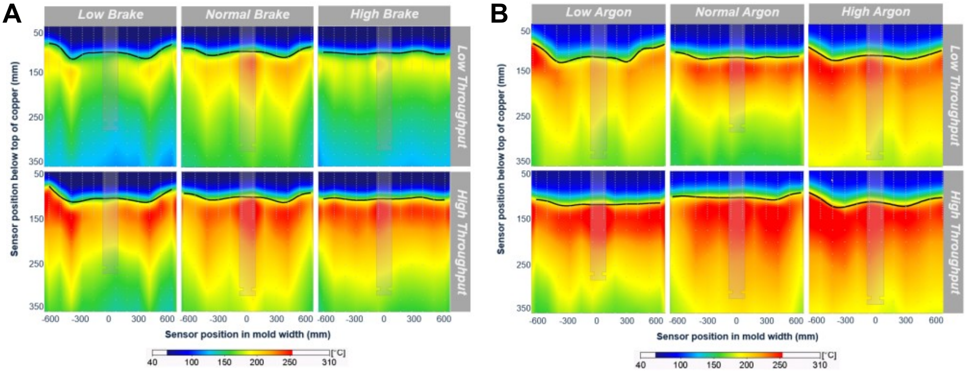

Figure 1. Measured meniscus profiles for different magnetic fields (A) and argon injection flows (B).

Having these screening trials, we could observe that to fully link the meniscus shape to the various setting combinations the meniscus wave height was not sufficient to describe all the features observed. One can notice that features such as the meniscus elevation in the center of the mold width, or the various asymmetric wave characteristics are as important as the meniscus wave height. For these reasons, we developed a series of meniscus shape coefficients.

Meniscus shape coefficients

We defined key figures that can describe the temporal development of the meniscus shape. For this purpose, the meniscus line f(x) is first approximated by a fourth order polynomial at each point in time:

$$f(x) = a_4x^4 + a_3x^3 + a_2x^2 + a_1x + a_0$$

Before fitting the polynomial, a range-transformation of the x-values is performed to get a better comparison for different mold widths. The polynomial is then decomposed into orthogonal Chebyshev polynomials and the corresponding coefficients (MSC Meniscus Shape Coefficients) are determined:

$$MSC_1 = a_1 + \frac{3}{4}a_3, MSC_2 = \frac{1}{2}a_2 + \frac{1}{2}a_4, MSC_3 = \frac{1}{4}a_3, MSC_4 = \frac{1}{8}a_4$$

In particular, the coefficients MSC_1 and MSC_3 are relevant for the description of the asymmetry of the meniscus shape and give insights in the magnitude as well as in the direction of the asymmetry (see Figure 2). MSC_2 and MSC_4 describe the proportions of the quadratic and fourth order Chebyshev polynomial and can therefore be used to describe the elevation of the meniscus line at the edges. If all coefficients are close to 0, this is an indicator for a flat meniscus line.

All the coefficients are calculated in real time and thus can be drawn as time series over the complete period of a sequence. Furthermore, to be able not only to follow the meniscus shape in real time but to have it accessible for evaluation of casting performance we implemented a dashboard with interactive visualizations which gives a good overview of the development of the meniscus shape (see Figure 3).
In figure 4 the relationship of the meniscus shape with respect to process conditions is shown. One can observe that the meniscus wave is more prominent for higher speeds, yet the distribution of the MSC_elevationBorder follows an opposite trend with respect to the MSC_elevationCenter when varying SEN immersion depth for each throughput subgroup. These key figures offer a way to further optimize flow with respect to surface quality.

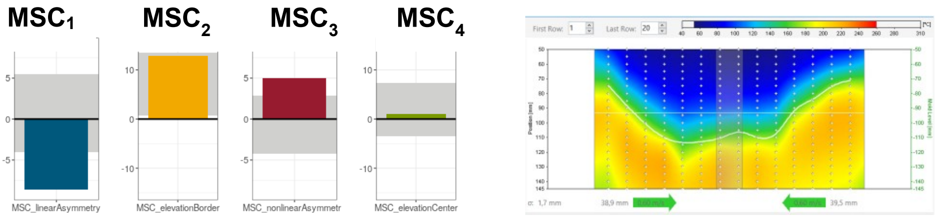

Figure 2: MSC coefficients for an asymmetric meniscus shape.

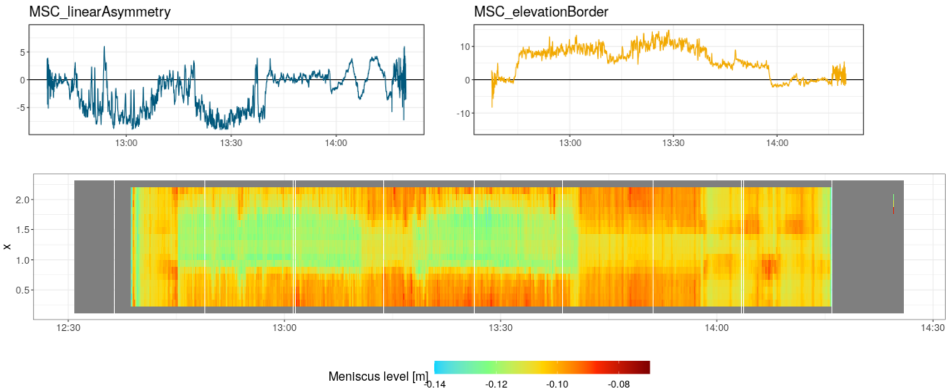

Figure 3: Development of meniscus shape and heatmap of meniscus level.

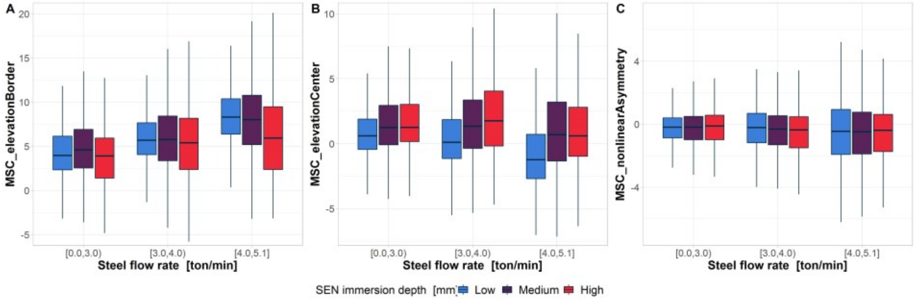

Figure 4. Statistical analysis of production data.

Moreover, the waves observed are not always fully symmetrical with respect to mold width and in many circumstances the evolution of these waves are a consequence of other phenomena that are inherent to the process, such as clogging.
The next example links meniscus shape and mold heat transfer during a case of SEN clogging. In the earlier part of the casting sequence no clogging is observed. The meniscus is rather flat and mold heat transfer is uniform (figure 5A). At some point, clogging is observed from the opening of the actuator. At the same time, the meniscus elevation at the narrow face increases, along with the mold temperatures in the sub-meniscus area. The increase of meniscus elevation can be explained by clogging at the SEN ports. Due to the narrower SEN port, the exit velocities increase, resulting in larger sub-meniscus flow velocities and an increase of the wave height at the narrow faces.

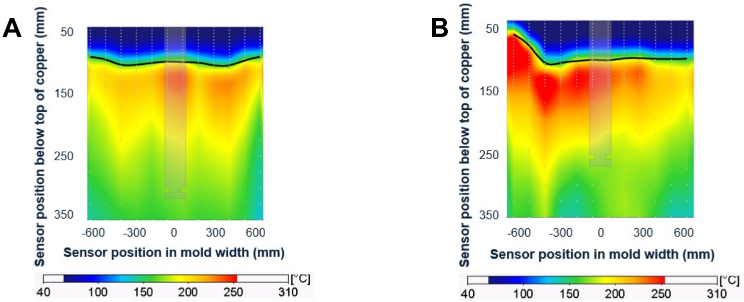

Figure 5. Meniscus shape and sub-meniscus heat transfer during normal operation (left) and clogging (right).

The associated increase of sub meniscus temperatures can be explained in two ways. First, a higher wave will reduce the thickness of the local mold slag layer on top of the meniscus, and this may reduce slag infiltration. Reduced slag infiltration leads to a thinner slag layer between mold and shell, thus to an increase in heat transfer and mold temperatures. A second explanation was suggested by Thomas et al[4],[5]. Increased sub meniscus flow velocities bring more superheat to the meniscus and reduce the formation of sub-surface hooks. As a result, oscillation marks become more shallow and heat transfer is increased. Further down the mold, these effects may be compensated by increased shell thickness and lower strand surface temperatures. This is why detection close to the meniscus is essential. Further work is required to investigate which of the two mechanisms prevail, and if FBG can be used as a means of early clogging detection.

Mold powder evaluation

Next to the efforts to understand and monitor mold flow and the initial shell formation in the meniscus area, we have also explored the behavior at the middle and bottom of the mold. Having the FBG system as permanent production installation in CC23 has enabled to monitor and recognize subtle differences between different mold powders for the same type of steel, as well as the behavior for the same powder over a range of steel chemistries. Although the full capabilities of the FBG system are still to be explored, in the next examples we will share our efforts to parametrize and evaluate the behavior of the mold slag during solidification. It is worth noticing that in the past this information has only been accessible via modelling where validation is not necessarily trivial. In the first place we were interested to look at the stability of the mold temperatures measured across our production package. As it is well known, the thermocouple instability increases with increasing of the carbon equivalent, having a maximum at around 0.13 where the peritectic behavior is observed. After this range and towards the medium carbon grades the temperature instability decreases.

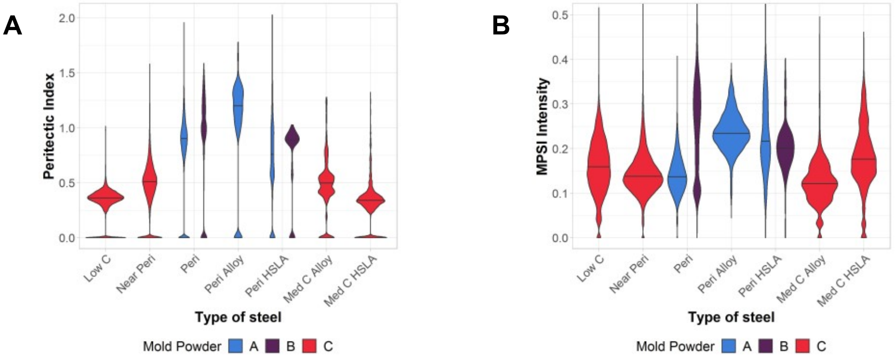

Figure 6. Distribution of (A) Peritectic Index and (B) MPSI Intensity across different steel grades.

To monitor the mold temperature instability in Mold Expert the Peritectic index is computed. This index is calculated based on the standard deviation in a defined time window of temperatures measured at the mold plates. In figure 6A the peritectic index distribution calculated from FBG temperatures at the top part of the mold for a part of our production package is shown. We can see from the density distribution of the subgroups that the peritectic index is not only highest for the alloyed peritectic subgroup, but also that the value ranges of the peritectic index are broader than when comparing to a low carbon subgroup.

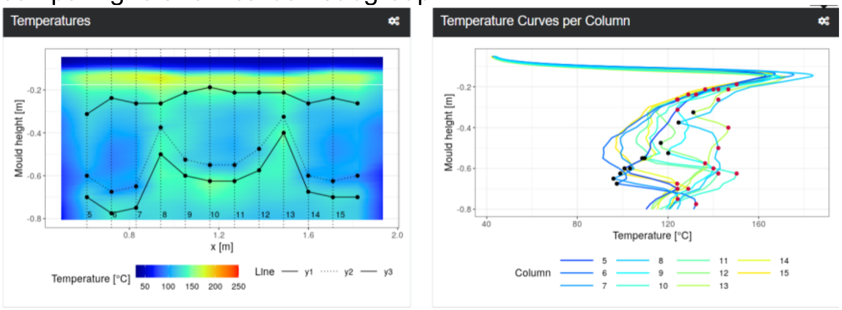

Figure 7: Temperatures in the mold and temperature curves along the columns.

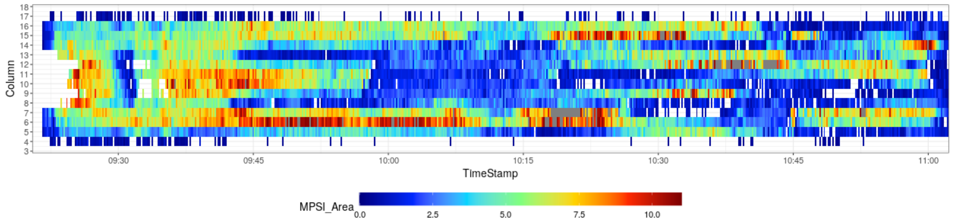

Figure 8: Heatmap of MPSI (Area).

Most knowledge of temperature instability is normally acquired with the mold thermocouples used for sticker detection and these are often located in the upper part of the mold. Having measured temperature points as deep as 800 mm from top of copper in the FBG system in CC23 motivated us to search for a numerical way to characterize the differences observed at the lower part of the mold.

We analyzed the mold temperatures in the vertical direction. At the top part of the mold, the temperature increases quickly and then in the lower part the temperature should decrease continuously. In order to detect abnormal temperature behavior, we calculated characteristic points, like local minimum and maximum values, from the temperature curves along each column (see figure 7). Then we derived various key figures, called Mold Powder Sheeting Indices MPSI, which measure the effect size of the deviations (areas, intensities, and temperature differences). One of them, MPSI (Area) is visualized as a heatmap in figure 8. In figure 6B the relationship between carbon content and MPSI Intensity is shown. In similar manner as for the peritectic index, the MPSI Intensity shows a higher value around the peritectic range, yet the spread for a same steel grade subgroups outside the peritectic range is higher.

Further analysis of MPSI's numerical trends focused on comparing performance of similar grades using the same powder. In figure 9 we can observe two examples of two different low carbon grades where we use same casting practices, including same casting powder. One can notice in the upper example for steel grade I (figure 9A and 9B) that the temperature along the vertical has a deep decrease of temperature, whereas in the bottom example for steel grade II (figure 9C and 9D) these temperature drops along the length of the mold is much more subtle. Whether this information can be used for mold powder choice and further fine tuning in steel chemistry to achieve the best castability of demanding grades requires further investigation.

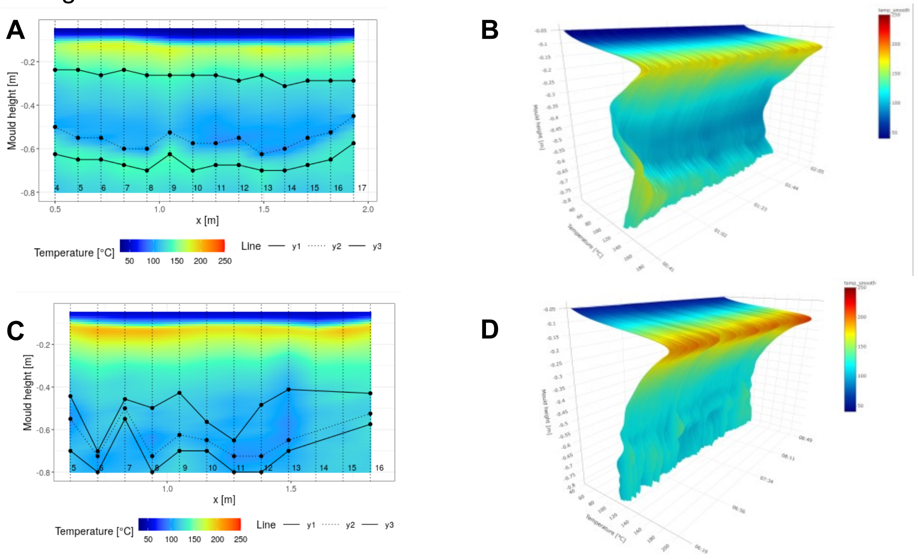

Figure 9. (A) Heatmap and (B) 3D heatmap for measured temperatures in column 10 for steel grade I. (C) Heatmap and (D) 3D heatmap for measured temperatures in column 10 for steel grade II.

A somewhat less explored area is the characterization of mold heat extraction and stability towards bottom of the mold. In this work we have shown the main trends in the form of the Mold Powder Sheeting Index which not only varies from powder to powder but also across grades with the same powder. First indications are that these new parameters can be used to evaluate and fine tune mold powder performance.

Conclusion

Mold monitoring using FBG temperature measurement has given access to essential process information to evaluate the quality of the solidification in the mold. Continuous visualization of the meniscus and the development of the numerical key figures (MSI’s) has sped up considerably the optimization of the electromagnetic flow control as well as the identification and thus improvement of process disturbances to assure surface quality. Furthermore, it has opened up the possibility to develop methods to characterize performance of mold powder via statistical analysis of numerical key figures. In the one hand we have the information of meniscus temperature that in combination with already well accepted knowledge of thermal stability in the region below the meniscus has enhanced process analysis. Our efforts are further focused on the application of the observed link between the peritectic index and the newest numerical key figures (MPSI’s). The focus lays on bringing the MPSI's as an additional tool for statistical evaluation of the process.

References

---

[1] S.P. Carless, A.E. Westendorp, A.A. Kamperman and J.P.T.M Brockhoff, Optimization of surface quality through mold thermal monitoring, Proc. AISTech 2010, Pittsburgh (2010), Volume 2, p.105.

[2] A.L. Spierings, A.A. Kamperman, H. Hengeveld, J.A. Kromhout and E.R. Dekker, Development and application of Fiber Bragg Gratings for slab casting, Proc. AISTech2017, Nashville (2017).

[3] Mul, Mathias; „Real-time Mold Temperature Control for the Purpose of Consistent Slab Quality,“ in 4th ESTAD, Düsseldorf, 2019.

[4] Yan, X., Jonayat, A.S.M. and Thomas, B.G., Thermal-fluid model of meniscus behavior during mold oscillation in steel continuous casting. In Proceedings of the 2016 TMS Annual Meeting & Exhibition, Nashville, TN, USA (pp. 14-18).

[5] Sengupta, J., B. G. Thomas, H. J. Shin, G. G. Lee, and S. H. Kim, “Mechanism of Hook Formation during Continuous Casting of Ultra-low Carbon Steel Slabs,” Metallurgical and Materials Transactions A, 37A:5 (2006), 1597-1611.