EXPLORING OPPORTUNITIES IN MOLD TEMPERATURE MONITORING UTILIZING FIBER BRAGG GRATINGS

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Abstract

Densely spaced temperature measurements using Fiber Bragg Gratings (FBG) has proved to be a viable technology for next generation mold monitoring system. Yield and quality issues are often related to events close to the meniscus, such as mold level fluctuations, stickers and deep oscillation marks. Consequently, high resolution temperature measurements enabled by fiber optical measurements is of outermost interest to understand and control critical processes during continuous casting of steel.

In a collaboration between ABB, Proximion and Tata Steel Europe (IJmuiden), a single broad face copper plate has been equipped with an FBG-based system, having as much as 2 660 temperature measuring points. The system has shown to be reliable and operationally robust. In the first eight months of operation, the system monitored more than 2 000 heats corresponding to more than 320 000 tons of cast steel.

The mold monitoring system uses 38 optical fibers each with 70 sensor points separated with a distance of 5 mm. The fiber optical sensors are connected to three interrogators that analyzes the frequency shift of each sensor and calculates it to a corresponding temperature. Using the fiber optical system presented here, it is possible to measure the temperature of the upper part of the mold over the full width at a rate of 2 Hz. Initial investigations show that the FBG system interfere less with the cooling process of the copper plate than the conventional thermocouple system used in parallel.

The FBG-technology enables a new level of insight in the thermal dynamics involved in steel casting and provides a way to obtain dynamic, high resolution data of the non-disturbed, temperature in the copper plate. For the first time, accurate vertical temperatures are obtained at all horizontal positions of the mold and these detailed measurements can be used as input for further refinement of existing models for continuous steel casting.

The high resolution real-time mold monitoring system allow for improved performance of conventional thermocouple systems and also for a number of new potential functionalities. As an example sticker and break-out protection systems can be improved and study of local thermal conditions can be made in detail. The system can also be used for evaluation of mold powder performance in relation to slab surface quality. Finally, densely spaced temperature measurements enable real-time estimations of the meniscus level. Together with an electromagnetic brake active control of the fluid flow becomes within reach.

Introduction

The conditions in the near-meniscus zone in the mold during continuous casting are critical in determining the yield and steel quality [1]. Quality issues are often related to mold level fluctuations, stickers, deep oscillation marks, and other events at or close to the meniscus [2]. These phenomena may be detected by monitoring temperature in the wall of the mold copper plates. Therefore, the legacy system for temperature measurements using thermocouples is almost always installed in the upper part of the mold. A standard temperature monitoring installation in mold of this size consists of at least two horizontal rows of thermocouples located at two vertical positions, in total 20 thermocouples. So called “Smart Molds” can have one or two rows additional of densely spaced thermocouples, increasing the total number up to 80 thermocouples. Installations with even larger number of sensors are rare as practical issues, such as handling of the electrical leads, become very cumbersome. The spatial resolution and the positions of the thermocouples are also governed by the water channel pattern in the copper plate.

Fiber optic sensors have a very small form-factor and can be installed in a much larger number and at places unavailable for traditional sensors, without interfering with physical properties of the monitoring system. By nature, these sensors are insensitive to both external electromagnetic fields and mechanical vibrations. Their small thermal mass also guarantees fast, sub-second, thermal response. Fiber optic sensors are connected to a read-out system, the so-called interrogator, with a single, non-conducting optical fiber with a diameter of 250 micron or less.

With Fiber Bragg Grating (FBG) technology the number of measurement points are determined by the number of optical fiber sensors inserted in the copper plate and the number of measurement points in each sensor. There are design trade-off between the number of measuring points per sensor and the maximal spatial resolution, typically resulting in fiber array installations which will have about 10-20 measurement points per fiber with a spatial resolution of 20-50 mm [3]-[4].

However, Proximion have with a combination of optimized spectral design and a unique method for FBG manufacturing produced fiber sensors with 70 measurement points with 5 mm spatial resolution using only 5.5 THz of optical bandwidth. Consequently, in the pilot installation presented here, the system has 38 fibers with a total of 2 660 temperature measurement points, which yields a new level of spatial resolution in mold monitoring.

System description

A common type of fiber optic sensor for temperature measurements is FBG, in which a periodic refractive index variation is written in the core of the optical fiber, usually using UV-light interference [5]. Light modes propagating along the fiber with a wavelength matching the period of the index variation, the so-called Bragg wavelength, will couple to a reverse travelling mode and will be reflected back by the FBG, while the remaining, non-matching wavelengths, will pass through the FBG unaffected, see figure 1. FBGs can also easily be connected in series thus enabling several measurement points on a single fiber.

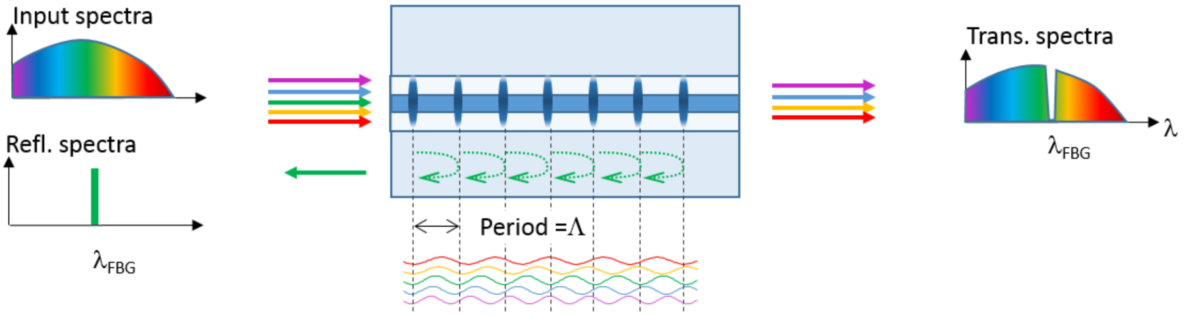

Figure 1: Illustration of FBG principle. Top left: Spectrum of broad-band light source and reflected spectrum. Middle: Illustration of the resonance Bragg condition for one wavelength. Right: Spectrum of the transmitted light.

The Bragg wavelength of a FBG is temperature dependent and this property can be used for temperature sensing. The principle is shown in figure 2 in which a fiber sensor with five separate FBGs is exposed to an external heat source. Each FBG is a separate sensor point distinguished by its position x_i and its Bragg wavelength λ_i. The temperatures are calculated from the measured spectral shift for each FBG. By measuring the wavelength spectrum and comparing it with the spectrum taken at a reference temperature, it is possible to calculate the temperature at each sensor point.

The fiber sensors used in the pilot installation consists of FBG-arrays each with 70 individual sensor points at 5 mm spacing, resulting in a total measurement length of 350 mm (located at 30-380 mm from top of the copper plate). These sensors are spectrally tailored to optimize performance and maximal number of sensor points for this particular copper plate.

A standard copper plate was modified with holes for the fiber sensor, grooves for the fiber routing and threads for connection boxes. A total of 38 fiber sensors are inserted in vertical holes of the copper plate (15 mm from the copper plate hot face) and permanently fixed in position, see figure 3. The fibers from the sensors are lead at the top of the plate to two air-cooled connection boxes where the sensors are connected to four 15 m long multi-strand fiber optical cables, specially adapted for the withstanding the environment around the mold. No

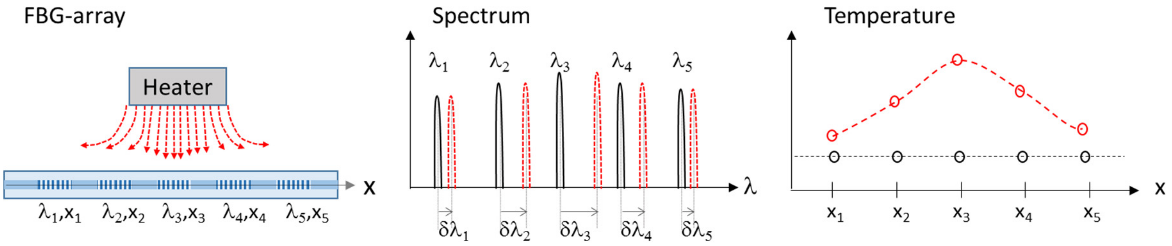

Figure 2: Temperature measurement with FBGs. Left: An FBG array with five FBGs at positions x_1, x_2,…, x_5 and with Bragg wavelengths λ_1, λ_2,…, λ_5. Middle: The spectrum at a reference temperature (black) and after local heating (red) to a temperature increase proportional to the spectral shifts $\delta\lambda_1$, $\delta\lambda_2$,…, $\delta\lambda_5$. Right: Calculated spatial temperature profile from the measured spectral shift of the FBGs.

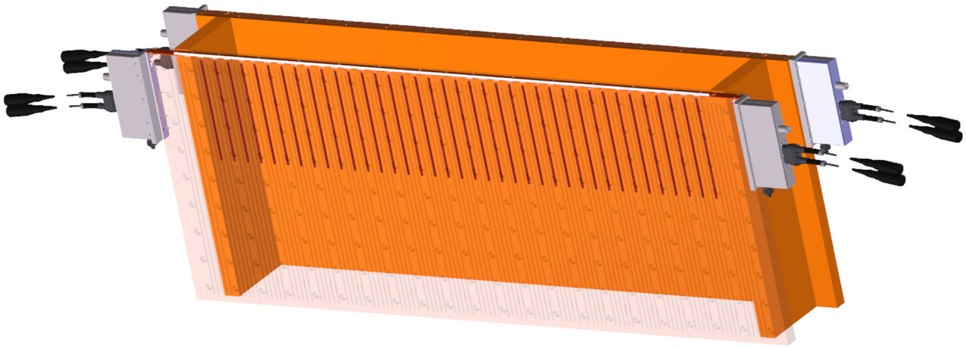

Figure 3: CAD-model of an entire mold with the sensor-equipped copper plates semi-transparent. Each vertical line is an embedded fiber sensor with 70 individual sensor point. The grey boxes are the extra connection boxes where the sensor fibers are connected to harsh-environment cables.

modification of the backing plate was needed for the installation of the system. The result is a total of 2 660 measurement points, monitoring an area of 1 900x350 mm in the upper part of the copper plate, with a spatial resolution, or thermal pixel size of 50x5 mm. A photograph of the copper plate after installations can be seen in figure 4.

The fiber optical cables from the connection boxes are terminated with expanded beam connectors, used extensively in defense industry as well as oil- and gas industry. In these industries, fiber optic sensing has been an enabling technology over the past 20 years by providing measurements where traditional technologies could not [6]. The steel industry share similar harsh environment considerations such as dirt, vibrations and high temperatures and is therefore equally suitable for fiber optical measurements.

Fiber optic sensing systems are not affected by the distance between the sensing element and the read-out unit, allowing for remote installation of the sensitive parts of the system at a controlled environment location. As a consequence, the fibers from the four cables of the mold are connected to a 125 m long transport cable in the intermediate box, which transfers the optical signals from the sensor to the interrogator units, as shown in figure 5.

Figure 4: Photograph of the modified copper plate after installation of the sensors, as used in Tata Steel Europe (IJmuiden).

The read-out unit consists of three WistSense Ultra interrogators, each capable of measuring 13 fiber sensor arrays. The interrogators are self-calibrated and have on-board processing and capable of measuring and calculating the temperature from the sensors at up to 10 Hz update frequency and with 0.1°C accuracy. The fiber sensors are illuminated by three separate broadband light sources. In order to improve the reliability of the system both interrogators and light sources have some build-in redundancy, which allows the system to operate with slightly reduced performance if one unit would fail.

The software assembles data from the 38 fibers covering the whole upper broadside of the mold. Data is presented as raw data heat maps with 38x70 pixels, sufficient to resolve local thermal anomalies at great detail without any dead-spots lacking sensor coverage. Besides heat map information, the process engineer can analyze the vertical and horizontal temperature profiles at several user-selected cursor positions for detailed study of local events. The software also calculates an estimated mold level at each horizontal position, the so-called FBG-meniscus level, using a proprietary fitting algorithm of the vertical temperature profile.

The monitor system including interrogators, light sources, fiber optical cables and sensors was installed at Tata Steel Europe (IJmuiden) in CC-21 at the loose side of the mold. The system has proven to be robust in the steel plant environment. To verify long-time robustness, continued operation is scheduled to May 2017, making it a total test period of 24 months. During the test period the mold has been installed and removed from the caster several times, including one mid-life repair of the copper plate, without any damage to sensors, cables or connectors. Since installation in June 2015 the mold has measured over 2 000 heats corresponding to more than 320 000 tons of cast steel.

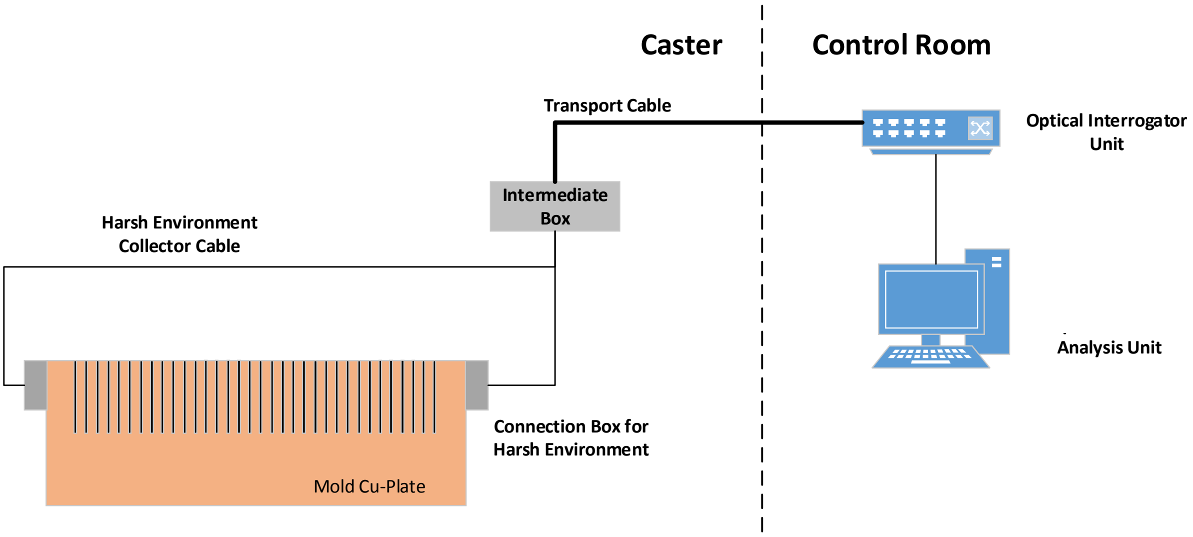

Figure 5: Schematic overview of the installation at Tata Steel Europe (IJmuiden). Main blocks are a) copper plate with sensors and connection boxes, b) collector cables with expanded beam connectors, c) intermediate box, d) transport cable with 48 fibers and e) evaluation unit consisting of interrogators, light sources and computer.

Results

The industry standard for measuring temperature in the mold is to use thermocouples that are fixed directly to the copper plate in holes drilled specially for this purpose. In the mold used for these experiments, thermocouples were also installed at the standard locations in-between the two deeper water channels of the copper plate. The FBG temperature sensors were mounted in vertical holes symmetrically spaced with respect to the shallower cooling channels in the copper plate. In figure 6 illustrates the distributions of sensors in the copper plate for the measurement system. From the figure it is clear that using fiber sensors one can extract much more temperature information of the interesting near-meniscus zone, where most of the surface quality of the steel is determined, compared to conventional techniques. Further on, it is obvious that vertical temperature profile extractions from sparsely spaced thermocouples will always need underlying assumption of the temperature profile.

Initial results showed a large discrepancy of as much as 25°C between the temperatures measured by the thermocouples and the FBGs located at the same vertical positions. A full 3-D thermal simulation of the copper plate, figure 7, revealed that the discrepancy could be explained by: a) actual horizontal temperature variations along the copper due to different cooling efficiency due to the varying spacing and depth of the water channels and b) reduced cooling at the location of the thermocouples caused by the introduction of the hole for the thermocouple. From simulations and experiments it is concluded that measuring temperature using FBG in contrast to thermocouples, do not interfere with the cooling process of the copper plate and therefore measures the real, non-perturbed temperature distribution of the copper plate.

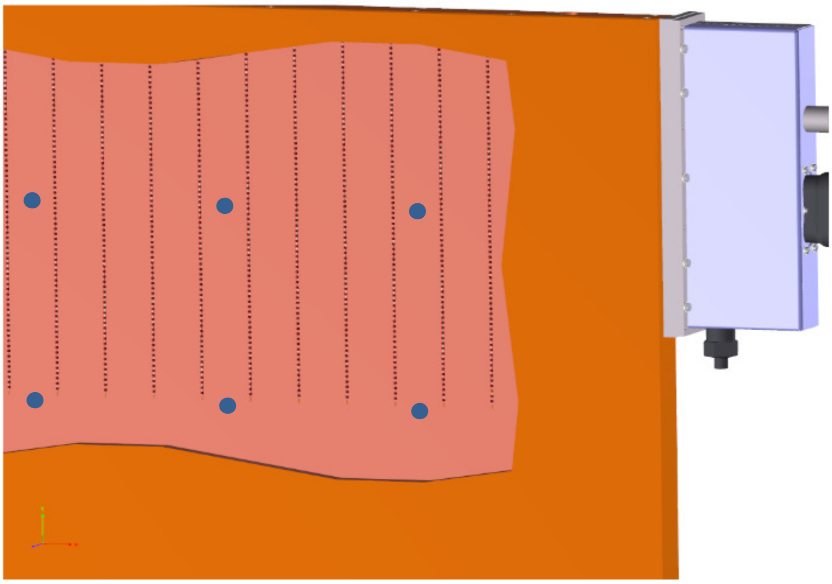

Figure 6: Close-up of the copper plate with the FBG-sensor point marked as black dots and the thermocouples as blue circles.

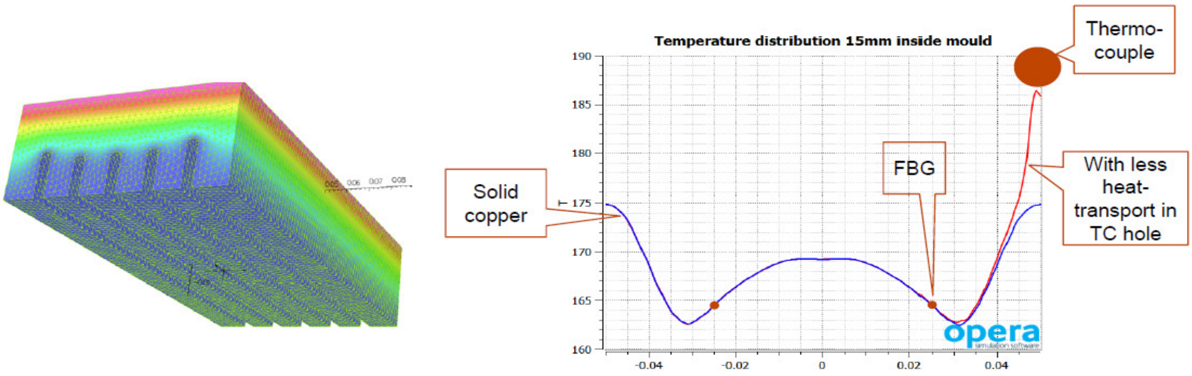

Figure 7: Left: 3D-simulation of the temperature distribution in the copper plate. Right: Temperature profile at the vertical position of one FBG and one thermocouple sensor, without TC-hole (blue line) and with TC-hole (red line). The measured temperature from the sensor elements are shown as small circles (FBG) and large circle (TC).

Heat transfer in continuous slab-casting is governed by many complex phenomena that can be modeled using numerical methods. One of the most commonly used models is the CON1D model developed at the University of Illinois at Urbana-Champaign (UIUC) [7]. Utilizing a system with high spatial resolution the heat transfer can easily be derived without any model parameters or other assumptions. With 70 measurement points (FBGs) over the upper 350 mm of the copper plate the vertical temperature profile is depicted for the first time with high accuracy and without the need for any profile shape assumptions. figure 8, shows a typical vertical and horizontal temperature profile during normal casting operations. With the systems 38 vertical optical fibers the temperature profile and resulting heat flux is available over the full width.

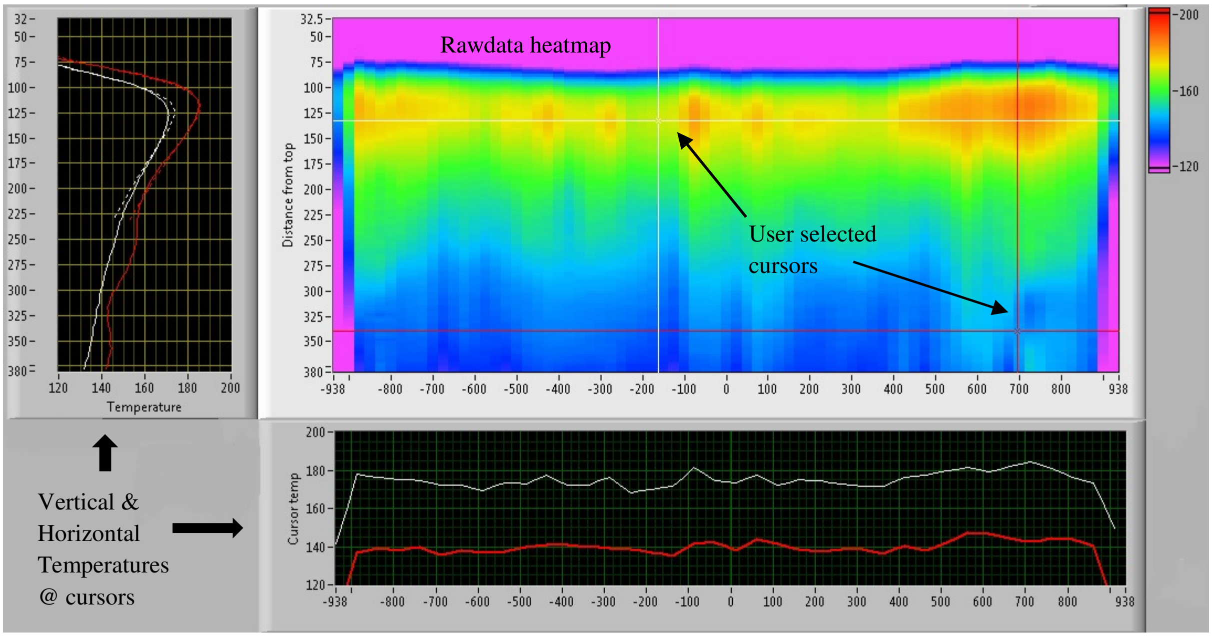

Figure 8: Temperature measurement at typical casting conditions. Middle: Raw data heat map from the 38 horizontal and 70 vertical temperature points with temperature legend to the right. User selected cursors can be moved to mark points for further investigation. Bottom: Horizontal temperature profile at the cursor positions. Left: Vertical temperature profiles at the cursors, with fitted profiles (dashed) for FBG-meniscus level estimations.

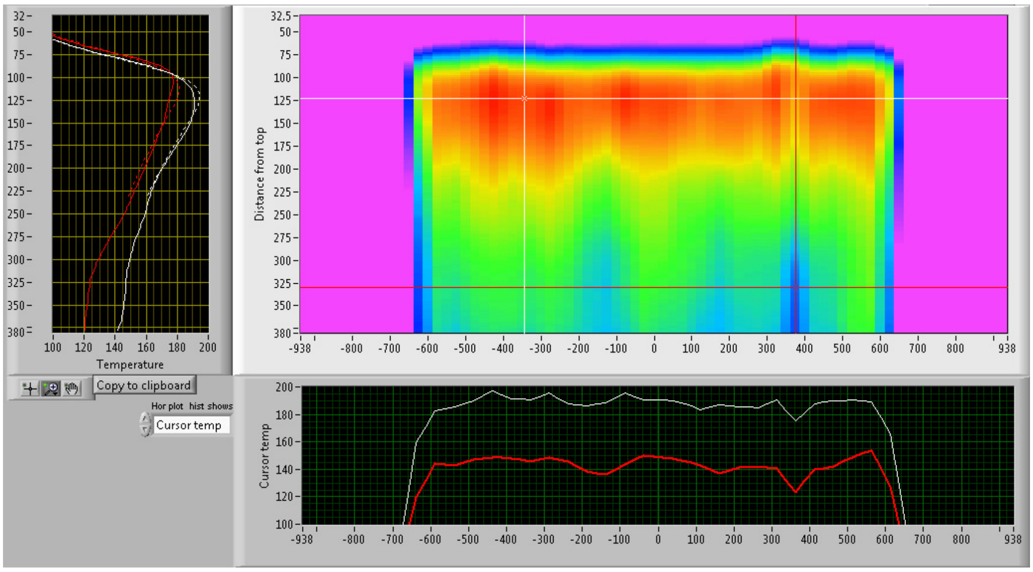

Figure 9: Finger print of a LFC indication at position x= 380mm. Middle: The LFC indication is visible as a yellow-blue vertical streak in the heat map. Left: Vertical temperature profiles at +/-380 mm indicate that the LFC indication is associated with a 10-15 ^{0}C temperature drop along the whole vertical profile. Bottom. Horizontal temperature profiles at 125 and 325mm below top-of-copper show the very narrow extent (<50 mm) of the heat distortion.

An advantage of the high horizontal resolution is the potential to directly detect longitudinal facial cracks (LFC) during the casting process. These are identifiable as local vertical, or V-shaped temperature dips at a specific horizontal position. For an example see x-position equal to 380 mm in figure 9. The temperature has dropped all along a vertical line of the mold. The heat distortion associated with the LFC is only observed at a single sensor position, implying that the thermal foot-print of these type of defects has a very narrow, less than 50 mm horizontal extent. As a consequence, it is essential with high spatial resolution for any system aiming at detection and/or reduction of cracks during casting.

The temperature measurements can also be used to estimate the horizontal shape of the steel meniscus and use this information to control the flow from the Submerged Entry Nozzle (SEN) with an electromagnetic flow brake system, see SCANMET V-conference paper by Martin Sedén [8].

High spatial resolution, in combination with fast response time, allows for study of rapid dynamic events that affect the heat distribution in the mold, which could not be detected using conventional thermocouple system located deeper in the mold. In figure 10, we show an example of such a local dynamic event that lasts for less than a minute. Here a cool spot appears at the meniscus region and it is clearly visible how the cool spot transports outwards and downwards in the mold. These type of dense and fast temperature measurements could also be essential for understanding and optimization of casting parameters and for understanding the behavior of mold powders during continuous casting as well as comparison of Low Carbon (LC), Ultra Low Carbon (ULC) or Peritectic mold powders.

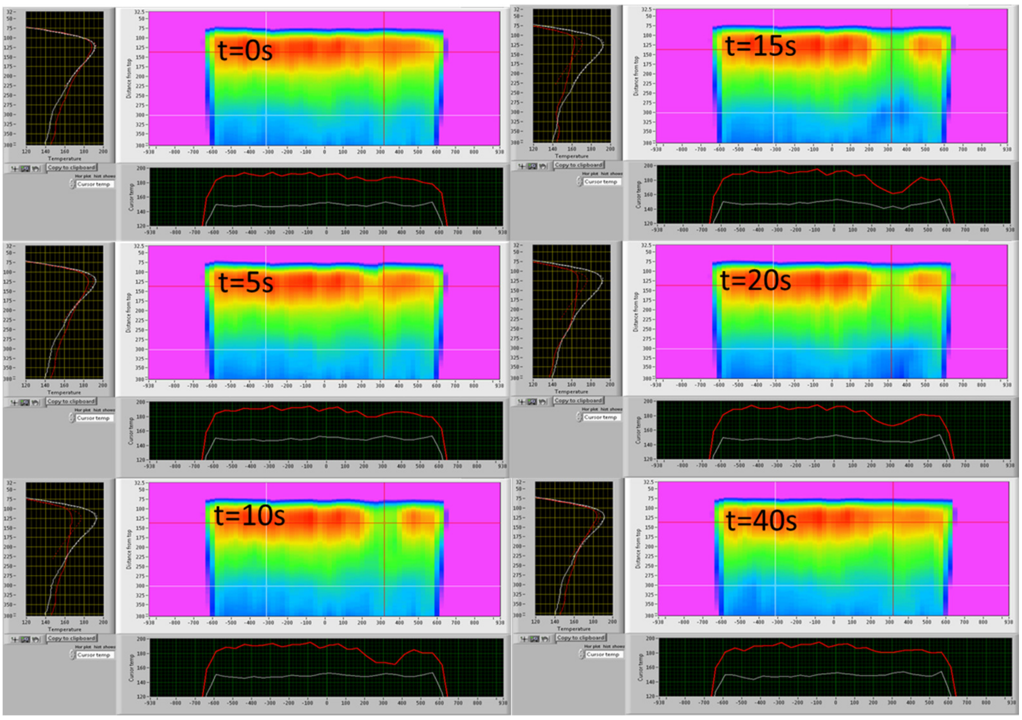

Figure 10: Dynamic event captured during casting. In this particular case, something in the casting process cause a local cool spot to appear in the surface region at horizontal position x=250mm (t=0s). The following images (t=5-20s) show how this cool area grows and moves down and out in the mold, until the process recovers and returns to normal conditions (t=40s).

With Proximion´s technology, it is also possible to extend the length of the sensor to cover the full vertical length of the mold with a single fiber. With custom-designed sensors, the position and the spacing of the sensor points can be varied along the fiber to ensure high spatial resolution and dense spacing in critical regions and coarser spacing in less critical ones.

Finally, by using the high resolution temperature it is possible to implement an advanced system for detection of stickers and subsequent prevention of a breakout in continuous casting. Stickers are as inverted vertical temperature profiles and detected by the thermocouples located at two vertical positions. If no countermeasures are initiated at an early stage of detection, these issues often result in severe consequences such as rejection of slabs or even breakouts. The detection probability of these stickers also increases with a high spatial resolution, minimizing the risk that these events result in a breakout. With today's FBG system, it is possible to detect and observe the growth and development of these stickers in an early stage and initiate countermeasures before a full sticker alarm is triggered when using a conventional thermocouple system.

Conclusions

The high resolution temperature fiber optic system developed by Proximion and ABB has been successfully operated and perceived as a robust temperature monitoring system for the first eight months of the two-year trial period at Tata Steel Europe (IJmuiden). More than 320 000 tons of steel have been casted with the new monitoring system.

The FBG-technology enables a new level of insight in the thermal dynamics of the steel casting process and provides a way to obtain dynamic, high resolution data of the non-disturbed, temperature distribution in the copper plate. For the first time, to our knowledge, accurate vertical temperatures are obtained at all horizontal positions of the mold and these detailed measurements can be used as input for further refinement of existing models for continuous steel casting. The functionalities of the high resolution real-time mold monitoring system also allow for continuous real-time monitoring of the dynamic processes during steel manufacturing such as active feed-back of the meniscus shape and fluid flow control using external electromagnetic systems

Initial investigations show that the system is sensitive enough to detect small-scale heat distortions not seen be the conventional thermocouple system. In addition, the system can detect stickers and potentially LFC earlier than a conventional thermocouple system, thus allowing for shorter reaction times for preventive actions to avoid quality degradation or even breakout. Finally, the system can also act as an enabler to evaluate difference in mold powder performance.

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