Online Flow Control with Mold Flow Measurements and Simultaneous EM Braking and Stirring

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Abstract
To obtain flow control of the molten metal in the mold where the initial solidification steps of continuous casting occur, a versatile electromagnetic actuator is required to enable both flow acceleration and stabilization to counteract different undesired flow phenomena. Various mold monitoring systems instantly give insights into the dynamics of the meniscus level, solidification status and molten steel flow characteristics during casting. An online mold flow sensor in combination with an electromagnetic actuator capable of applying time varying braking and stirring forces simultaneously, enable closed loop mold flow control with automatic handling of regular as well as sudden variations in the casting conditions in real time.

A control package for the FC Mold G3, a combined two-level electromagnetic actuator with a brake in the bottom of the mold and a combined stirrer and brake in the top of the mold, reacting on varying macroscopic casting conditions has been used in steel plant production to minimize quality and operational issues. The control relies on predictions of the amount of surface defects based on experience and numerical simulations of the fluid flow. Plant quality results, collected during a year of full production, show a surface defect reduction of more than 50% with FC Mold G3 on critical ULC grades for exposed automotive body panels [1]. In the next step, real time information taken directly from process monitoring will dynamically control the FC Mold with further improved slab cleanliness and surface quality as a result.

Key words: Flow control, electromagnetic stirring (EMS), electromagnetic braking (EMBR), FC Mold, slab, surface quality, cleanliness, FBG, temperature measurement, level measurement

Introduction
Building on the success of the FC Mold to stabilize and optimize the mold flow in the continuous slab casting process with resulting enhanced slab quality, the subsequent step is to incorporate a more sophisticated mold flow detection device in combination with an increasingly flexible EM actuator to be able to catch and react on localized casting deviations. Local meniscus fluctuations, undesired flow fluid velocities or patterns and crack indications are examples of events that may call for an adjustment in the electromagnetic field distribution imposed on the molten metal in the mold during casting. Furthermore, the mold fluid flow may display asymmetric features due to deviations from ideal conditions in the entry nozzle or mold. Examples of this are inhomogeneous SEN clogging, asymmetric stopper or slide-gate positioning, or asymmetric argon injection. Even with a perfectly aligned and symmetric geometry, the turbulence of the fluid flow in the SEN and mold induces flow variations that cause asymmetric flow patterns. These asymmetric flows may lead to local variations of the metal end product quality, e.g. one side of a slab may contain large clusters of non-metallic inclusions close to the surface due to violent meniscus behavior and mold powder entrainment on this side.

By applying asymmetric mold flow control by means of a flexible EM device, a more stable and symmetric casting process can be maintained. E.g., excessive meniscus fluctuations and flow speeds on one side of the mold can be mitigated by extra stabilization and braking in this area, or an uneven speed relationship between the SEN jets due to SEN clogging can be homogenized by applying more braking or stirring on one side of the mold. A homogeneous and stable casting process yields a homogeneous solidified end product, with both quality and financial benefits for the steelmaker and the end-product consumer.

FC Mold
The FC Mold is a two-level electromagnetic device producing an upper field above the SEN outlet ports, close to the meniscus, and a lower field below the SEN ports in the lower portion of the mold. In the lower level, a static DC magnetic field is created across the mold thickness to brake the SEN jets, reduce downward penetration, and stabilize the flow pattern in the mold. For modern and flexible FC Mold units, another DC field is applied in the upper level either by itself, or simultaneously with AC stirring. This allows the near meniscus flow to be braked if flow speeds are too high, or accelerated with stirring should the flow speeds in this region be too low. In the Combi Mode, both DC and AC fields are applied and the meniscus fluctuations can be stabilized at the same time as a steady rotative stirring keeps the fluid moving in a robust way [7]. In modern FC Mold versions, the magnetic core and electrical drives allow full flexibility in
controlling the magnetic fields in both the upper and lower levels, as well as on left and right sides independently.

**Mold Flow Measurements**

A high resolution thermal mold plate monitoring method based on optical Fiber Bragg Grating (FBG) sensors has been developed, and a pilot installed in one broad face copper plate in a continuous slab caster at the TATA Steel, IJmuiden works [2]. This technology allows a multitude of simultaneous temperature sensors along a single optical fiber, and by mounting a set of fibers inside a mold plate, more than 2500 FBG temperature sensors are distributed over the mold plate. The sensors measure the local temperatures and the system provides a sharp thermal image of the mold, updated during each scanning period of 0.5 s. Out of this pilot sensor setup, the OptiMold Monitor® system for mold thermal and fluid flow monitoring has evolved.

The operation principle of the FBG sensor technology is broadband pulses of light incident on the fiber gratings which produces a reflection wavelength spectrum based on the configuration of the gratings along the fiber. When exposed to the heat of the molten steel in the mold, the well-defined thermal expansion along each optical fiber produces a shift in the wavelengths of each grating. By the material parameters of the fiber, the wavelength shift can be directly translated to a specific temperature increase.

Utilizing a vertical sensor point spacing of 5 mm, where each sensor point has a measurement error less than 0.7 °C, local thermal phenomena such as the meniscus shape can be clearly resolved as visualized in the thermal distribution image in Fig. 1. The meniscus shape is a finger print of the flow pattern in the mold and the flow velocities in the molten steel near the meniscus level. E.g., in a standard double roll flow pattern commonly seen in slab casters for medium to high casting speeds, the flow momentum from the SEN jets impinges on the mold narrow faces and is then partially split upwards and downwards along the narrow face as illustrated in Fig. 2. The upward flow creates a wave crest and is then redirected and follows the meniscus toward the SEN in a standing wave shape where the flow speed is related to the height of the wave. This means that by measuring the meniscus shape, the flow speed of the meniscus can be indirectly estimated. A set of nailboards have been submerged into the meniscus flow to tune and quantify this correlation [3].

![Mold Temperature Distribution](image1)

**Fig. 1:** Measured high resolution temperature map of broad face mold plate, 237x1100 mm, 1.0 m/min.

![Double roll fluid flow pattern](image2)

**Fig. 2:** Double roll fluid flow pattern in caster strand and magnetic field locations of the FC Mold.

Over a measurement campaign during production at TATA Steel IJmuiden, mold temperature distributions, and indirectly meniscus wave and speed profiles, were collected for more than 1700 cast slabs of selected steel grades. In the same caster, an FC Mold, a double level DC electromagnetic brake is installed [4]. In roughly half of the cast slabs of the test period, the static magnetic fields of the FC Mold were engaged, and in the rest of the slabs the FC Mold was turned off. Real time meniscus wave profile characteristics such as wave height and flow speed on both left and right sides of the mold were logged continuously and then averaged over the casting time of each slab. In this trend analysis, each slab provides a single point in the set of data from all cast slabs of the measurement campaign.

An asymmetry index, $AI$, of the meniscus wave shape of the fluid steel is defined as

$$AI = 100 \frac{h_L - h_R}{h_{ref}}$$

where $h_L$ and $h_R$ are the standing wave heights of the meniscus on the left and right sides respectively, related to a
reference height $h_{\text{ref}}$ of 20 mm. If the absolute value of $AI$ is constantly high, then there is a stable meniscus shape asymmetry caused by biased mold flow indicating e.g. asymmetric clogging in the SEN. If $AI$ is varying with a large $\sigma$ over time, then this indicates a swaying biased flow. Both of these asymmetric flow features may be detrimental to the end quality of the steel as an inhomogeneous solidification is taking place, and excessive flow speeds or oscillations may pull mold powder into the bulk of fluid steel.

Based on the full data set from the measurements, a linear regression of the average absolute value of the asymmetry index per slab, $|AI|$, is in Fig. 3 plotted against throughput. The slabs composing the measurement campaign are cast with a wide variety of conditions, but all slabs used in the analysis are cast with constant casting conditions within each slab. With upper and lower level DC magnetic fields from the FC Mold acting across the mold thickness to brake the SEN jets and stabilize the flow pattern in the lower mold region and to brake meniscus speeds and stabilize the flow in the upper region, the results in Fig. 3 show that the mean meniscus asymmetry is reduced for all throughputs. In Fig. 4, a linear regression of the measured $\sigma$ of the asymmetry index $AI$, i.e. the time standard deviation of $AI$ per slab, is shown versus throughput. The stabilizing functionality of the DC magnetic fields of the FC Mold reduces the swaying over time in the biased meniscus flow generally, but also makes variations in asymmetry nearly independent of casting throughput.

**Numerical Simulations of Flow Asymmetry when Exposed to FC Mold EM Fields**

A numerical CFD simulation has been conducted to illustrate the effect of asymmetric magnetic fields on an asymmetric flow field. Using a fictive skew inlet flow condition over a cross section in the SEN for a 237x1100 mm slab format cast at 1.9 m/min, the effects of a partially clogged nozzle have been modelled. A snap-shot of the simulated velocity distribution in the center slice of the mold during these conditions is shown on the left of Fig. 5.

**Fig. 3:** Mean absolute value of the asymmetry index vs. casting throughput. With and without FC Mold.

**Fig. 4:** Standard deviation of the asymmetry index over time within a slab. With and without FC Mold.

**Fig. 5:** Simulated flow velocity distributions in mold center slice for skew inlet flow. Without FC Mold (left) and with asymmetric FC Mold DC field distribution with stronger DC field in the top right corner (right).
In Fig. 6 the transiently simulated meniscus flow speeds at the center thickness of the mold, \( y = \pm 0.385 \text{ m} \) for the left and right sides, are shown for a time period of 210 s. In the first 60 s of the simulation, the FC Mold is turned off. From here until \( t = 75 \text{ s} \), horizontally homogeneous and symmetric DC magnetic field distributions in both levels of the FC Mold are ramped up, with the result that between 75 and 135 s, the meniscus flow speeds are reduced and fluctuations stabilized. However, the gap between the left and right flow speed curves of Fig. 6 is only closed in the last 60 s of the simulation when the biased flow is symmetrized. This is the result of a horizontally asymmetric field distribution in the upper FC Mold level where a 25% boost is applied to the DC magnetic flux density on the top right. The stronger flow speed on the right side of the meniscus is in this way subject to extra braking to obtain the same flow speed as on the left side. The flow speed pattern in the mold during asymmetric braking is illustrated on the right in Fig. 5.

**FC Mold Control**

By accurately measuring the flow speeds of the meniscus in the mold with the high resolution method described above, and at the same time monitoring asymmetric flow pattern deviations, the FC Mold is via a closed-loop control system in the FC Mold Autonomous Control Mode set up to apply varying braking and stirring electromagnetic fields to counter-act meniscus speeds that are too low or excessive. In the same way, the control works together with the flexible FC Mold to mitigate flow pattern asymmetries. E.g. a stronger flow speed in one side of the mold is suppressed by a locally strengthened DC field, or an insufficient flow in one side of the mold is accelerated by locally controlled AC stirring to create a homogeneous flow speed distribution over the full width of the slab. Robust PI-methods are used in the controller implementation. Control can also be carried out against an electromagnetic level sensor where high frequency feedback can be utilized to obtain detailed level and fluctuation information in the probing locations. This enables stability control of the meniscus level and the upper part of the mold.

**Summary**

Flow asymmetry induced by e.g. SEN clogging can according to simulations be counter-acted by an asymmetric FC Mold magnetic field distribution to achieve a homogeneous flow speed distribution over the entire meniscus level. With modern FC Mold equipment, the DC and AC magnetic fields are configurable independently not only in the upper and lower levels, but also on the left and right hand side regions. This, in combination with the high resolution flow monitoring capabilities of the OptiMold Monitor® makes it possible to control the magnetic fields of the FC Mold autonomously against different online flow measurement parameters such as the meniscus speed on the left and right sides of the mold. The dynamic control of the FC Mold guided by the process monitoring of OptiMold Monitor® unlocks potential for further improved slab cleanliness and surface quality of the cast steel.

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