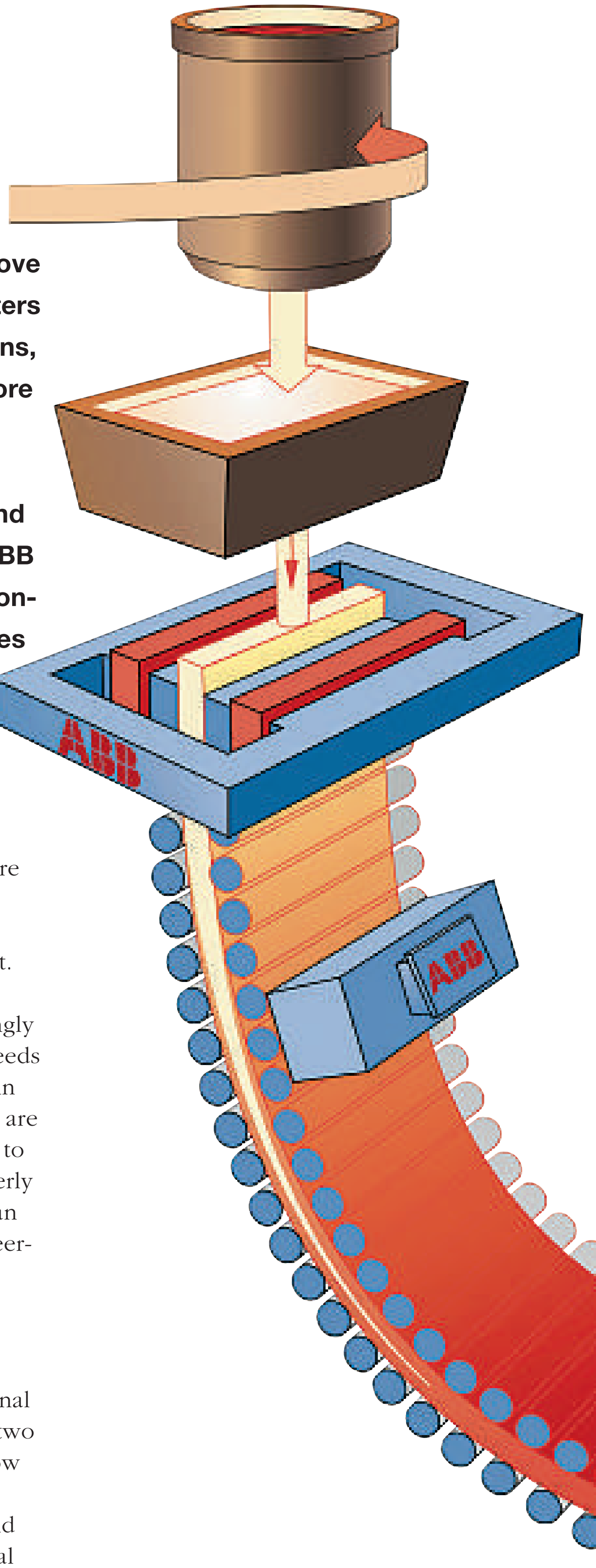
Speed limit!

Direct control of electromagnetic braking for faster thick-slab casting

Sten Kollberg, Peter M. Lofgren



Compelled by market forces to keep raising productivity and improve quality, steelmakers are being pressed to run their continuous casters at ever-higher speeds while reducing harmful non-metallic inclusions, such as slag or gas. But here there is a problem: inclusions are more likely, the faster the casters are run.

The Electromagnetic Brake (EMBR) was developed to solve this and related problems. Now, to make EMBR performance even better, ABB is introducing a new tool called EM Control (for Electromagnetic Control). By optimizing the flow in the mold, it overcomes the difficulties that can be caused when casting conditions change.

Producing high-grade steel is more than just a matter of getting the chemistry right. Control of the fluid flow in the mold is just as important. This is because continuous casting, especially of thin slab, but increasingly of thick slab also, takes place at speeds that can easily produce turbulence in the mold. The problems this causes are well known (see panel), and it was to solve them that ABB and JFE (formerly Kawasaki Steel Corporation) of Japan began in the early 1980s their pioneering work on electromagnetic brake technology.

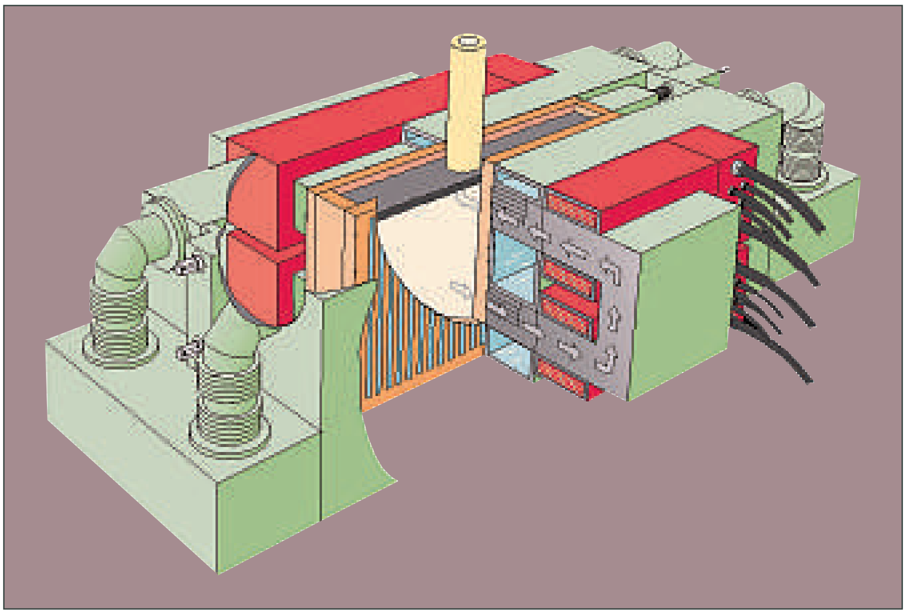
The outcome of this work was the local field type EMBR for conventional slab casting. This technology, with two braking areas acting on the steel flow out of a two-port nozzle, was soon seen to be a major breakthrough and EMBR equipment was sold to several

Speed trap

Continuous casting is a complex process, and harmful non-metallic inclusions, such as slag or gas, can easily become entrapped in the molten metal. The risk of inclusions increases with the casting speed, since the jet of molten steel penetrates deep into the mold, pulling mold powder and other impurities down with it. The presence of such impurities in the solidified metal seriously impairs the quality of the steel.

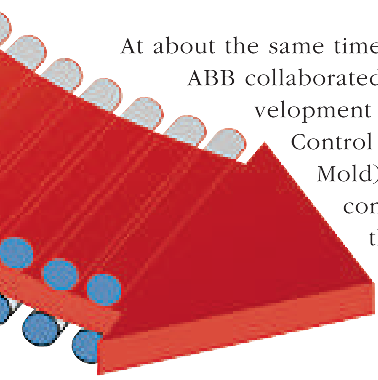
The electromagnetic brake (EMBR) developed and patented by ABB uses a static magnetic field to control the flow of hot metal in the mold. By ensuring a uniform velocity and temperature for the molten steel over the entire strand width, the EMBR allows the casting speed to be increased without any degradation of the steel slab quality.

1 FC Mold type of EMBR



major Japanese steel companies. Refined over the intervening years, the local field type is today used mainly in thin-slab casting.

By the early 1990s further development work had produced the EMBR Ruler, a configuration in which a single magnetic field acts on the total width of the slab. The basic idea here is that all the steel flowing from the nozzle passes through a zone in which it is subjected to a braking force. EMBR equipment using this configuration was subsequently supplied to several steelworks, where it is deployed primarily for thin-slab casting.



At about the same time, JFE and ABB collaborated in the development of the Flow Control Mold (FC Mold) 1. In this configuration there are two equally strong static magnetic fields, one controlling the metal speed at the level of the meniscus, and another in the lower part of the mold to control (ie, reduce) the penetration depth of the steel jets flowing from the caster nozzle 2.

Metallurgical results with FC Mold

Increasing demands made on product quality, coupled with the need to raise productivity are presenting steelworks managers with a dilemma. While a lower casting speed will normally result in a higher product quality, productivity inevitably drops. As if that were not enough, adding extra argon gas (to reduce the risk of clogging) can cause the product quality to drop too.

FC Mold addresses these problems by reducing turbulence in the molten steel and controlling the meniscus metal flow speed. One result of this is less meniscus fluctuation. Also, the temperature at the meniscus is increased by the reduced turbulence and by the hot steel from the submerged

2 Flow in a continuously cast strand without FC Mold (left) and with FC Mold (right)

1 Inclusions
2 Thin powder film
3 Disturbed meniscus
4 Vortices
5 Calmer and hotter meniscus
6 Location of iron cores
7 Reduced penetration depth

entry nozzle (SEN) being higher up in the strand (a result of the steel jets not penetrating so deep). Slowing the penetration speed downstream of the steel jets not only allows higher casting speeds but also contributes to a cleaner product since, as already

> Slowing the penetration speed downstream of the steel jets not only allows higher casting speeds but also contributes to a cleaner product.

stated, any inclusions that are present will float upward, toward the meniscus. Just as importantly, FC Mold effectively eliminates fluctuating biased flow – a factor contributing as much as anything else to a more stable and higher product quality.

The very stable meniscus profile obtained with FC Mold is a logical result of the static magnetic field's primary function, which is to damp the high frequencies that cause turbulence in the molten steel. This function alone makes FC Mold superior to any stirrer with a traveling magnetic field.

But this is not all FC Mold has to offer. 3 shows what can happen when the production rate exceeds a certain limit. Without FC Mold, both surface and internal defects increases substantially at a casting speed of around 2 m/min, heavily impairing the end-product quality. FC Mold allows production managers to increase production without the trade-off of lower quality. Alternatively, a dramatic increase in end-product quality can be reached while maintaining production at the same level.

Metallurgical tests carried out in Japan with vertical bending and curved mold

FC Mold: function and equipment

The main electrical components of the new version of FC Mold are a power transformer, two thyristor converters for independent control of the upper and lower fields, a control cubicle, the FC Mold coil and a cooling water station.

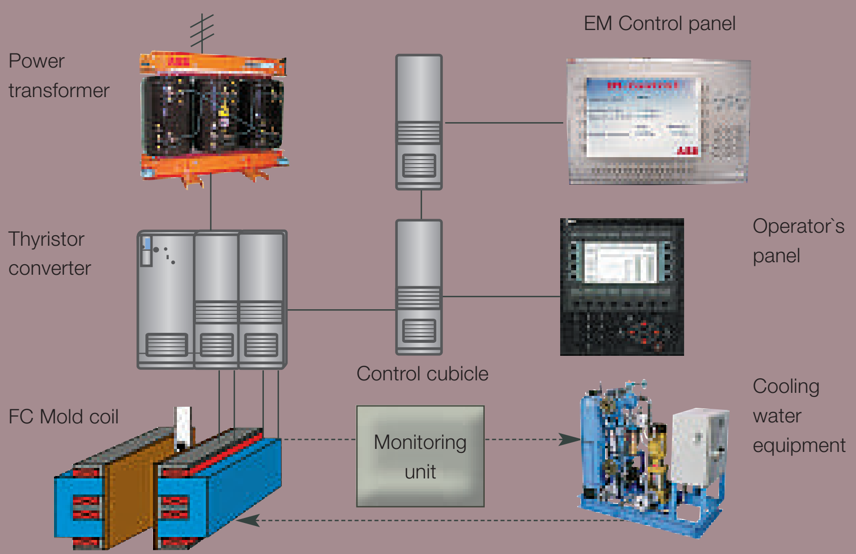
FC Mold works by applying two static magnetic fields across the mold, perpendicular to the casting direction. The steel flow induces voltages and thus electric currents in the melt that, together with the static fields, produce a force acting in the direction opposite to the steel flow. The higher the casting speed, the faster the molten steel flows and the stronger the braking force.

The task of the FC Mold coil is to convert the direct currents from the thyristor converters into static magnetic fields. It is divided into four sections (two on each side of the mold), each of which has an iron core passing through it. These coil sections and the rear magnetic yokes together form a magnetic circuit with two 200 to 400 mm long gaps across the mold. The magnetic field in the gaps covers virtually the entire width of the mold.

The coil sections are enclosed in non-magnetic austenitic stainless steel cases and are normally custom-designed for each mold. Within the coil sections, the electric windings (hollow copper sections) are connected in series and cooled by de-ionized water from the closed-loop cooling water system.

Two different versions of FC Mold are available:

- *Internal* (see 1 on page 7). In this version, which is typically chosen for existing casters, the coil sections, magnetic cores and yokes are built into the mold and are taken into and out of the caster with the mold. The air gap is small, so less power is required, but the EMBR coil has to be connected and disconnected each time the mold is exchanged, and the oscillation mechanism has to support the extra weight, typically 10 tons.
- *External*, normally chosen for new casters. To avoid each mold having to be equipped with coils, which have to be disconnected and connected whenever the mold is exchanged, this design has coils with cores and yokes that can be fastened to manipulators and retracted during mold changes. When the new mold is in place, these coils (with their cores and yokes) are pushed forward and fastened to the new water jackets.



casters have confirmed that FC Mold reduces mold powder entrapments and increases flotation of non-metallic inclusions in both cases.

The need for better control

Notwithstanding the usefulness of the brake technology as it stands today – with a magnetic field that is adjusted only at the start and when major changes are made to the casting parameters – it was recognized that with on-line control it would be even better.

Process experts and researchers from ABB therefore set up a team to devise a way to calculate the steel quality and control the EMBR. The goal was to optimize the flow of steel in the mold by controlling the brake's magnetic field.

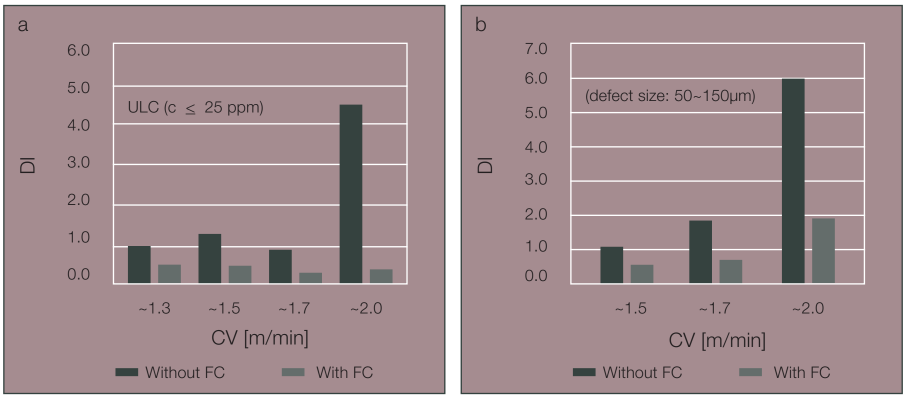
A new version of FC Mold with independent control of the upper and lower magnetic fields was used to provide the capability required for even low-speed casting. This new version optimizes the flow pattern by controlling (mainly with the upper field) the meniscus flow speed and minimizing (mainly by controlling the lower field) the downward penetration in the strand 4. Non-metallic inclusions entering with the molten steel float upward toward the meniscus, where, by controlling the turbulence and flow speed, mold powder inclusions are practically eliminated. As a result, there are far fewer inclusions in the final product.

> Notwithstanding the usefulness of brake technology as it stands today, it was recognized that with on-line control it would be even better.

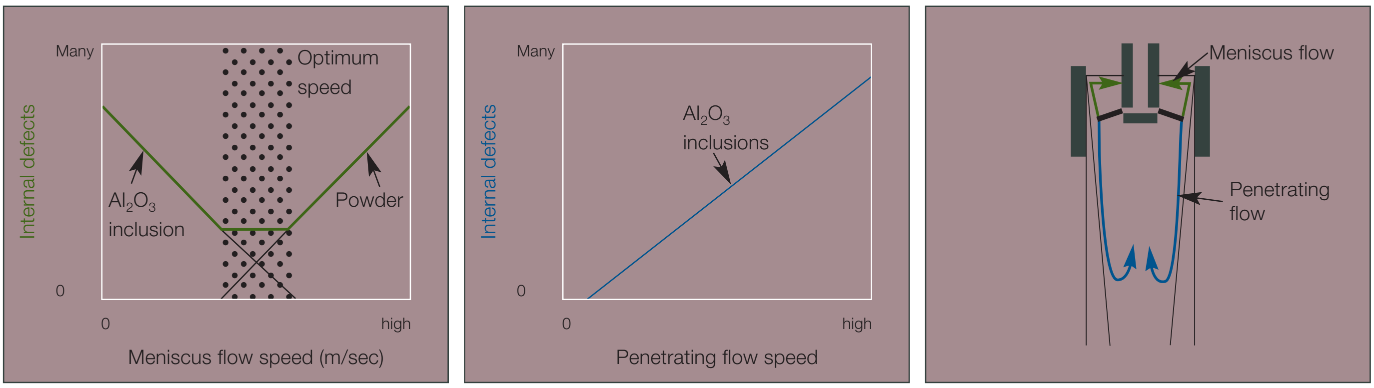
However, several inter-related problems first had to be solved. For example, the upper field has to be controlled in order to arrive at the optimum meniscus speed while (normally) keeping the lower field strong to minimize the penetration depth. Further, the meniscus speed has to be maintained at an optimum value during variations in the argon gas supply, changes of casting speed and slab width, and especially during clogging with biased flow. It was to solve these problems, during casting as well as when commissioning FC Mold, that ABB began development of a closed-loop, on-line control system. The outcome of this work is EM Control.

3 Comparison of surface (a) and internal (b) defects as production, here of hot-rolled coils, increases, with and without FC Mold (Source: JFE)

DI Defect index CV Casting velocity

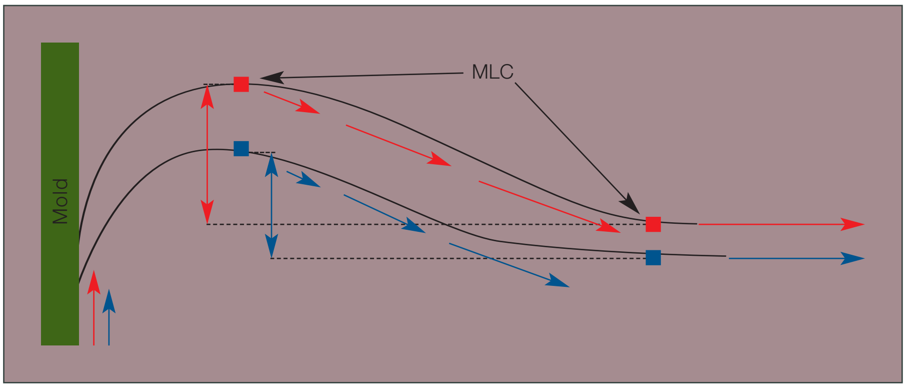


4 Optimal flow conditions in a slab mold



5 Meniscus velocity versus height difference
MLC Mold level control

Red Higher velocity
Blue Lower velocity



EM Control

No measuring device on the market today can reliably measure the metal speed at the meniscus, where the temperature is typically 1600 °C, by direct means, especially in the presence of a strong magnetic field. This speed therefore has to be measured indirectly. The best solution at the present time would seem to be to use two electromagnetic mold level sensors to measure the meniscus height 5. Computer flow simulations indicate that the meniscus flow speed can be reliably calculated by measuring the meniscus height difference based on these two sensors' readings.

The next step is more difficult: how to use the height difference signal to control FC Mold's electric currents in order to obtain the desired meniscus flow velocity. This requires a computer program for the magnetic field calculations as well as a fluid flow simulation program. ABB developed the EM Tool for the simulation of fluid flow as the key part of this package. Among its many features are the following for describing the flow characteristics of the molten steel as well as how slag and inclusions move within the mold:

- 3-dimensional MHD[1] modeling
- Transient simulation with full Reynold stress modeling (RSM) of turbulence
- Two-phase modeling (steel plus gas)
- Transient particle tracking (for inclusion control)

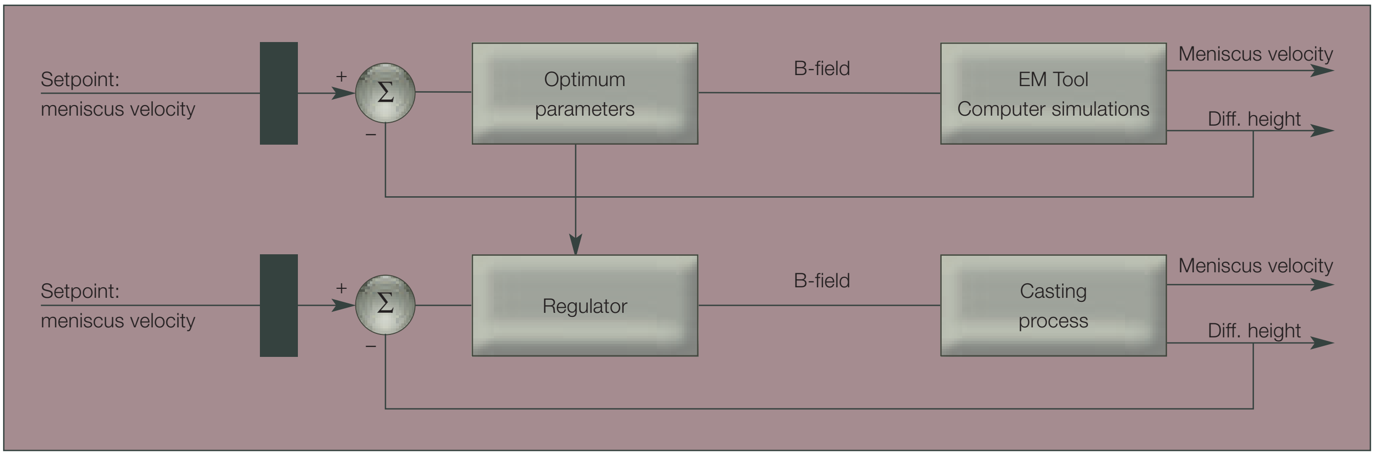
To minimize risk during hot commissioning and initial trials, the parameters calculated for the EM tool regulator are implemented in the casting process only when the results look promising 6.

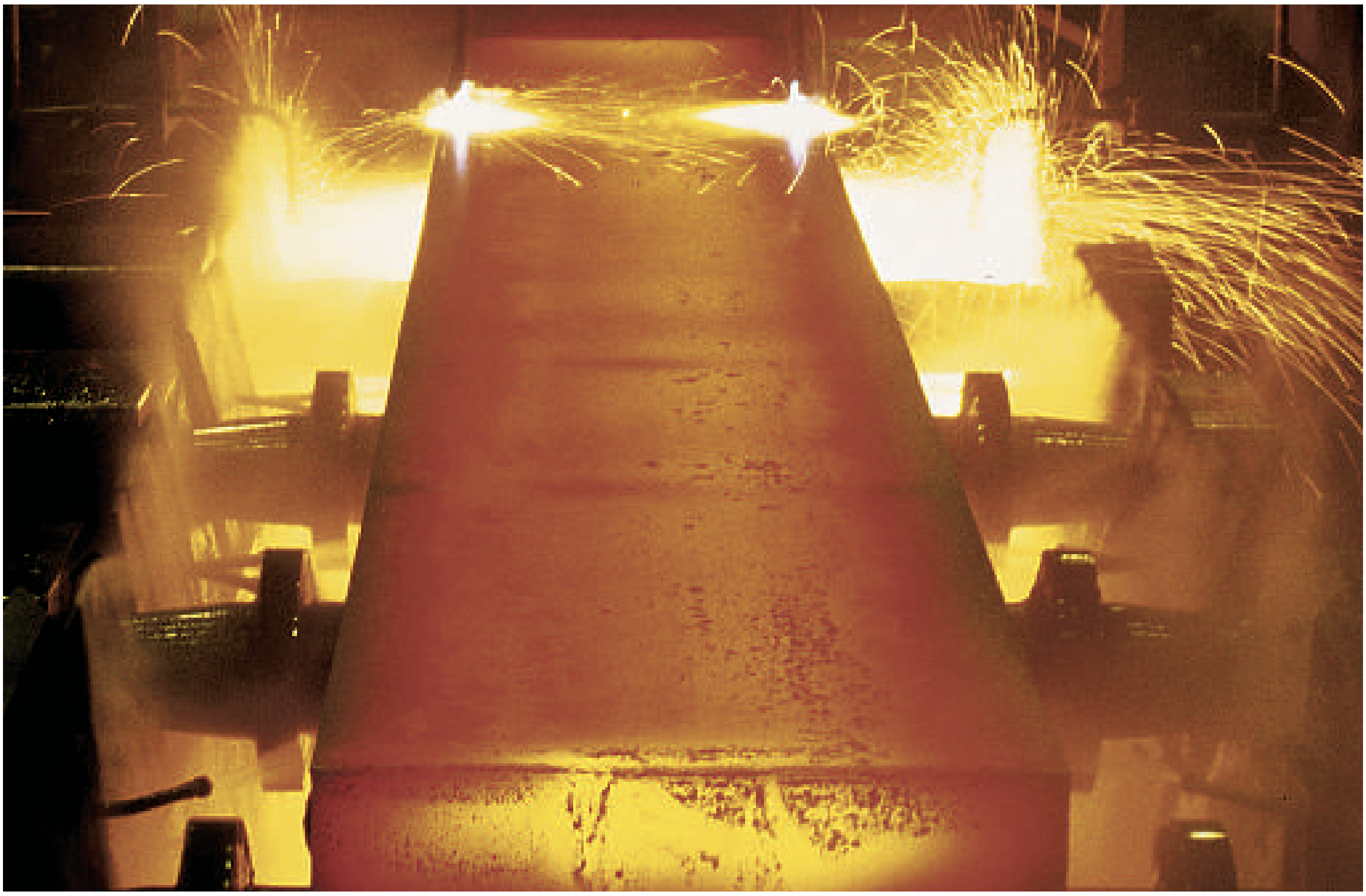
Reliable measurement of the metal speed at the meniscus requires a computer program for the magnetic field calculations as well as a fluid flow simulation program.

A casting sequence with a curved mold was simulated to illustrate the EM Tool's capabilities. The parameter settings for this simulation were: strand dimensions 230 × 1300 mm; casting speed 1.5 m/min; 10 l Ar/min; 2-port casting nozzle.

[1] Magneto Hydro Dynamics

6 After being optimized, the parameter settings are transferred to the EM Control regulator.

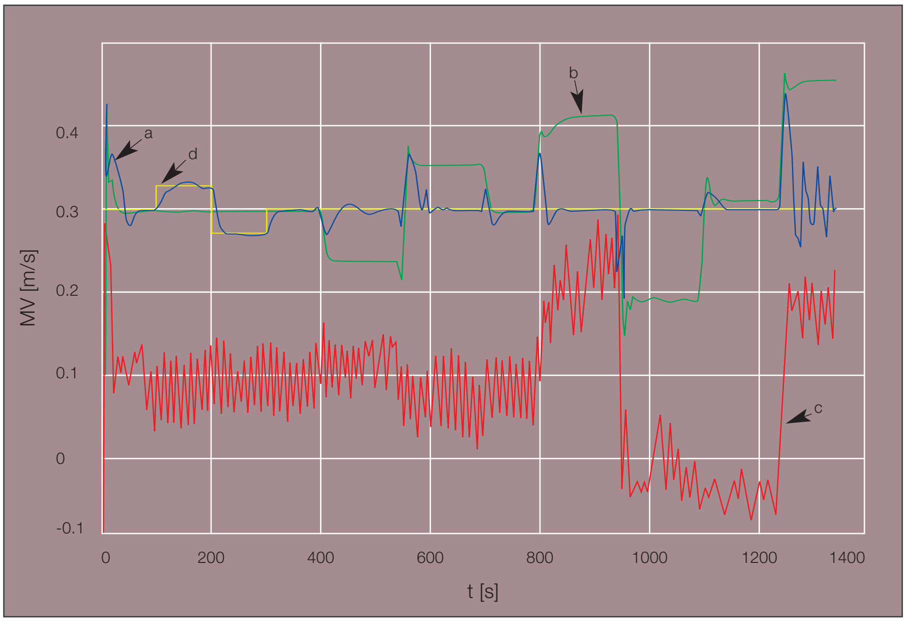




Changes/disturbances were initiated at different times in order to vary the measured meniscus speed (height difference); the controlled magnetic field in FC Mold was varied and the meniscus speed brought back to the velocity setpoint. The four graphs in 7 show the meniscus flow speed with EM Control (blue line, a), the optimum case with FC Mold's magnetic field constant (green, b), the flow speed when no EMBR is used (red line, c), and the velocity setpoint (yellow, d).

The same casting sequence, with the same changes, is also seen in photos taken from a video recording of a computer simulation of the casting process 8. These snapshots show the flow speeds in the middle of the strand for three cases: FC Mold with fixed optimal magnetic field strength; FC Mold with EM Control; without FC Mold. It can be seen that FC Mold actually increases the flow speed at the meniscus. The reason for this

7 Results of a simulation of a casting sequence with curved mold, performed to illustrate the EM tool's capabilities



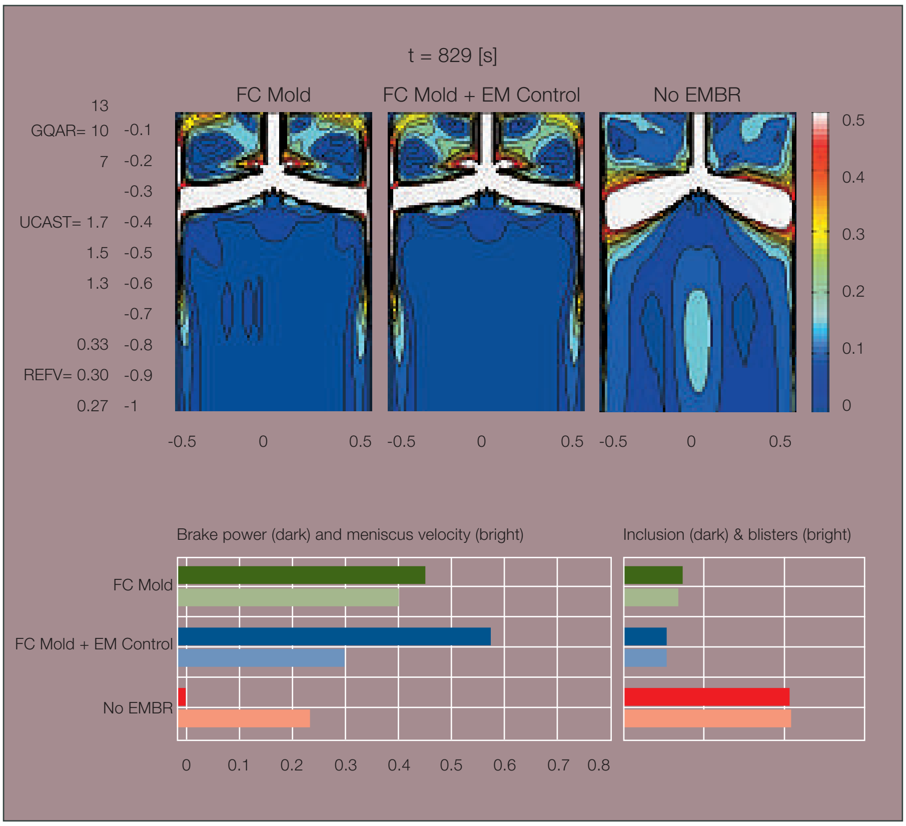
a Flow speed with EM Control active
b Flow speed with optimum fixed field strength (lower and upper fields)
c Flow speed without EMBR
d Velocity setpoint for meniscus speed

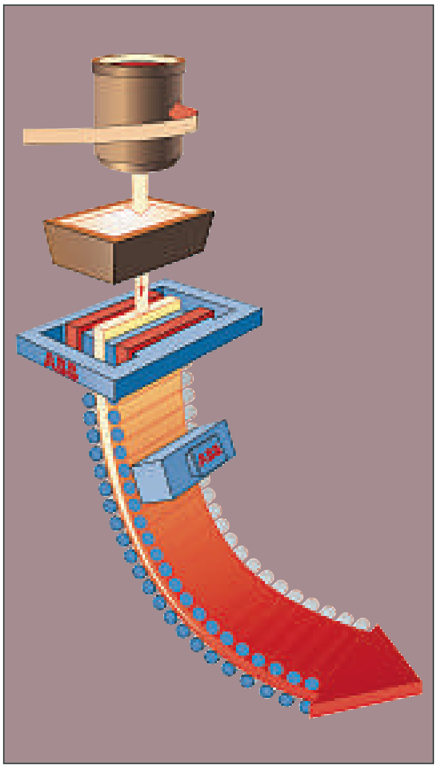
speed being less than optimal without FC Mold is that FC Mold guides the jet flow from the nozzle toward the slab's narrow sides, and only brakes hard if the meniscus flow speed becomes higher than the velocity setpoint.

The product of a substantial research effort, EM Control solves age-old problems in what is still largely a traditionally minded industry.

The graph at bottom left of 8 shows the magnetic field strength (brake power) and meniscus velocity for the three cases. Using the EM Tool, it can be calculated which inclusions will float up and disappear in the mold powder and which will become trapped in the solidification front and contribute to poorer quality. At bottom right are the calculated quality indices: a sliver index (inclusions) and a blister index (inclusions plus argon gas).

8 Flow speed in center of mold, magnetic field strength and meniscus flow speed changes (from video recording)





The more symmetrical the biased mold flow is, the better the result will be. FC Mold brakes harder at higher metal flow speeds, which tends to even out the meniscus speed differences in the mold. EM Control further enhances this already positive effect.

A leading niche product

The product of a substantial research effort that included many thousands of hours of simulations of different casting conditions, EM Control solves age-old problems in what is a largely a traditionally minded industry. As a leading niche product, being offered by ABB as a consulting service, it has considerable market potential. EM Control is expected to be ready for its market launch during the second half of 2004.

Sten G. Kollberg
ABB Automation Technologies
SE-721 67 Västeras, Sweden
sten.g.kollberg@se.abb.com

Peter M. Lofgren
ABB AB
Corporate Research
SE-721 78 Västeras, Sweden
peter.lofgren@se.abb.com