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The mold temperature mapping with Ultrasonic Contactless Technology is the key for the real-time initial solidification process control tools

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The Ultrasonic Thermal MAPping (UT-MAP) technology is the new Ergolines's approach for real-time temperature detection of the copper mold, enabling to obtain key information on the first solidification based on the heat flux extracted in the meniscus area. The intrinsic features of the system enable the implementation of several process control tools, such as mold powder thickness control, liquid steel level control or thermal mapping of the copper mold. Potential developments include breakout prevention and quality tracking.
The ultrasonic technology is different with respect to thermocouples or optical fibres because it is contactless, requiring no machining of the copper tube at all: In fact, since the ultrasonic sensor is installed on the water jacket, the copper tube remains unaltered and can be replaced easily.
Ergolines' ultrasonic sensor measures the copper temperature at several locations along the copper mold. Each temperature is averaged over a "copper volume" of about 2 cm^3. The number of measuring points depends on sensor model and number of sensors installed. Each sensor can measure up to sixteen temperature points. The sensor provides two different datasets: the copper temperature trends over time and the meniscus thermal profile, namely the vertical temperature distribution in copper in the meniscus region.
One interesting application of Ergolines ultrasonic sensor is the mold level control in open stream casting (ULD - Ultrasonic Level Detector). A single array of detection points (typically four to sixteen) can precisely estimate the liquid steel level, as shown by comparing the ultrasonic steel level measurement with the radiometric signal.
When steel level is controlled by a pre-installed radiometric sensor, the ultrasonic sensor can be used to keep the powder thickness constant by associating it with a powder feeding machine operating in closed-loop mode with the feedback from the ultrasonic sensor.
Mold thermal mapping provides powerful information also for breakout prevention. By analysing the thermal map, an algorithm calculates any deviation from standard conditions generating warning and alarms based on custom thresholds which can be set by the steel plant metallurgists. Historic data form the ultrasonic sensor can be collected in the steel plant database, correlated with quality control reports on tracked billets/blooms and used to improve the casting parameters and operative practice. Ergolines' ultrasonic sensor therefore represents a key tool for Metallurgists, Quality Control experts and Productivity managers.

KEYWORDSS: ULTRASONIC SENSOR, CONTACTLESS, MOLD THERMAL MAPPING, MOLD LEVEL CONTROL, MOLD POWDER FEEDING CONTROL, STEEL LEVEL CONTROL, BREAKOUT DETECTION;

INTRODUCTION: INITIAL SOLIDIFICATION AND COPPER MOLD TEMPERATURE PROFILE

The initial solidification which takes place within the copper mold tube has always been a main focus for steelmakers, engineers and academics, because the performance of the Continuous Casting Machine and the quality of the cast products are highly influenced by this crucial part of the solidification process[1-4].

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During the last decades, technical efforts have been made in order to develop solidification models, validated with dedicated instrumented molds. Industrial solutions based on thermocouples (TC) or optical fibers cables (OFC)[5] were developed to detect the copper mold temperature, providing mold thermal monitoring mainly addressing breakout detection or qualitative control of mold lubrication. However, both TC and OFC require invasive machining of the copper mold, while the ultrasonic sensor developed by Ergolines provides a fully contactless measurement of the copper temperature (UT-MAP – Ultrasonic Thermal MAPping).

The detection of the copper mold temperature provides real-time information on the effectiveness of heat transfer in the mold: The measured temperature profile is in fact related with the heat flux flowing from the liquid steel through the mold walls. Beside many other parameters, the heat flux is directly linked to the thickness of the solidified steel skin and the lubrication effectiveness.

The heat flux in the mold is characterized by a peak in the meniscus area, which progressively decreases with a hyperbolic law if the solidification conditions are in a steady state situation. The heat flux peak located in the meniscus area is typically of the order of 4-6 MW/m^2, and it progressively decreases to less than 1 MW/m^2 at the mold exit. The steel meniscus is located slightly above the peak of the copper temperature. As a consequence, the position of the liquid steel level can be determined from the copper thermal profile by applying dedicated algorithms based on heat flux modeling.

Due to the high thermal conductivity of copper, the heat flows from the hotter to the colder face of the mold with a fast step response: If a step temperature of 1000°C is imposed at the inner wall of the mold in order to simulate an increase of the steel level (or a bleeding), it takes approx. 0.6 s for the temperature to cross a 10-mm-thick copper wall reaching the 67% of the steady state temperature (Fig. 1).

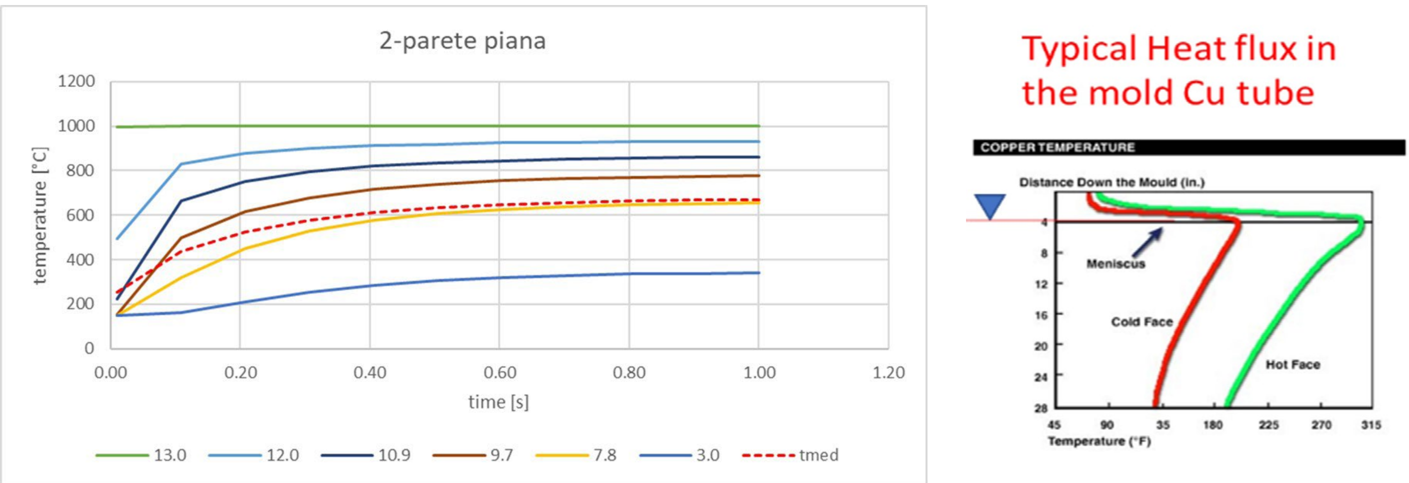

Fig.1 - Simulation of heat flux in the mold and temperature step response inside a copper tube.

Both TC and OFC probes are installed into channels machined within the copper, requiring expensive and invasive machining. The probes are cemented into the channels by means of thermo-conductive resins (and/or springs). However, these resins are much less conductive than the copper, thus creating a small thermal resistance which slows down the step response of the TC/OFC probes. For this reason, the thermal answer of these probes is not suitable for a fast-reacting control since the heat flow needs too much time to cross the copper and the resin layers (even considering no air in between).

Furthermore, the drawbacks of this kind of installation affect the cost of spare parts since every single mold must be machined. In addition, the installation is complex due to the presence of multiple cable outlets, because each TC/OFC probe comes with its own cable cemented into the copper, which must be disconnected at each mold change.

This technology is generally not used for mold level control but mainly to prevent the breakouts, and today it is limited to the CCM for slabs. This is the case not only because of the importance of slab CCMs, but also because the slab mold is made of flat plates, which are much easier to machine with respect to copper tubes. For billet CCMs, which employ curved copper tubes, any CNC machining of the copper becomes complex and much more expensive.

CONTACTLESS ULTRASONIC SENSOR

Ergolines solved these problems by using a completely different approach: Ergolines developed a non-intrusive, real-time and fully contactless ultrasonic system for mold thermal mapping, requiring no machining of the copper tube at all, providing a cost-effective system, with a long life and virtually no maintenance [6-11].

Ergolines' UT-MAP (Ultrasonic Temperature MAPping system) has very compact dimensions. As a main key-point, the installation of the UT-MAP ultrasonic sensor is inside the water jacket (Fig. 2). This is a considerable advantage because it requires minimal machining of the water jacket only (long life component) while the copper tube remains unaltered and can be replaced easily.

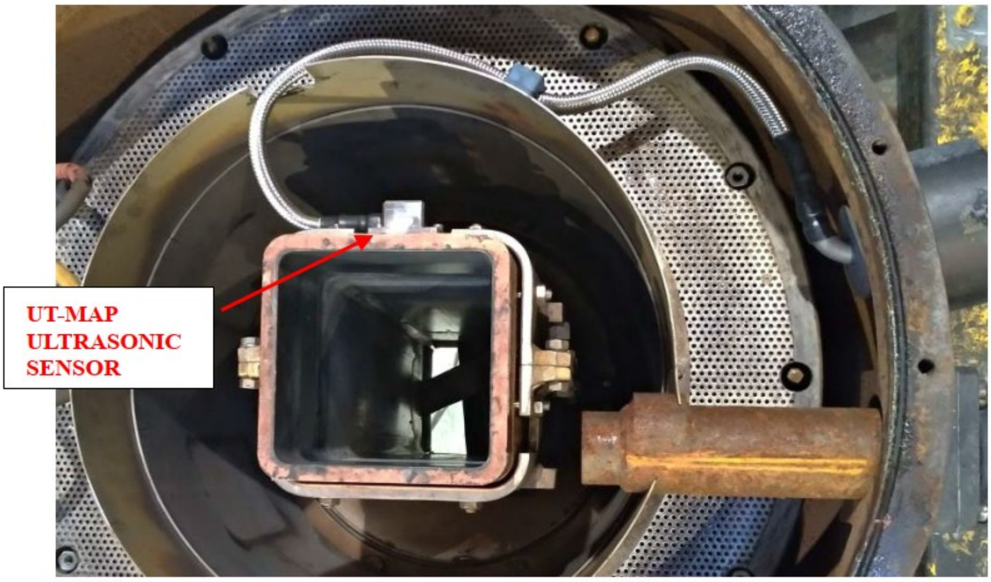

Fig.2 - Installation of Ergolines' ultrasonic sensor in the water jacket for Ultrasonic Thermal MAPing (UT-MAP).

The Meniscus Thermal Profile is obtained by plotting the four temperature values of each copper volume in front of the sensor versus their respective vertical positions along the mold side. In the case of a 4-points thermal profile, the temperatures are labelled T1, T2, T3 and T4, where T4 is the closest to the top of the copper tube and T1 is in the lowest position in the mold. A schematic representation of the UT-MAP concept is provided in Fig. 3 and 4.

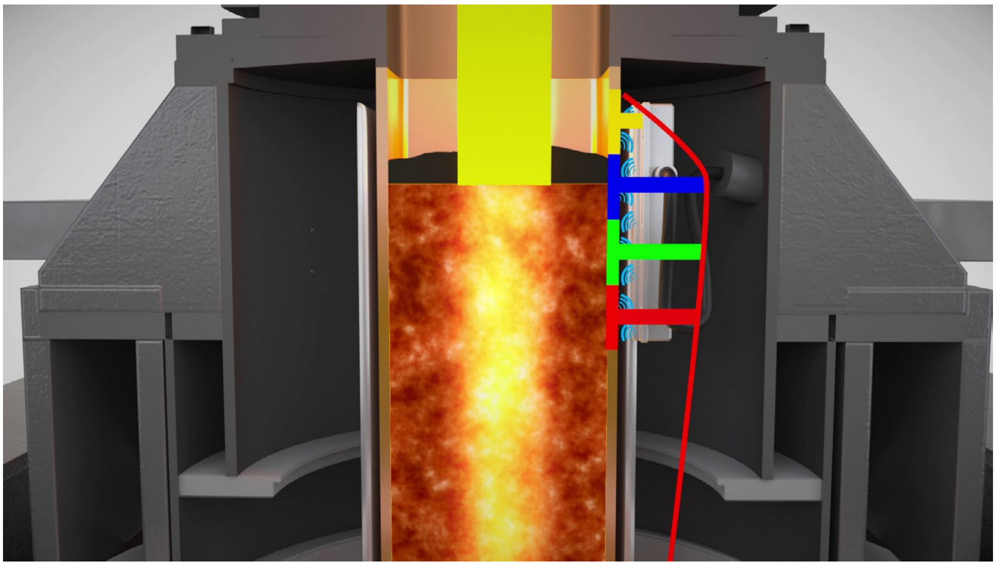

Fig.3 - Concept of ultrasonic temperature measurement: 1) Ultrasound propagates through the water gap and along the mold wall; 2) signal processing converts the ultrasonic signals into copper temperatures (colored beams); 3) the meniscus thermal profile is reconstructed (red line).

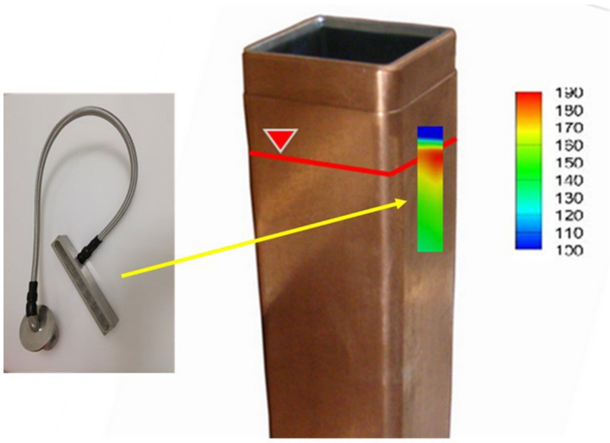

Fig.4 - Schematic representation of a typical UT-MAP measuring area: Copper temperature is mapped vertically in the meniscus region

The mechanical engineering of the sensor has been conceived to be modular. Presently there are different configurations, based on either 4, 8 or 16 detection points. The sensor with 4 measuring points is a small unit of approximately 40x50x200 mm, extending to 260 mm in length for the 16-point model. Thanks to the sensor modularity, multiple modules can be installed on the mold, depending on the extension of the mold area to be thermally mapped.

The ultrasonic sensor provides the copper temperature trends and the meniscus thermal profile in real-time (Fig. 5).

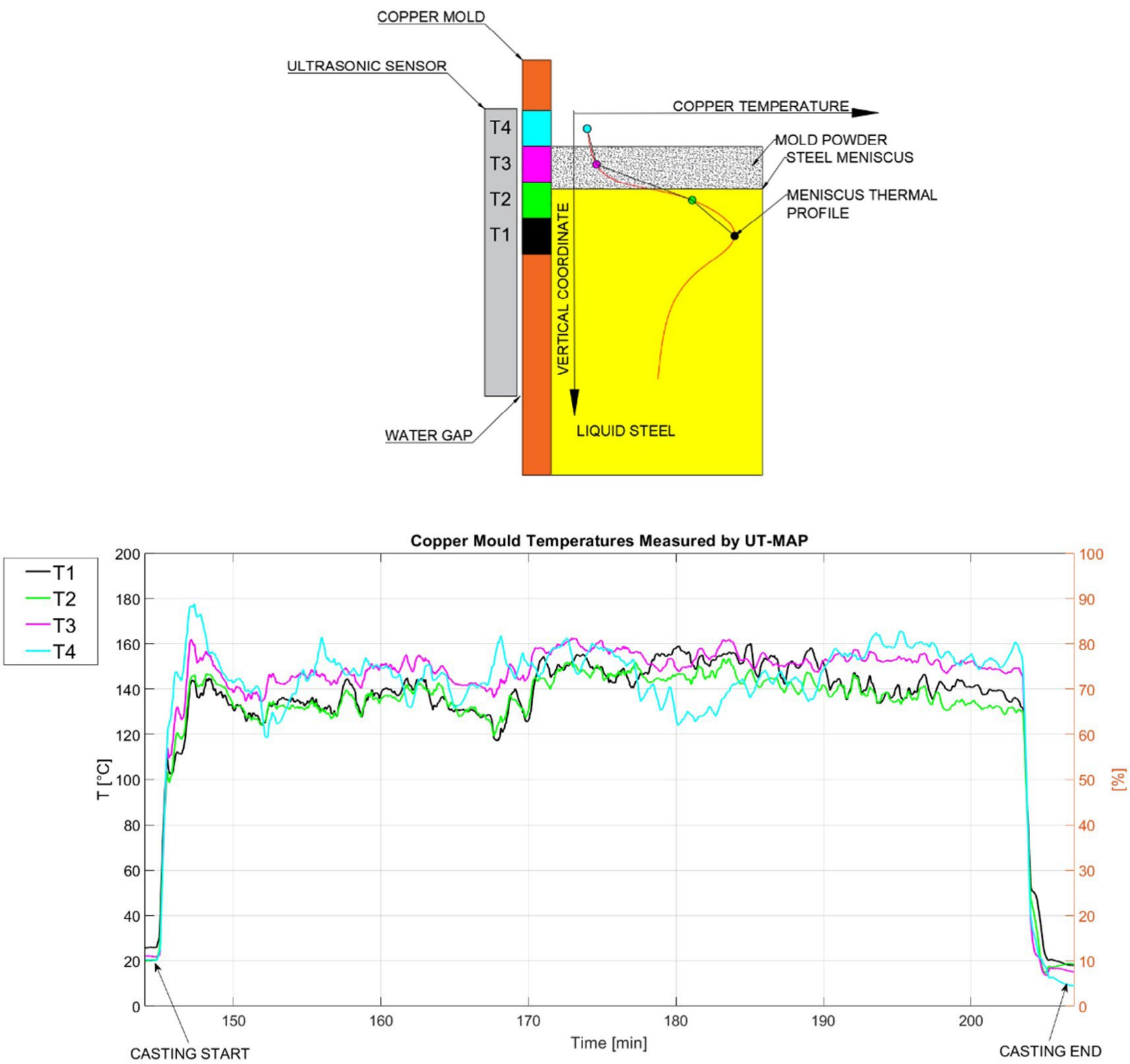

Fig.5 - Example of copper temperature data measured by the ultrasonic sensor: The location where each temperature is measured is represented in the diagram above the graph.

The working principle of the ultrasonic sensor relies on the dependence of ultrasound velocity on copper temperature. A dedicated algorithm developed by Ergolines based on mathematical inversion and FEM modeling enables to determine the copper temperatures by inverting the ultrasonic signals. In the example in Fig. 5, the data provided by UT-MAP represent the average copper temperature at four vertical locations in the meniscus region. Each temperature is averaged over a copper volume of approximately 2 cm^3 in between the hot and the cold face of the copper tube.

The system is able to detect even small temperature variations of the measured volume because the ultrasonic wave crosses the complete copper volume from the inner to the outer tube walls with high frequency. The sensor measures the temperature values several times per second, providing real-time information about what happens on the hot face (i.e., steel level fluctuation corresponding to instantaneous temperature variations). Beside its non-invasive installation and contactless measurement, one further advantage of the ultrasonic sensor with respect to TC or OFC is its "direct" (contactless) measurement of copper temperature with virtually no delay due to heat transmission through cementing resins: In fact, before reaching the TC or OFC probe, the heat must propagate through the resin used to cement the probe into the channel, and only after thermalization of the resin does the probe reach thermal equilibrium with the copper and provide a correct temperature measurement. On the other hand, the ultrasonic sensor provides a fully contactless temperature measurement, which involves no probes inside the copper and no cementing resin. As a consequence, the copper temperature variation is detected by the ultrasonic sensor instantaneously, with no delay due to the thermalization of the resin. As a consequence, the ultrasonic sensor response is faster with respect to TC or OFC.

Summarizing, when compared to the TC or the OFC, Ergolines' ultrasonic technology is more performing for at least two fundamental reasons:

- The non-invasive installation in the water jacket, which leaves the copper tube unaltered
- A faster response to any temperature variation associated with a steel level fluctuation due to contactless measurement

MOLD LEVEL CONTROL

Ergolines' ultrasonic sensor can also be applied to mold level control (ULD-Ultrasonic Level Detector). The fast response time provides an interesting technical advantage to Ergolines' ULD compared to the TC or OFC when the application needs a reactive process control tool such as the mold steel le vel control or the breakout detection system. The steel level detection by the radiometric system is based on the density variation of the mass moving inside the reading window (steel and mold powder), while the ULD reads the actual steel level based on the heat transfer conditions from the steel to the cooling water (meniscus thermal profile).

The radiometric mold level reading is an average of liquid steel level and powder thickness based on the respective densities of steel and powder. In fact, mold powder has a density which is typical 1/3 with respect to the density of liquid steel. As a consequence, each time powder is added manually, the radiometric reads the powder addition as a fictitious increase of the steel. Consequently, the system reacts by decreasing the actual steel level to restore the initial value of the radiometric setpoint. When the powder is consumed, the steel level rises again for the opposite mechanism of powder consumption.

Contrary to the radiometric, the ultrasonic sensor detects the actual steel level and it is not affected by powder addition.

When casting in open stream, the control feedback is made on the motors of the withdrawal unit. The ULD has been tested as a stable and reliable system for steel level regulation and automatic casting start in open stream casting.

The radiometric system has a real time detection of the steel movement and needs a proper number of samples to have a more stable information (i.e. moving average and filtering of the signals). The reaction time of the system is fast, and this is the reason why up to today this is the winning system on the market.

The systems based on TC or OFC need more time to react due to resin thermalization, as discussed above, and are therefore intrinsically less reactive and precise than the ultrasonic system.

ULD INDUSTRIAL APPLICATION TO STEEL LEVEL CONTROL

Beside its application to mold thermal mapping and closed-loop powder thickness control, Ergolines' ultrasonic sensor can also be used for steel level control[12]. Fig. 6 below shows comparative field data from a pilot installation in open casting, where liquid steel level was simultaneously measured by the ultrasonic and radiometric sensor, with steel level control based on the radiometric feedback. The blue graph is the radiometric setpoint, while the red one is the steel level measured by the ultrasonic sensor (data are not filtered). The steel level is expressed as percentage of the reading range of the two sensors, while time is expressed is seconds x 10^4. This casting sequence was particularly interesting since it offered the opportunity to measure the sensor response to a step variation of the radiometric setpoint: The steel level was kept at 75% of the radiometric range for about one hour and then lowered to 50%. It can be seen that the red trend of the ultrasonic sensor follows very closely the blue radiometric level at both casting start and step variation.

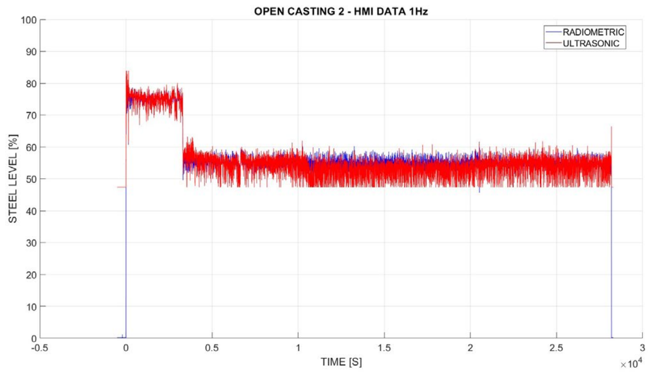

Fig.6 - Comparison of ultrasonic (red) and radiometric sensor (blue). Steel level was controlled by radiometric and measured with ultrasonic sensor (HMI unfiltered raw data sampled at 1 Hz).

Another interesting casting sequence is shown in Fig. 7. Also in this case the steel level was controlled by the radiometric sensor (blue graph) and it was simultaneously measured with the ultrasonic sensor (red graph) for comparative purposes. Since the ultrasonic range is different from the radiometric one, the ultrasonic graph has been scaled in order to be compared with the radiometric trend (for this reason the ultrasonic level before casting start has a non-zero value). The plot also displays casting speed (green) and the temperature of primary cooling water (black), which is also the temperature of the outer case of the ultrasonic sensor. The vertical axis is the steel level expressed as percentage of the radiometric range. The reason why this sequence is interesting is that three clogging events are clearly visible (at times 1400 s, 1900 s and 2500 s), offering the opportunity to assess the ultrasonic sensor response to a "spike", namely an abrupt increase in the steel level immediately followed by an abrupt decrease. Clogging occurs when steel momentarily freezes at the tundish outlet, causing the steel flow in the SEN to diminish. When the operator removes the solidified steel with an oxygen lance, the liquid steel level in the mold rises abruptly. This event can be seen as a spike in the radiometric signal (at times 1400 s, 1900 s and 2500 s). The radiometric feedback reacts to the spike by increasing the speed of the withdrawal unit (see green trend at the same instants of time), and then lowering it again as the steel level approaches the setpoint again. It can be clearly seen that the ultrasonic steel level measurement (red trend) follow the radiometric signal (blue) very closely during the whole sequence. It is interesting to note that the ultrasonic signal clearly detects the clogging events. Even if the ultrasonic response reflects the thermal delay due to heat propagation through copper, the graphs in Fig. 6-7 demonstrate that the ultrasonic sensor is able to reliably measure the liquid steel level both in stationary and transient regimes (such as casting start, step variations and clogging).

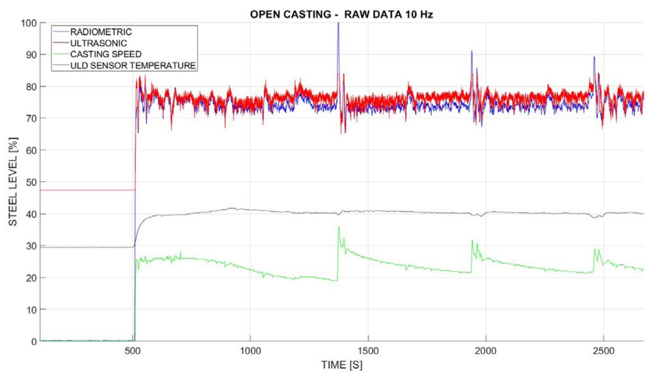

Fig.7 -Comparison between ULD and radiometric level signals. Steel level was controlled by radiometric and measured with ultrasonic sensor. Open casting with clogging events.

APPLICATION TO QUALITY TRACKING AND MOLD POWDER THICKNESS CONTROL

As previously reported in the literature[6], Ergolines' ultrasonic thermal mapping system was successfully applied to quality tracking in billet casters. The results reported in Fig. 8 demonstrate the advantage of applying ultrasonic thermal monitoring to the copper mold. The graph shows the temperature trends measured at different locations in the meniscus region during a three-ladle casting sequence. The first 120 minutes correspond to manual feeding, clearly recognizable from the typical sawtooth pattern in the trends, which is due to the well-known[13-15] radiometric feedback reaction to manual powder feeding. After minute 120, an automatic powder feeder operated in open-loop was activated: It is seen that the temperature trends stabilize significantly. At about minute 155 an 8% increase in the casting speed is seen to cause an increase in the T1 and T2 temperatures, which are measured below the meniscus, demonstrating UT-MAP effectiveness in monitoring the local heat transfer conditions in the mold. The ultrasonic temperature trends were correlated with data from Quality Control on tracked billets: A marked reduction of both surface (bleedings) and internal defects (defects due to powder entrapment events) was found in the billets cast under automated feeding if compared to the ones casted before minute 120 under manual powder addition. In fact, the stability of liquid steel level in the mold is known to have a direct impact on steel quality1,2. These results are an example of how the ultrasonic sensor can be used in UT-MAP mode to provide key information which can be exploited to improve the casting practice.

Based on Ergolines experience on powder thickness control technologies[13-20], the ultrasonic sensor can also be used to implement automatic powder feeding in closed-loop mode. In fact, the position of the liquid steel meniscus can be determined from the meniscus thermal profile by means of a dedicated algorithm developed by Ergolines. If the steel level is controlled by a pre-installed radiometric sensor, then the ultrasonic sensor can be used to keep the powder thickness constant. This is possible since the radiometric sensor response is affected by both steel and powder, while the ultrasonic sensor detects the actual steel level. As a consequence, when powder is added by the automatic feeding machine, the radiometric feedback causes the actual steel level to decrease (3 cm of powder attenuate the gamma rays roughly as 1 cm of liquid steel). This decrease in the steel level is detected by the ultrasonic sensor and used by a PID controller to drive the powder flow rate accordingly, keeping the powder thickness constant, leading to increased meniscus stability and significant quality improvement.
As a further example, the effectiveness of Ergolines' UT-MAP technology associated with fine-tuned mold powder dosing in closed-loop mode has been demonstrated by extensive data collection campaigns on special steels, leading to high quality billet surfaces, as recently reported in the literature[21].
Ergolines' ultrasonic sensor applied to mold powder thickness control is currently installed in several steelplants.

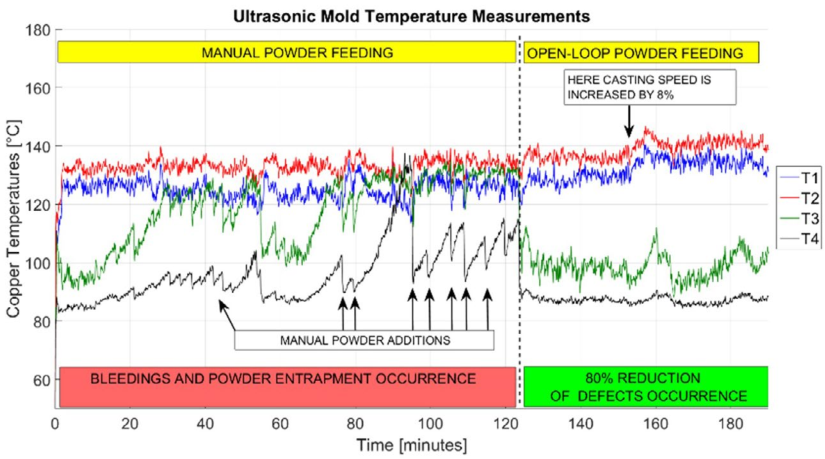

Fig.8 - UT-MAP trends detect difference between manual feeding, leading to defects occurrence on tracked billets, and automatic feeding (open-loop), leading to marked defect reduction[6].

OTHER POTENTIAL DEVELOPMENTS

Breakout detection

Since the UT-MAP system has been designed to be modular, its extension to different areas of the mold is possible. The concept of mold thermal mapping, today applied to the slab casters only, can be applied to the billet or bloom curved mold. In general, the upper area of the mold is more interesting for thermal mapping applications, reserving the mapping of the last segment of the mold mainly for the tapering optimization.

The thermal mapping applied to the first 200-300 mm has been demonstrated to be enough to effectively implement the breakout detection systems. It is evident that the thermal mapping extended to the complete mold is more "safe and complete" but the major problems related to breakout are generated by bleeders and sticking in the initial solidification.

Typical temperatures trends, as deeply documented in literature, between two consecutive vertical points where the sticker occurs show a double temperature peak (upper and lower detection point), with a propagation speed a bit lower than the casting speed. The UT-MAP software can recognize a deviation from the normal conditions and provide a diagnostic variable to the strand PLC characterized by "normal", "warning" and "alarm" mode, based on custom thresholds which can be set by the steel plant metallurgists.

Quality tracking

A further application of mold thermal mapping is related to the billet quality tracking. It has been proven by ULD installations on SBQ CCM, that some of the parameters can be associated to quality issues. What the UT-MAP provides is the copper temperature at several points (4 up to 16 points) in the meniscus area. From this data, key information on the quality of the heat exchange in the monitored area can be obtained. In fact, the factors related with heat flux variations include:

- Steel level fluctuation
- Abnormal oscillation mark formation
- Bleedings
- Stickers
- Insufficient or improper lubrication
- Non correct position of the SEN

The UT-MAP data can be collected in the plant database and used by the metallurgists to associate the segments of the cast billets where the temperature fluctuations were detected with a qualitative benchmarking, thus providing a qualitative tracking of the product.

The problems in general can be resumed into two categories: Surface quality and Geometrical quality. On one hand, surface quality is mainly influenced by local / spot deviation from the normal conditions: bleedings, surface or subsurface cracks are an example. On the other hand, geometrical problems are related with a non-homogeneous behavior of the heat transfer along the four sides of the mold. An example of this case is the rhomboidity, which is generated when uneven heat flux conditions occur in the mold.

CONCLUSION

Ergolines' developed and successfully tested an ultrasonic sensor for contactless temperature mapping of the copper mold tubes (UT-MAP – Ultrasonic Temperature MAPping). The sensor is able to monitor the temperature of the copper mold tube in real-time, providing both temperature trends over time and the meniscus thermal profile. Contrary to thermocouples or optical fibre cables, which require invasive and expensive machining of each copper tube, the ultrasonic sensor is installed in the water jacket and therefore does not require any copper machining at all. Correlation of ultrasonic sensor data with quality control reports on track billets demonstrated the effectiveness of the UT-MAP technology in providing key information to the metallurgists, enabling improved steel quality. Ergolines' ultrasonic sensor, currently used in several steel plants for powder thickness control, can also been applied to steel level control, as shown by comparative field-data with the radiometric sensor on pilot plants.

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