Electromagnetic braking improves steel quality in continuous casting

Electromagnetic 'braking' of the hot metal flow in the mold of a continuous casting machine improves the quality of the cast steel by reducing the penetration of non-metallic inclusions. These are especially likely to occur during high-speed casting. Numerical studies carried out at ABB Industrial Systems provide an insight into the influence electromagnetic braking exerts on the behaviour of the metal flow in the mold.

Continuous casting was developed as the answer to industry's demand for an improved steel quality and higher production rates. Instead of discrete ingots, continuous casting produces, as its name suggests, a continuous slab for rolling into sheet metal or sectional steel, etc **1**.

Continuous casting is, however, a complex process in which harmful non-metallic inclusions, such as slag or gas, can easily become entrapped in the molten metal. The risk of such 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.

To eliminate this problem, ABB developed and patented the electromagnetic brake (EMBR). The EMBR uses a static magnetic field to control the flow of hot metal in the mold, allowing a uniform casting speed and temperature to be achieved over the entire strand width **2**. By reducing the risk of non-metallic inclusions, the EMBR considerably improves the quality of the cast steel.

Although 'electromagnetic brake' has become the generic name for systems of this kind, their function is described better by the term 'electromagnetic flow controller', this name also helping to explain the apparent paradox in the statement that the 'casting speed is increased by the electromagnetic brake'. The EMBR ensures a uniform velocity for the molten steel over the entire cross-section of the strand; hence, the casting speed can be increased without any degradation of the steel slab quality.

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Various arrangements of the static magnetic fields have been tested, and some major improvements have been achieved through this work. However, the tests are costly and time-consuming; furthermore, the ambient conditions pose a problem. In view of this, ABB Industrial Systems has focused its attention on developing theoretical models for computing the flow behaviour with different field coil arrangements [1, 2].

With the help of a developed turbulence model for the steady-state condition in the strand, three different EMBR configurations were studied **3**:

I *Conventional EMBR*, in which two magnetic fields are placed and act locally across the strand width.

II *EMBR Ruler*, in which one magnetic field covers the entire strand width.

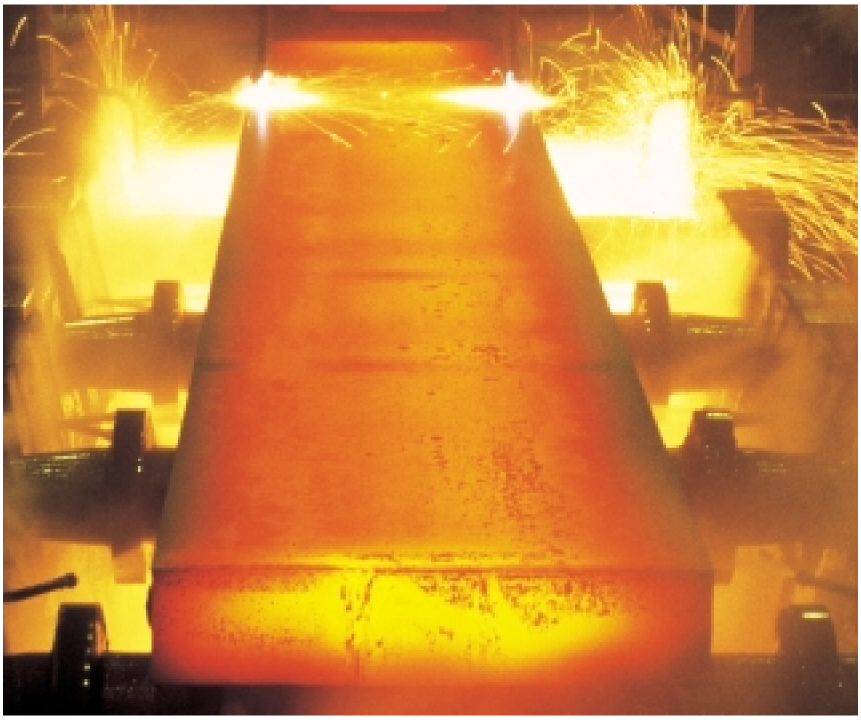
III *FC Mold* (Flow Control Mold); here, the entire width of the strand is covered by two parallel magnetic fields, with the nozzle for the molten steel lying between them.

The mathematical model was verified by comparing the computed fluid flow with results from full-scale measurements in different installations.

Conclusions drawn from the numerical studies

The most important results of the studies can be summarized as follows:

- The argon gas and the static magnetic field have a considerable influence on the molten steel flow in the strand. Electromagnetic braking is most effective at improving the flow field when the jet of steel is directed towards the zone covered by the magnetic field.
- Non-metallic inclusions penetrating deep into the center of the slab are reduced by the magnetic field configuration acting on the full strand width as compared with the configuration with two magnetic fields acting locally.
- The temperature at the meniscus is raised by 5–15 °C when electromag-



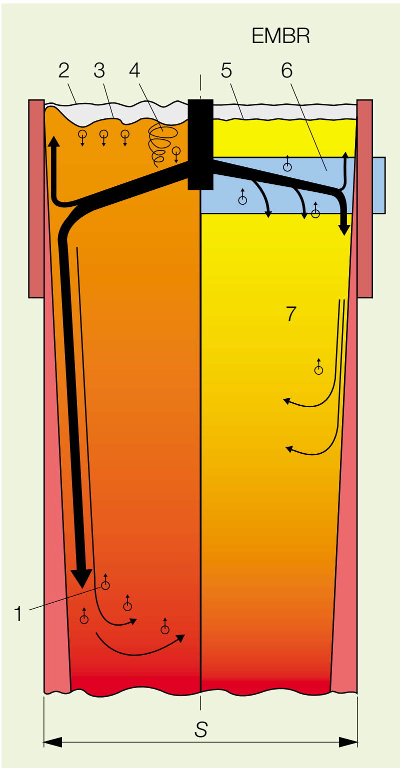
Continuous slab casting in the SSAB steelworks in Luleå, northern Sweden **1**

netic braking is used. When casting wide slabs at a low speed it is possible that the power will have to be reduced with the EMBR Ruler, since the steel flow at the narrow faces of the slabs could become stagnant if the braking effect is too strong. Under certain circumstances, this might reverse the desired effect, ie, the temperature becomes too low and the molten steel at the meniscus freezes.

- The action of a static magnetic field in the mold will often cause a strong reduction in the average velocity of the steel directly below the meniscus.

With the FC Mold configuration, in which the nozzle lies between the two parallel magnetic fields, limited 'braking' of the jet occurs in the direction of the narrow faces, resulting in a smaller reduction in the average velocity at the meniscus. This configuration has the advantage that the steel flow from the narrow faces towards the nozzle can be maintained.

- The depth of the jet's penetration is reduced with all three configurations compared with 'unbraked' casting. However, the optimum flow and steel quality are largely dependent on the arrangement and the strength of the magnetic field.
- The tendency for low-frequency, high-amplitude oscillation to occur at the meniscus is suppressed very effectively by the action of the static magnetic field in the mold. The risk of mold powder being pulled downwards with the flow is reduced, since such pull-down is the result of high acceleration and a high average velocity of the flow at the meniscus.
- Further areas of application for electromagnetic braking in continuous casting may be expected in the context of smaller strand sizes: the reduced penetration depth of the steel jet and the higher sub-meniscus temperature have a positive effect on the quality of the steel. With the help of the EMBR it should therefore be possible in the future to use significantly higher casting speeds without the quality being degraded. This has special advantages for the casting of thin slabs.

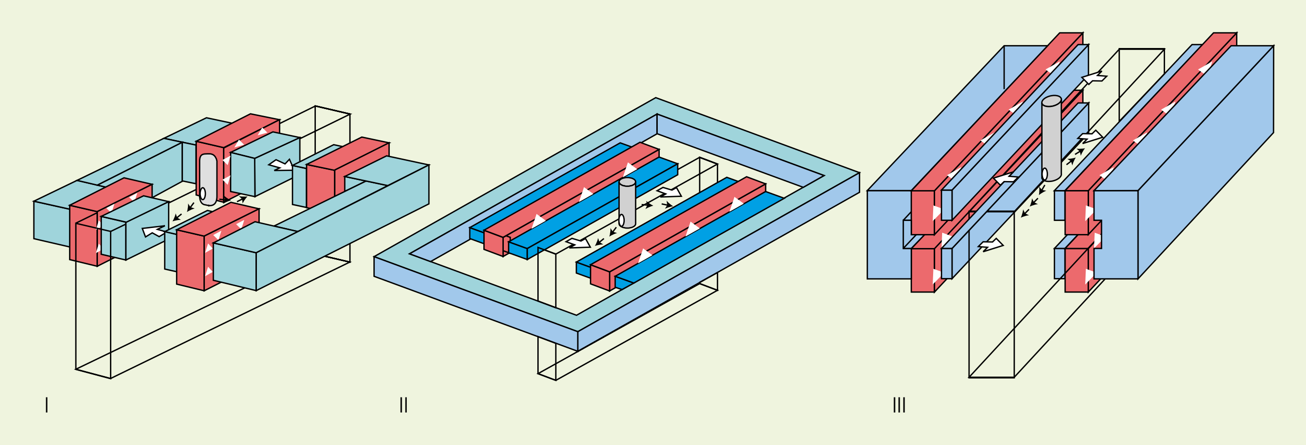


Flow in a continuously cast strand without EMBR (left) and with EMBR (right) **2**

S Strand width

Without EMBR
1 *Deep penetration of non-metallic inclusions*
2 *Mold powder layer*
3 *Disturbed meniscus*
4 *Vortices*

With EMBR
5 *Calmer, hotter meniscus*
6 *Braked area*
7 *Reduced penetration depth of non-metallic inclusions*



Configurations of the electromagnetic brake (EMBR) **3**

I *Conventional EMBR: two magnetic fields are placed and act locally across the strand width*
II *EMBR Ruler: one magnetic field covers the entire strand width*
III *FC Mold: two parallel magnetic fields cover the entire strand width; nozzle opening between fields*

Conventional EMBR – local magnetic fields

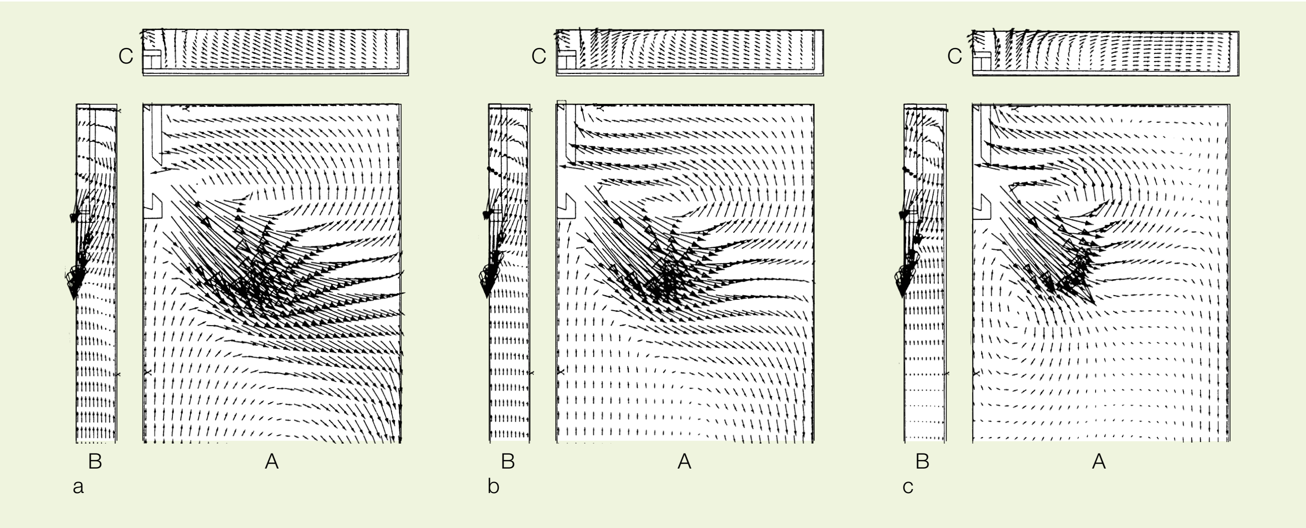
In the first-generation EMBR two magnetic fields were placed and act locally across the strand width **3**. It was developed to suppress deep penetration of the molten steel flow in the strand as well as to reduce the number of non-metallic inclusions. Generally, the results of measurements have shown that this configuration reduced the penetration depth by up to 50 percent, while the temperature just below the meniscus rose by 5 to 10 °C. However, there is a risk of the flow stagnating when the full braking power is applied. What is more, when casting narrow slabs a single, main flow channel caused by the zero magnetic

Basic EMBR configuration: calculated flow field at cross-sections* A, B *and* C *for different flux densities B of the local magnetic fields **4**

A *Cross-section in middle of strand*
B *Cross-section 100 mm from nozzle towards narrow face of strand*
C *Cross-section 20 mm below meniscus*

a $B = 0$ T
b $B = 0.16$ T
c $B = 0.32$ T

Strand size 245×1600 mm
Casting speed 1.6 m/min
Submerged nozzle depth 190 mm
Nozzle outlet angle –45°
Specific meniscus power 75 kW/m²
Argon gas flow 10 l/min
Superheat temperature 10 °C

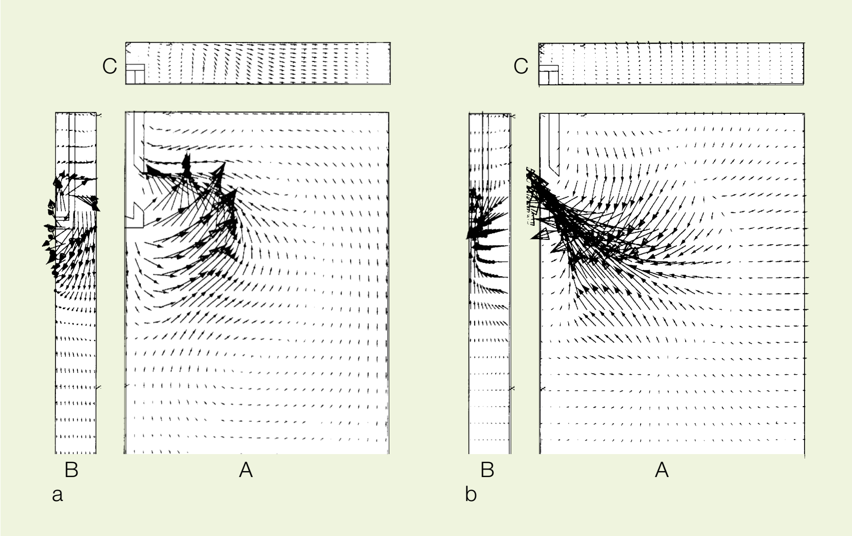


field in the middle of the strand sometimes causes an increase in the non-metallic inclusions entrapped in the solidified shell. This underscores the importance of carrying out simulations to determine the optimum configuration for EMBRs.

The calculated three-dimensional flow is shown in **4**, the induced currents and Lorentz forces in **5**.

EMBR Ruler – one magnetic field covers the entire strand width

The second-generation EMBR, known as the EMBR Ruler **3**, uses one magnetic field which acts on the entire strand width. The first EMBR of this type was in-



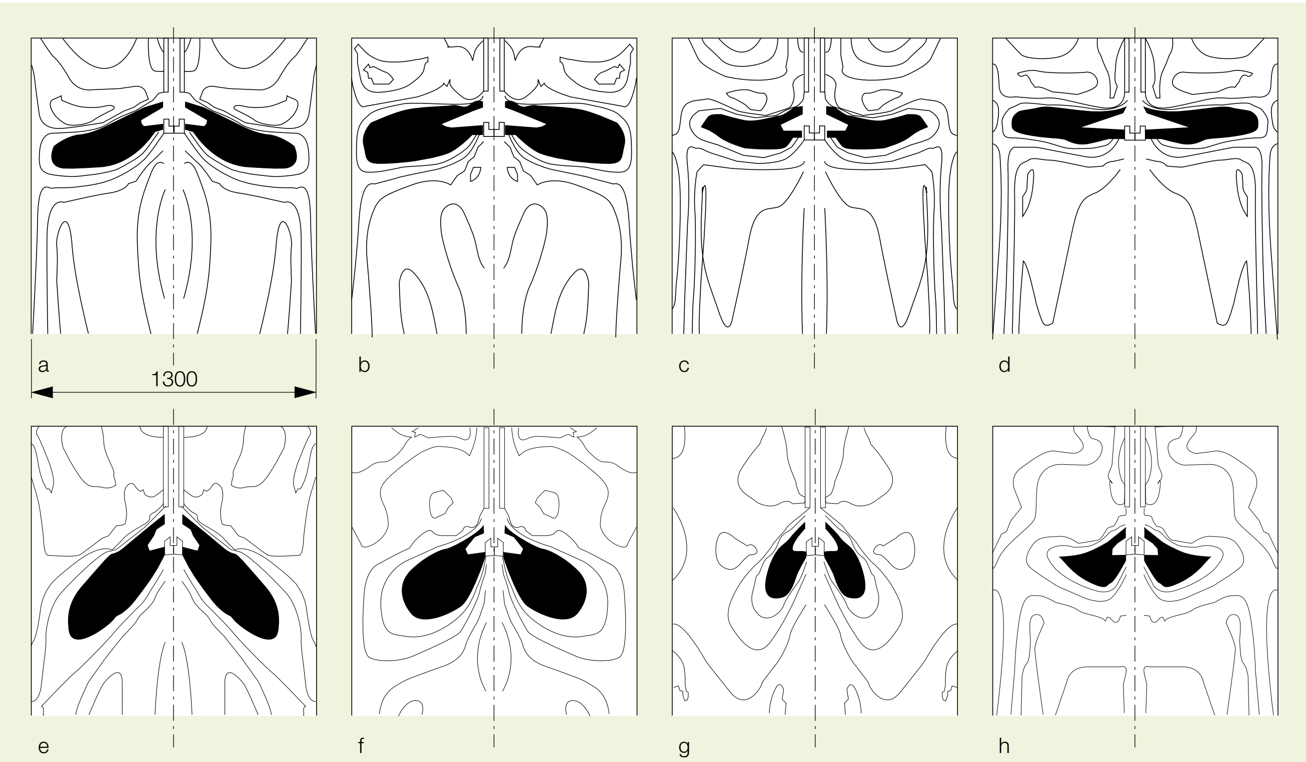
Induced currents (a) and Lorentz forces (b) in cross-sections* A, B *and* C *with local magnetic fields. **5**
The casting data is the same as in Fig. 4, however, with a magnetic flux density of 0.32 T

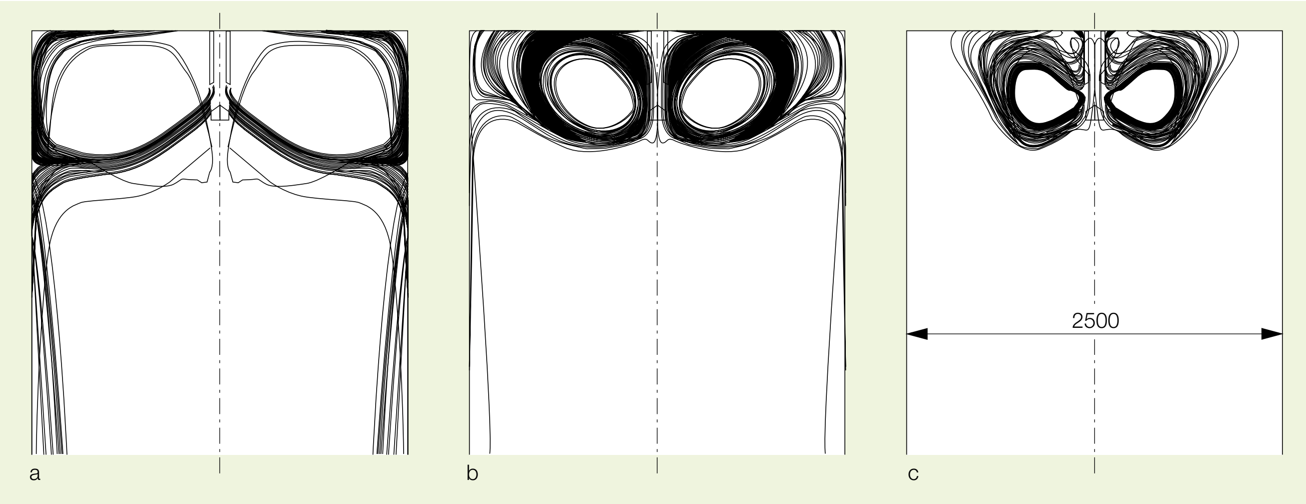
EMBR Ruler: absolute velocity maps in the cross-section through the middle of the strand. The velocity in the black regions is 0.4 – 1.0 m/s. **6**

Submerged nozzle depth 150 mm, nozzle outlet angle 0°
- a *EMBR off, argon gas flow 0*
- b *EMBR off, argon gas flow 10 l/min*
- c *EMBR on, argon gas flow 0*
- d *EMBR on, argon gas flow 10 l/min*

Submerged nozzle depth 250 mm, nozzle outlet angle –30°
- e *EMBR off, argon gas flow 0*
- f *EMBR off, argon gas flow 10 l/min*
- g *EMBR on, argon gas flow 0*
- h *EMBR on, argon gas flow 10 l/min*

Data valid for all maps:
Strand size 225×1300 mm
Casting speed 1.5 m/min
Specific meniscus power 75 kW/m²
Superheat temperature 20 °C
Max. flux density 430 mm below meniscus 0.3 T





EMBR Ruler: tracking of 200-μm particles in the middle of the strand for a magnetic flux density of 0 T (a), 0.15 T (b) and 0.30 T (c) **7**

Strand size 250×2500 mm
Casting speed 0.9 m/min

Submerged nozzle depth 225 mm
Nozzle outlet angle –20°

Specific meniscus power 150 kW/m^2
Argon gas flow 5 l/min
Superheat temperature 15 °C

stalled in 1991 at the *Sollac* casting plant in Dunkirk, France, and at *Hoogovens* in IJmuiden, Holland.

The impact of the amount of argon gas and the depth of the submerged nozzle on the absolute velocity is shown in **6**.

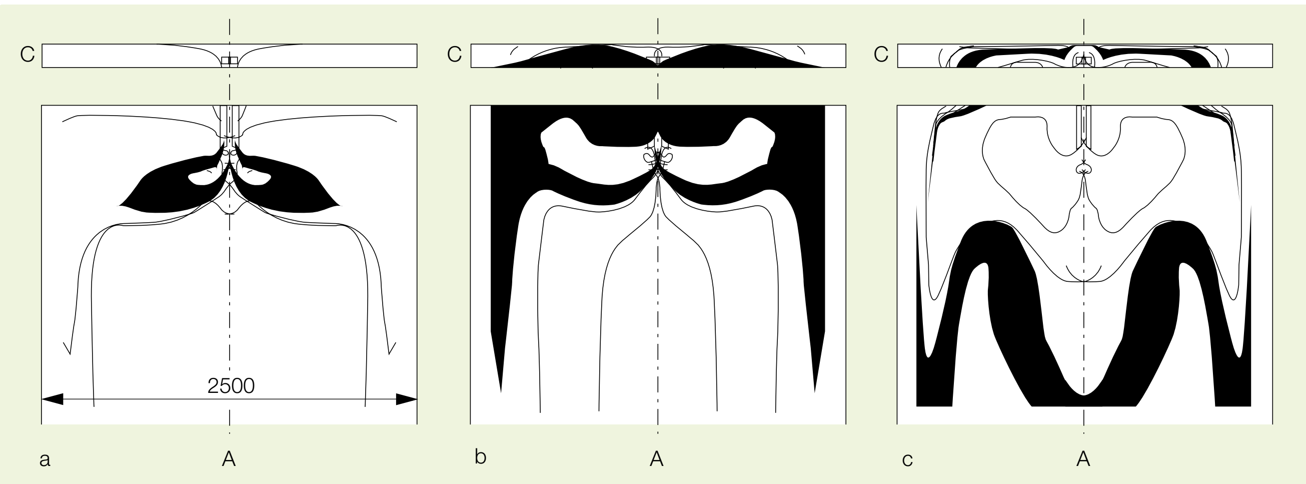
If the submerged nozzle is located at a shallow depth and the outlet flow is almost horizontal, the fluid flow will tend to float above the magnetic field region. Increasing the depth of the nozzle and pointing the nozzle further downwards causes the molten steel to penetrate the magnetic field region direct, resulting in effective braking of the nozzle jet. If the EMBR is positioned too high, however, argon gas bubbles may collect close to the nozzle. As a rule, the EMBR Ruler increases the temperature at the meniscus by 5 to 15 °C.

Calculations and field measurements have shown that a static magnetic field in the mold can be used to control the flow at the meniscus. If there is no EMBR, the flow is normally determined by the slab size, casting speed, amount

Temperature maps for a 2500 mm wide strand, with EMBR Ruler; the magnetic flux densities are 0 T (a), 0.15 T (b) and 0.30 T (c).
The superheat temperature in the black region is 6–8 °C (casting data, see Fig. 7). **8**

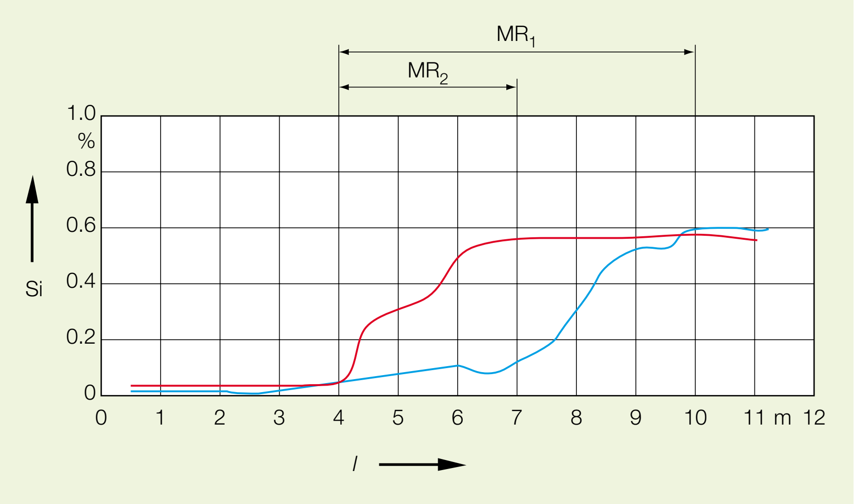
A *Cross-section in middle of strand*

C *Cross-section 20 mm below meniscus*



Reduction in mixing zone from 6 to 3 m during a grade change at Preussag Stahl AG in Salzgitter, Germany, without EMBR (blue) and with EMBR (red) **9**

l *Strand length*
Si *Silicon content*
MR_1 *Mixing zone without EMBR*
MR_2 *Mixing zone with EMBR*



of argon gas and configuration of the nozzle. The velocity at the meniscus can be controlled when an EMBR is installed. Usually, a reduction in the velocity is desired. However, excessively strong braking can reverse the flow, directing it from the submerged nozzle towards the narrow faces. The risk of solidification is increased by the difficulty involved in predicting when the flow at the meniscus will reverse.

200-µm particle tracking is shown in **7**, the temperature maps for a 2500 mm wide slab being given in **8**. In **8**, the flow close to the narrow faces has become almost stagnant at full braking power.

If the superheat temperature is low there is a risk of freezing at the narrow faces of the meniscus. To prevent this happening either the magnetic flux density has to be reduced, the casting speed increased or the nozzle opening made smaller.

The EMBR has also proved to be very effective at suppressing the penetration depth of inclusions. As measurements at *Preussag Stahl* in Salzgitter, Germany, have shown, electromagnetic braking reduces the mixing zone that occurs in the strand during grade changes **9**.

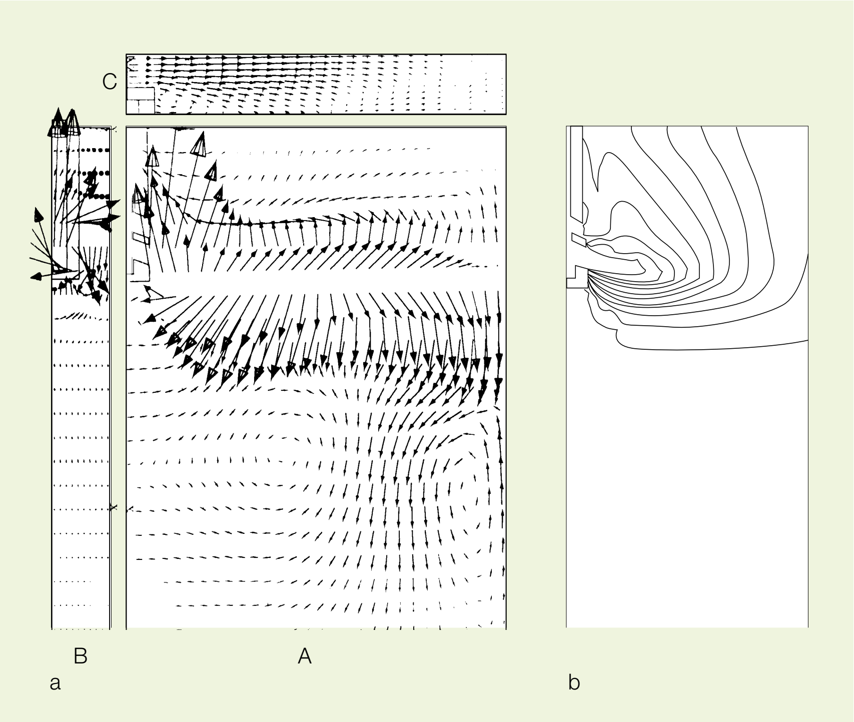
FC Mold – two parallel magnetic fields cover the entire strand width

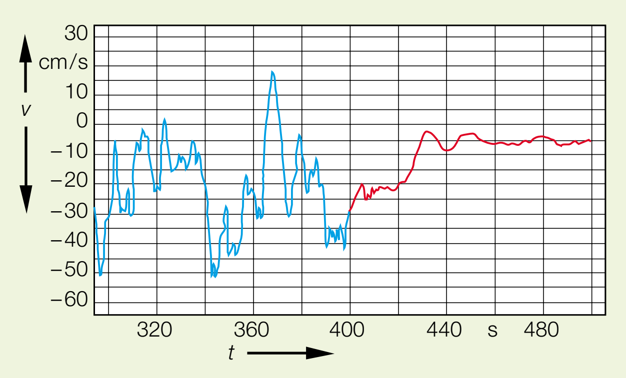
The FC Mold configuration **3** was developed by Kawasaki Steel Corporation of Japan in collaboration with ABB. Its main features are two parallel magnetic fields

FC Mold configuration: currents induced in cross-sections A, B and C (a) and argon gas void fraction in cross-section A (b).
Flux density 0.3 T.
The four outlets of the nozzle lie between the two magnetic fields. Although the magnetic flux density is relatively low and the induced currents flow in different directions, the penetration depth of the inclusions is reduced by up to 50 percent.
Field results verify this. **10**

A *Cross-section in middle of strand*
B *Cross-section 100 mm from nozzle towards narrow face of strand*
C *Cross-section 20 mm below meniscus*

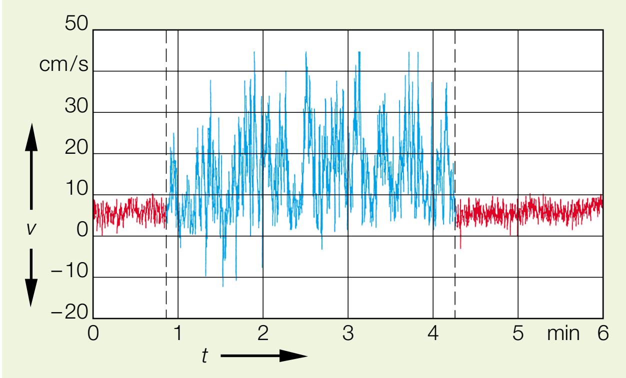
Strand size 260×1700 mm
Casting speed 1.7 m/min
Submerged nozzle depth 200 mm
Nozzle outlet angle –20°
Specific meniscus power 75 kW/m²
Argon gas flow 16 l/min
Superheat temperature 25 °C





Velocity v at meniscus without EMBR (blue) and with EMBR (red), calculated with the help of the LES model **11**

Strand size 50×1300 mm
Casting speed 5.5 m/min



Measured velocity v at meniscus, without EMBR (blue) and with EMBR (red) **12**

Strand size 225×2100 mm
Casting speed 1.3 m/min

that act on the full width of the strand in the mold. The induced currents in the molten steel and the argon gas void fraction when the FC Mold arrangement is used are shown in **10**.

Although the magnetic flux density is relatively low and the induced currents have different directions, the penetration depth has been reduced by up to 50 percent. The average sub-meniscus velocity is not reduced very much, but the braking efficiency can be controlled, as with the EMBR Ruler, by changing the depth and outlet angle of the submerged nozzle.

Results with the transient model

A static magnetic field is effective at reducing the low-frequency, high-amplitude oscillations in the mold. In contrast to the temperature rise, which takes place only after about 2 minutes, the damping of the oscillation becomes noticeable immediately after the EMBR is switched on. The calculated sub-meniscus velocity 325 mm from the middle of the strand is shown in **11**.

Field measurements from several EMBR installations have confirmed the effective damping of the oscillations. For example, the *Hoogovens* casting plant in the Netherlands **12** reported a striking reduction in both the average velocity and the oscillations. This reduction considerably lessens the risk of mold powder entrapments.

Physical and mathematical principles applying to the models

The following two mathematical models were developed for the purpose of predicting the effect of electromagnetic braking on the molten steel flow:

Steady-state turbulence model. This is used to determine the average steel flow in the strand for different configurations, and takes account of the lifting force of the argon gas in the molten steel as well as the distribution of inclusions under different electromagnetic field conditions. The three-dimensional magnetic field was computed using the TOSCA code from Vector Fields and subsequently employed in the Harwell Flow3D flow simulation program.

Transient LES model. A so-called transient LES turbulence model (LES stands for Large Eddy Simulation) is used to study the influence of electromagnetic braking on the oscillation of the meniscus.

References

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[2] G. Tallbäck et al: Simulations of EMBR influence on fluid flow in slabs. 17th Advanced Symposium 1994, Phoenix, AZ/USA, Report GRT 40681 (1994).

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