IMPROVED QUALITY AND PRODUCTIVITY IN SLAB CASTING BY ELECTROMAGNETIC BRAKING AND STIRRING[1]

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Abstract
Increasing the productivity and improving the product quality are today permanent demands in the continuous casting process. Many serious quality problems, including non-metallic inclusions and gas bubble entrapments, are directly associated with the flow pattern in the mold. The molten metal flow in the mold is influenced by many variables, including the nozzle design and submerged depth, mold geometry, steel flow rate and argon injection rate. Various electromagnetic actuators have been developed to control the flow pattern in the mold. Especially during recent years this technology has gained extensive interest from many steel plants all over the world. The purpose of this paper is to describe today's existing electromagnetic technologies, discuss optimum flow conditions based on actual plant results and numerical simulations, and finally serve as a guideline for the selection of the ideal electromagnetic devices for various casting practices.
Keywords: Electromagnetic stirring; Electromagnetic braking; Continuous casting; Defects; Mold flow; Flow pattern; Inclusion removal.

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INTRODUCTION

Increasing the productivity and improving the product quality are today permanent demands in the continuous casting process. Many serious quality problems, including non-metallic inclusions and gas bubble entrapments, are directly associated with the flow pattern in the mold.[Erro! Fonte de referência não encontrada.]
The fluctuations at the meniscus level increase with increased casting speed and reduced mold thickness.[Erro! Fonte de referência não encontrada.] For thin slab casting the turbulence is very pronounced and the use of an ElectroMagnetic BRake (EMBR) is today state-of-the-art technology for high-productivity casters. The result is suppression of the fluctuations and stable casting conditions in the meniscus area.
Conventional slab casting is more complex. It is important not only to assure stable flow conditions at an optimum meniscus flow velocity for improved surface and subsurface quality but also to minimize the downward flow from the submerged entry nozzle (SEN) in order to reduce the internal non-metallic inclusions and gas bubbles being entrapped in the solidified shell. The challenge of optimum fluid flow in conventional slab casting has been addressed by different technologies and different companies over the last decades. Today mainly four technologies remain.

DIFFERENT TECHNOLOGIES

M-EMS

Nippon Steel Corporation (NSC) in Japan has developed an in-mold electromagnetic stirrer, M- EMS, consisting of four part stirrers, two on each wide side of the mold, placed high in the mold.[Erro! Fonte de referência não encontrada.] Two part stirrers are electrically connected cross-wise to two frequency converters in order to facilitate different Lorentz force combinations along the meniscus level. The M-EMS creates a circulating meniscus flow (Figure 1), resulting in less non-metallic inclusions entrapped in the initial solidified shell and an improved shell growth homogeneity and thus a decreased number of longitudinal cracks. The M-EMS is installed at most NSC slab casters and in some cases also in combination with an EMBR field at the bottom of the mold.

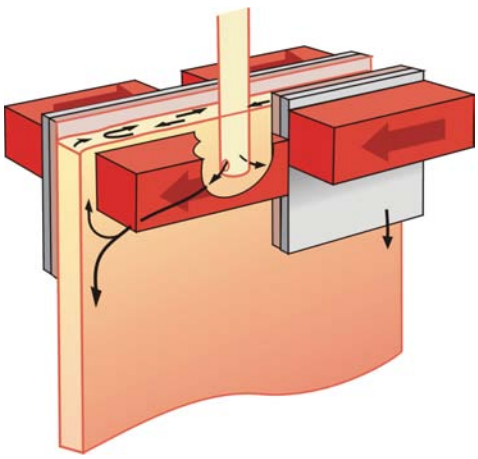

Figure 1. M-EMS

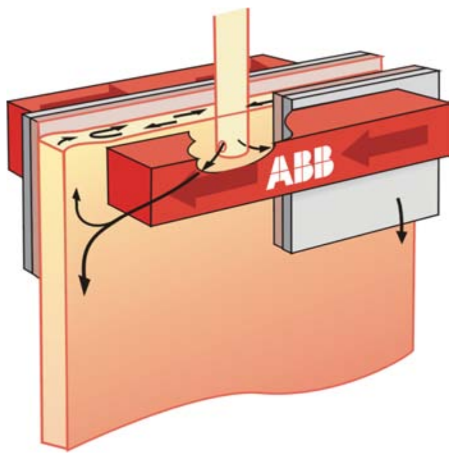

Figure 2. FC MEMS

FC MEMS

The ABB FC MEMS consists of two part stirrers, one on each wide side of the slab, placed high in the mold and controlled from one common frequency converter,[4} (Figure 2). A longer pole pitch of the coil makes it possible to achieve a stronger magnetic flux distribution in the mold and to maintain normal copper thickness, and with the benefit of reasonably low power consumption. The FC MEMS creates a circulating meniscus flow (Figure 2), resulting in less non-metallic inclusions entrapped in the initial solidified shell and an improved shell growth homogeneity and thus a decreased number of longitudinal cracks. The FC MEMS is intended for low to medium speed casters and is also recommended for crack sensitive grades, i.e. peritectic steel grades, and for wider strands.

MM-EMS (Multi Mode EMS)

The MM-EMS consists of four stirrers, located in the middle of the mold, two on each wide side of the slab mold,[5] (Figure 3). The stirrers on the right and on the left respectively are series connected and each fed by one frequency converter. The stirrers are normally operated in two different modes.

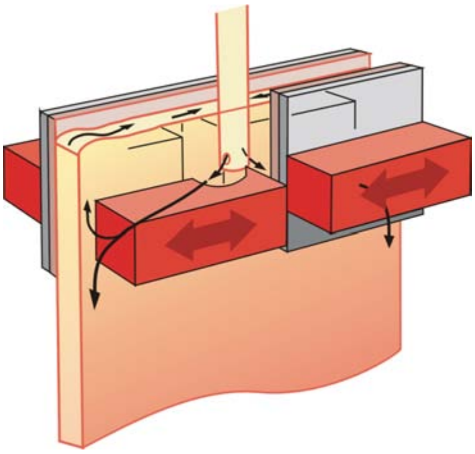

Figure 3. MM-EMS

EMLS-mode[6,7] (stabilizing) is used for high speed casting when the meniscus velocity is too high. The force of the stirrers is then directed towards the SEN and counteracts the metal jets, reducing the velocity of these jets and thereby also the meniscus velocity.
EMLA-mode[7] (accelerating) is used for low speed casting when the inertia in the jets from the SEN is not sufficient to reach the minimum meniscus metal flow velocity required. The force of the stirrers is then directed towards the narrow faces, accelerating the steel in the center of the mold and increasing the meniscus flow velocity.
EMRS-mode (stirring) is a third mode that is intended to rotate the steel in the middle of the mold. However, it is not clear from the literature what the effect is and whether new mold powder inclusions appear with this low position in the mold[5] nor when it is intended to be used.

FC Mold

The FC Mold uses two static magnetic fields, an upper field at the slab meniscus level to control the meniscus metal flow velocity and a second independently controlled lower field at the bottom of the mold to minimize the penetration depth of the steel jets from the SEN.[6,8] Simultaneous and independent control of the meniscus flow speed and the penetration can only be achieved by the FC Mold.

The FC Mold is a tool for medium to high speed casting. The metal jets from the SEN is braked by the DC magnetic field and when reaching the narrow sides one flow path will turn up towards the meniscus and the upper field can then control this flow velocity. The second flow path will turn downwards and the lower field will minimize the penetration down into the slab. The FC Mold can also be used to increase the metal flow velocity at meniscus, should this velocity be lower than optimal. This is the most common electromagnetic device with totally 35 strands equipped or sold up to today.

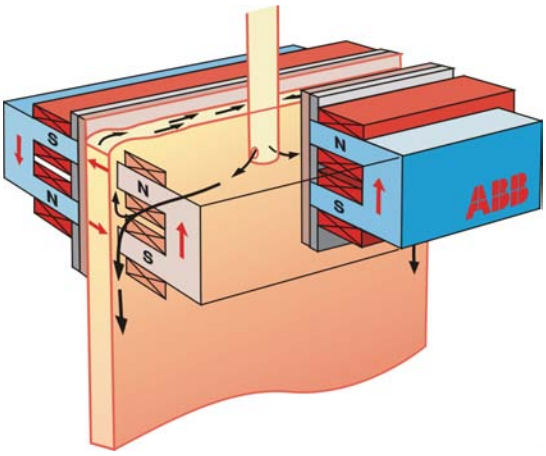

Figure 4. FC Mold

OPTIMUM FLOW IN MOLD

From a theoretical point of view an optimal flow in the mold can be defined. The aim is to minimize internal and surface defects and thus achieve superior metallurgical results.

Enhancing Internal Quality

Inclusions coming out from the SEN will either float up to the meniscus or follow the steel flow and later be trapped in the solidified shell. The penetrating flow velocity of the steel jets from the SEN should be kept as small as possible in order to minimize inclusions being brought deep down into the strand (Figure 6). This penetrating flow increases with increasing casting speed. The entrapment of inclusions causing internal defects is usually a problem, especially for medium to high speed casting. A special concern is the internal quality of IF steel grades. The major problem related to the production of these grades is the formation of blister and sliver defects appearing in the final product after cold rolling and annealing operations.[9,10]. Inclusions and gas bubbles can be entrapped in a solidifying liquid by engulfment and entrapment and a good control of the steel flow in the mold is essential to improve the situation.[11]

Therefore the flow control device should ideally minimize the penetrating flow velocity for medium to high speed casters, especially for IF steel grades, and at the same time promote a high temperature at the meniscus level.

Enhancing Surface and Subsurface Quality

The meniscus flow velocity, on the other hand, should be kept in a certain range (Figure 5). It should be kept stable and not varying, neither in absolute velocity over time nor the swaying from the left- to the right-hand side of the SEN, i.e. biased flow. The flow from the SEN can ideally be characterized as single or double roll or, via a stirrer, a rotational stirring pattern at the meniscus. However, what is important is to secure a stable flow pattern for an efficient washing of non-metallic inclusions to prevent them from being entrapped in the solidified shell.[**Erro! Fonte de referência não encontrada.**] A stable flow will also homogenize the temperature of the molten steel in the mold, thus preventing longitudinal cracks and minimizing the hook depth. This is specifically essential for crack sensitive steel grades such as peritectic steel grades. Particularly inclusions with a size of 200 µm or more are entrapped by the hook structure of the initial solidification of ULC steel. By increasing the temperature in the meniscus area this hook can be suppressed.[6] An insufficient flow velocity results in an increased risk of entrapment of inclusions causing subsurface defects and cracks. On the other hand, an excessive flow velocity results in mold powder entrapments. The ideal flow control device should therefore keep the meniscus flow velocity at a constant level for various casting conditions and promote a temperature increase at the meniscus area. The literature usually specifies this velocity to be around 0.2-0.4 m/s.

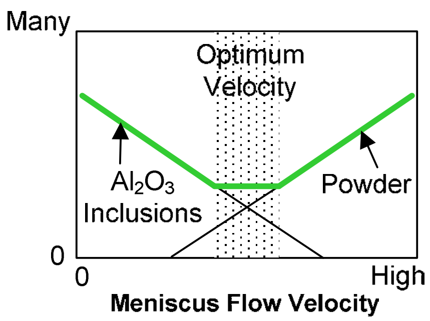

Figure 5. Meniscus flow velocity

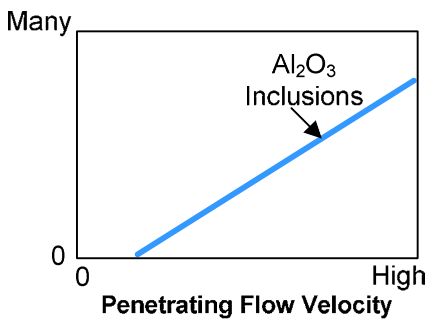

Figure 6. Penetration flow velocity

METALLURGICAL RESULTS

For the different types of MEMS described above there are a number of publications that present metallurgical results.[3-11] There are increasing demands on productivity, i.e. higher throughput, as well as an increased use of argon. This means that there is an increased risk of deterioration in quality. These problems can be addressed with the help of the FC Mold, which lowers turbulence in the steel, controls the meniscus metal flow velocity and minimizes the steel penetration into the strand. The meniscus level fluctuations have therefore been measured as a function of time with and without the FC Mold (Figure 7). The result is a very stable meniscus profile when using FC Mold.

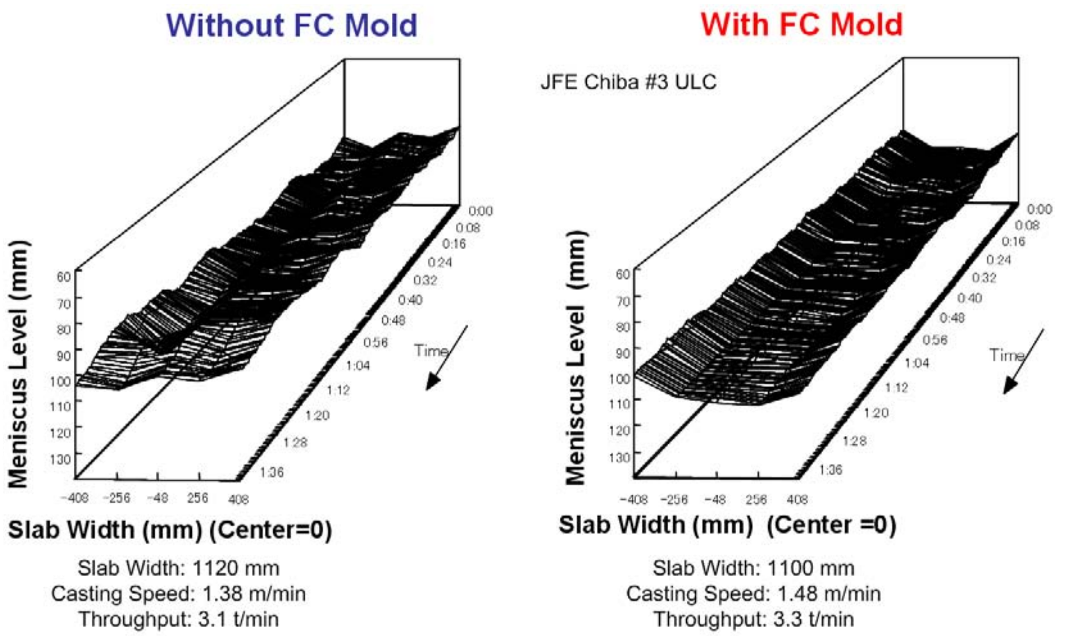

Figure 7. Meniscus shape measured by thermocouples in the Cu plates is more stable with FC Mold

The production results for hot rolled coils are summarized in Figure 8, where an index of surface defects is presented. It is evident that when the production rate reaches a certain level, the end product quality is greatly impaired unless an FC Mold is used. This allows for a higher production rate without resulting in quality downgrading. A dramatic increase in end product quality can be achieved for the same production rate.

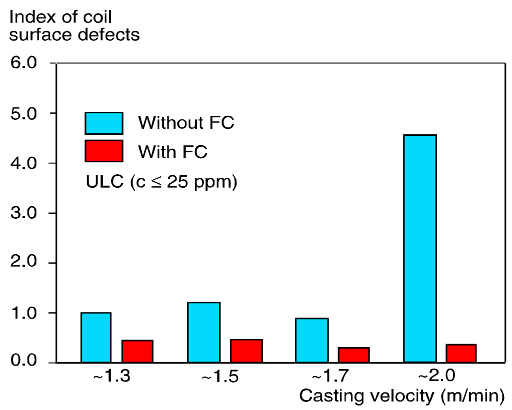

Figure 8. Reduced reject ratio with FC Mold

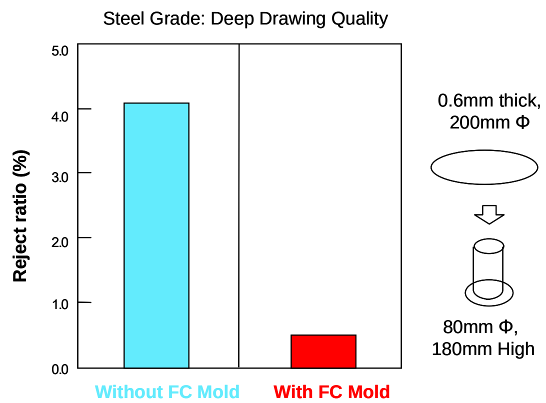

Figure 9. Rejection ratio for two-piece cans is substantially reduced with FC Mold

Rejection ratios on final products with and without an FC Mold have also been evaluated. Figure 9 shows rejection ratios from the manufacturing of two-piece cans, a process that is very sensitive to inclusions. This shows that the rejection ratio is substantially reduced when FC Mold is applied.

Thanks to the possibilities of individual control of the fields, the FC Mold can not only brake, but also accelerate the steel flow at the meniscus. This has been verified at JFE as well as at Meishan.

COMPUTER SIMULATIONS

Computational Methods

Over the years, ABB has conducted a great deal of experimental and computational work to optimize the use of electromagnetic solutions for different casting situations. Metallurgical feedback from installations in combination with ABB's 3D computer simulations of the electromagnetic fields and the fluid flow, EM Tool, has resulted in a good understanding of how the different technologies work and how to optimize them.
The EM Tool is a computer program system characterized by the following characteristics:

- 3-D computer program for calculation of AC and DC electromagnetic fields.
- 3-D transient 2-phase Reynold Stress Turbulence fluid metal flow simulation model incorporating argon gas flow, electric potential, electromagnetic fields and Lorenz forces.
- Transport equation for the anisotropy of the turbulence caused by the magnetic field.[Erro! Fonte de referência não encontrada.,Erro! Fonte de referência não encontrada.]

Measurements from real steel work on-site slab caster installations as well as a physical water model are used to validate the results of the simulations.

Medium to High Speed Casting

Braking & Accelerating

The static magnetic field of the FC Mold is used to control the flow speeds of the molten metal in the slab caster. The strong lower field minimizes the penetration down into the slab. The upper field acts as a brake and controls meniscus metal flow speeds. A properly optimized combination of upper and lower fields can also be used to accelerate the meniscus metal flow. In such an arrangement, the lower field bends the nozzle jet flow toward the meniscus along the narrow side of the strand at the same time as the upper field strength is reduced to allow a stronger meniscus flow.
Figure 10 shows a time averaged computer simulation result of 180 s of meniscus metal flow in a slab caster of strand size 200x1500 mm with a casting speed of 2.2 m/min, an Argon flow rate of 10 L/min and a SEN angle of -15°. The flow pattern without an electromagnetic device gives a high meniscus velocity reaching peaks of 0.55 m/s and an unstable meniscus wave with a substantial amplitude. The FC Mold slows down the flow to an optimum meniscus speed, which stabilizes the meniscus and prevents mold powder entrapments.

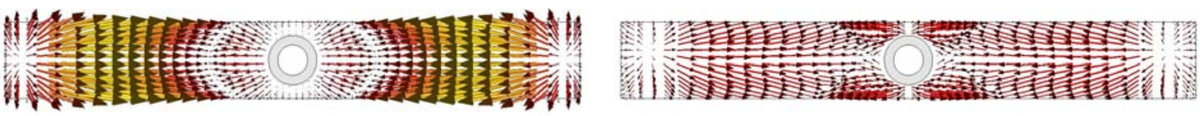

Figure 10. Meniscus metal flow velocities, no electromagnetic device (left), FC Mold controlling the meniscus flow (right).

Figure 11 displays the time averaged meniscus metal flow velocities in a slab caster of strand size 210x1500 mm with a casting speed of 1.2 m/min, an Argon flow rate of 7 L/min and a SEN angle of 0°. Without an electroma gnetic actuator, the meniscus flow is weak. With proper upper and lower FC Mold magnetic fields, the flow from the narrow sides toward the SEN can be accelerated, thus leading to a decreased risk of freezing and inclusion entrapments.

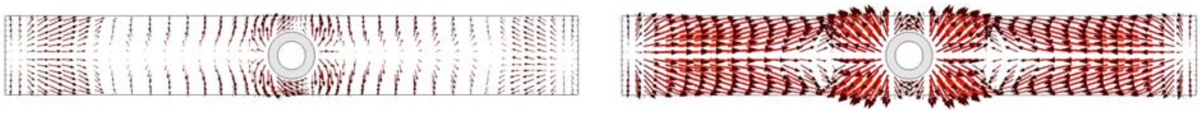

Figure 11. Meniscus metal flow velocities, no electromagnetic device (left), FC Mold accelerating the meniscus flow (right).

Meniscus Stabilization

The upper static magnetic field of the FC Mold is an effective turbulence reducer that stabilizes meniscus flows and fluctuations. The curves in Figure 12 show the simulated meniscus height fluctuations along the center line of the meniscus for a 200x1500 mm slab, at a casting speed of 2.2 m/min, Argon flow rate of 10 L/min and SEN angle -15°. The standard deviation of the fluct uations is calculated over a period of 180 s. It is clear that the wave height of the fluctuations is drastically reduced when the FC Mold is applied to stabilize the meniscus. This ensures improved surface and subsurface quality.

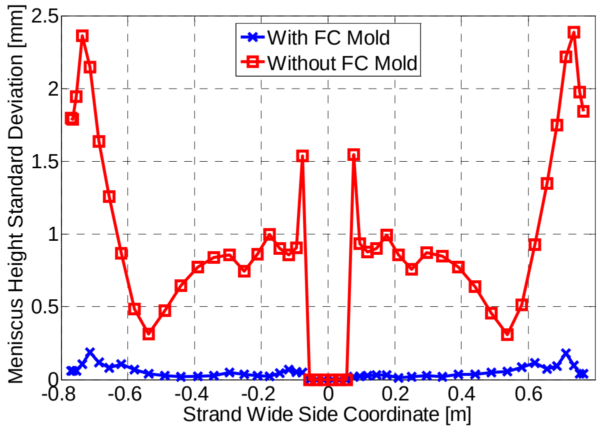

Figure 12. Standard deviation of height fluctuations along the meniscus center line.

Low to Medium Speed Casting

Meniscus Acceleration

The meniscus flow at low casting speed is often too weak for a sufficient homogenization of the melt temperature distribution in the critical initial shell growth regions. The risk of entrapment of inclusions causing subsurface defects is also imminent with a low meniscus metal flow speed. Figure 13 displays the calculated increase of the meniscus flow speed with a 1500 mm long FC MEMS compared to casting without an electromagnetic actuator. The slab caster strand format is 250x2000 mm with a casting speed of 0.7 m/min, an Ar flow of 6.1 L/min and a SEN angle of -15°.

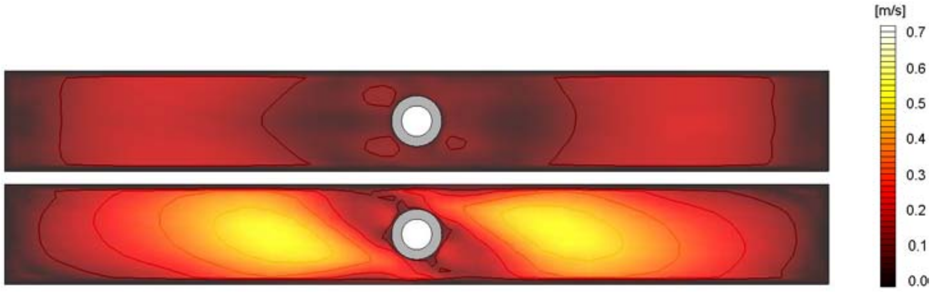

Figure 13. Meniscus metal speeds, no electromagnetic device (top), FC MEMS increasing meniscus velocity (bottom).

The results exhibit an increase in meniscus flow speeds with an FC MEMS. In areas close to the SEN, the FC MEMS prevents flow stagnation. The flow speed distribution at the same casting conditions is quantified in Figure 14 which shows the simulated tangential flow speed 10 mm inside one of the wide sides of the strand at the meniscus.

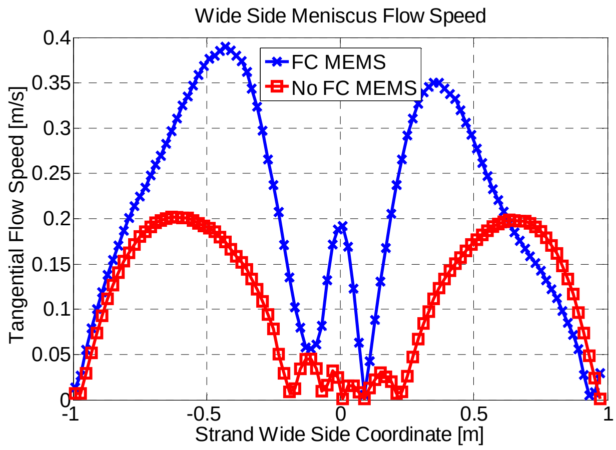

Figure 14. Meniscus velocities 10 mm inside wide side of strand.

These results indicate that the FC MEMS doubles the meniscus flow speed at the solidification front, thus ensuring temperature homogenization and preventing non-metallic inclusions from being entrapped in the solidifying shell. In areas close to the SEN, the FC MEMS prevents flow stagnation.

Importance of Stirrer Position

The stirring obtained from an AC device depends strongly on the location of the stirrer. The electromagnetic force on the molten steel is greatest with as much molten steel as possible close to the stirrer. However, the combination of the stirring force and the inertia of the SEN jets will define the flow pattern in the melt.

The schematic in Figure 15 illustrates a stirrer center line displacement Δx where the stirrer location has been varied vertically with respect to the meniscus level. Computer simulations have been carried out for different stirrer locations. Figure 16 presents the resulting time averaged meniscus flow speeds for a 1500 mm long stirrer applied with center line 0, 100, 200, 300 and 400 mm below meniscus. The strand format is 250x2000 mm, with casting speed 0.7 m/min, Argon flow rate 6.1 L/min and SEN angle -15°.

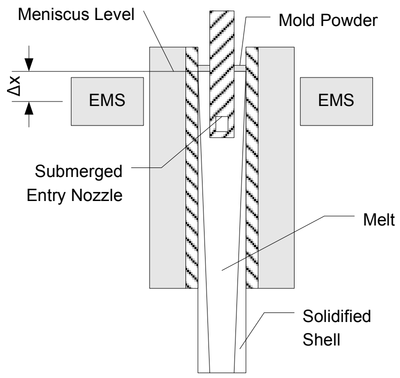

Figure 15 Variation of Stirrer Position

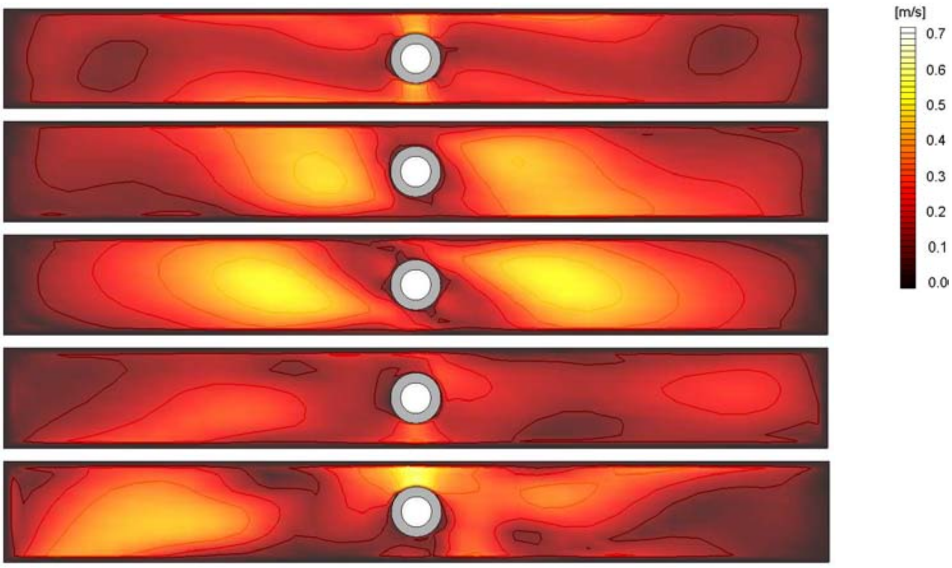

Figure 16. Meniscus metal flow speeds for a stirrer applied with center line 0, 100, 200, 300 and 400 mm below meniscus.

When the stirrer is applied at the very top of the strand, a meniscus motion separated from the nozzle jets is induced close to the wide sides of the strand. As the distance from the meniscus to the stirrer center line increases, a larger mass of molten metal is exposed to the stirrer fields, and the magnetic flux from the stirrer is able to induce a larger Lorentz force. At Δx = 250-300 mm and below, the stirrer starts to interfere with the nozzle jet flows, resulting in unstable and irregular flow patterns with an increasing risk of flow stagnation close to the SEN.

The curves in Figure 17 show the computed tangential meniscus speeds along a line 10 mm inside one of the wide sides of the meniscus for a set of different stirrer locations. The strand format is 250x2000 mm with casting speed 0.7 m/min, Ar flow rate 6.1 L/min and SEN angle -15°.

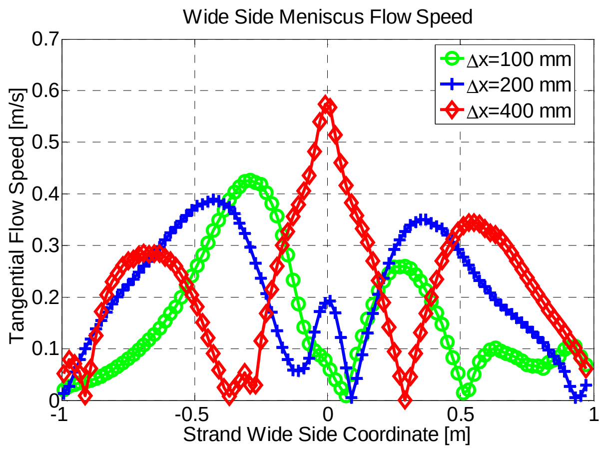

Figure 17. Meniscus speeds 10 mm inside wide side of strand. Stirrer center line 100, 200 and 400 mm below meniscus.

At the 100 and 200 mm positions, the flow speed distributions along the wide sides are similar. The distributions on opposite wide sides are also symmetric for these positions. With the stirrer mounted at the 400 mm position, there are certain regions of flow stagnation and an excessive flow speed peak at the center of the wide side. Due to the irregular meniscus flow at the low stirrer position, the speed distributions along opposite wide sides are not symmetric. A stable, symmetric and sufficiently strong meniscus flow is only found for stirrers with center line positions above 250 mm.

Washing of Inclusions from Shell

A strong tangential flow at the phase transition between the solid shell and the molten steel in the upper part of the strand washes away non-metallic inclusions caught between columnar dendrites in the critical initial stage of the shell solidification. As the liberated inclusion particles agglomerate in the melt, they float towards the meniscus where they are caught by the mold powder. Reducing the amount of inclusions prevents subsurface defects.

The ‘washing effect’, a measure of the inclusion washing flow, is defined as the mean horizontal, tangential flow speed over an area from the meniscus and 100 mm down the strand, 10 mm inside the wide side shell. This definition is schematically clarified in Figure 18.

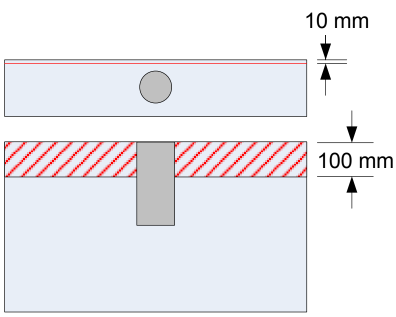

Figure 18. Washing effect region

Figure 19 demonstrates the calculated washing effect with different locations of stirring. The strand format is 250x2000 mm with a casting speed of 0.7 m/min, an Ar flow of 6.1 L/min and a SEN angle of -15°. Stirring at the top of the strand yields the best washing of inclusions at the transition to the solidified shell.

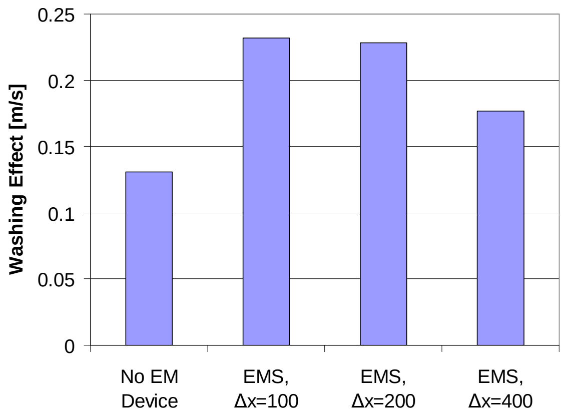

Figure 19. Mean wide side tangential flow speed ('washing effect') for different stirrer locations.

Comparison of 2-Pole and 4-Pole Stirring

A major difference between the AC stirrer technologies is the difference in the length of each part stirrer. In all the AC technologies described here, a single part stirrer covers two poles to be able to fit a complete AC period over the stirrer length. With an FC MEMS, the stirrer is long, and the pole pitch is greater than for the technologies where two part stirrers are mounted on each side of the strand. A larger pole pitch allows a stirrer to reach higher magnetic flux densities with less power consumption.

The computational results in Figure 20 give the relationship between stirrer force and apparent power for a 2-pole (FC MEMS) and a 4-pole (M-EMS) stirrer constellation. The total length of the respective stirrer configuration is assumed to be 2000 mm. The stirrer center line is 150 mm below the meniscus level, and the total time averaged horizontal stirring force component tangential to the strand wide sides is calculated for a 250x2000 mm strand.

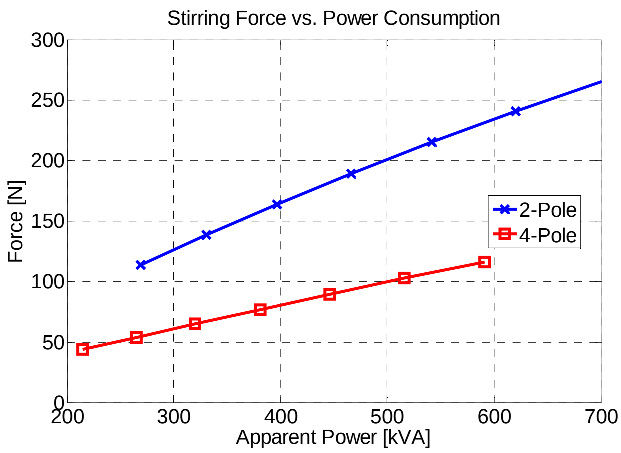

Figure 20. Stirring force as a function of apparent power for 2-pole (FC MEMS) and 4-pole (M-EMS) stirrer arrangements

The 2-pole FC MEMS reaches twice the total force with the same the apparent power as the 4-pole M-EMS arrangement meaning that the FC MEMS is superior to the M-EMS technology in terms of power efficiency.

DISCUSSION ON VARIOUS TECHNOLOGIES

Is there today any electromagnetic device that can always control the flow in the mold in an optimum way? As the penetration depth should be minimized and the flow velocity optimized for all casting conditions, it is obvious that two independent control devices are required. The M-EMS and the FC MEMS can efficiently control meniscus flow velocity, since they are installed in the upper region of the mold, but both have a limited effect on the penetration depth. Both of them are ideal devices for lower casting speeds and for crack sensitive grades, such as plate grades, but also for wider slab casters of more than 2200 mm where it is important to control the flow all the way out to the narrow faces. FC MEMS, however, has the advantage of a stronger magnetic field or lower power consumption.
The MM-EMS claims to be the ideal tool for all casting conditions, but does it really work? Only the flow pattern at the meniscus is considered for optimization, thus the effect on the downward velocity is only a consequence of the mode selected to secure a double roll pattern in order to reach an optimum meniscus velocity. The EMLA mode is applied for low casting speeds whereas EMLS is chosen for high casting speeds in order to reach this desired pattern. For high casting speeds EMLS will have a positive effect on the penetration flow but full effect can never be achieved, since the current fed to the coil is chosen to optimize the meniscus flow pattern, not the penetration depth. At lower casting speeds, the acceleration of the flow with EMLA may actually increase the risk of inclusions being flushed down into the strand. With the EMRS in the middle of the mold, the control of the meniscus flow velocity does not become easy to control. The stirring will instead interact with the fluid flow from the nozzle jet, thus causing additional turbulence in the mold.
With the FC Mold, meniscus flow velocity <u>and</u> down flow can both be optimized for medium to higher casting speeds. Results confirm this independency and that the slab surface <u>and</u> the slab inner quality are both heavily improved by the FC Mold. Especially ULC steel grades are sensitive to internal defects and the temperature increase at the meniscus with the FC Mold will suppress the formation of hooks. The FC Mold is also applicable for medium casting speeds, as the steel jets from the SEN are reflected upwards by the lower field, thus increasing the metal flow velocity at the meniscus. This accelerating effect has been verified at several plants with good metallurgical results. The upper field is then used to slow down this velocity down to its optimum value. For really low casting speeds, the momentum of the steel coming out from the SEN is not sufficient to give a suitable acceleration at the meniscus, thus a mold stirrer is more suitable.

CRITERIA FOR PRODUCT CHOICE

For thin and medium slab casting the electromagnetic brake, EMBR, has become state-of-the-art technology and about 40% of all thin slab casters are today equipped with an EMBR. The turbulence increases with reduced thickness of the strand and the need to dampen fluctuations in the mold increases with casting speed. For conventional slab casting, however, there is not a single perfect electromagnetic flow control device for all casting practices. Stirring in the meniscus region seems to be the best choice for low casting speeds and when internal defects are not a problem. For medium to high casting speeds the FC Mold with individual control of the downward and the meniscus flow has proved to be the best choice.

In order to select the best electromagnetic device for the control of the fluid flow in the mold, the turbulence index has been plotted for various slab thicknesses for a slab width of 1400 mm in Figure 21. The turbulence index is defined according to Manfred Wolf [**Erro! Fonte de referência não encontrada.**] in equation (1). TI is the turbulence index, W the slab width (m), D the slab thickness (m), V_c the casting speed (m/min) and V_r the throughput (tons/min).

$$TI = 0.33 \bullet \sqrt{\frac{W}{D}} \bullet V_C \bullet V_r \qquad (1)$$

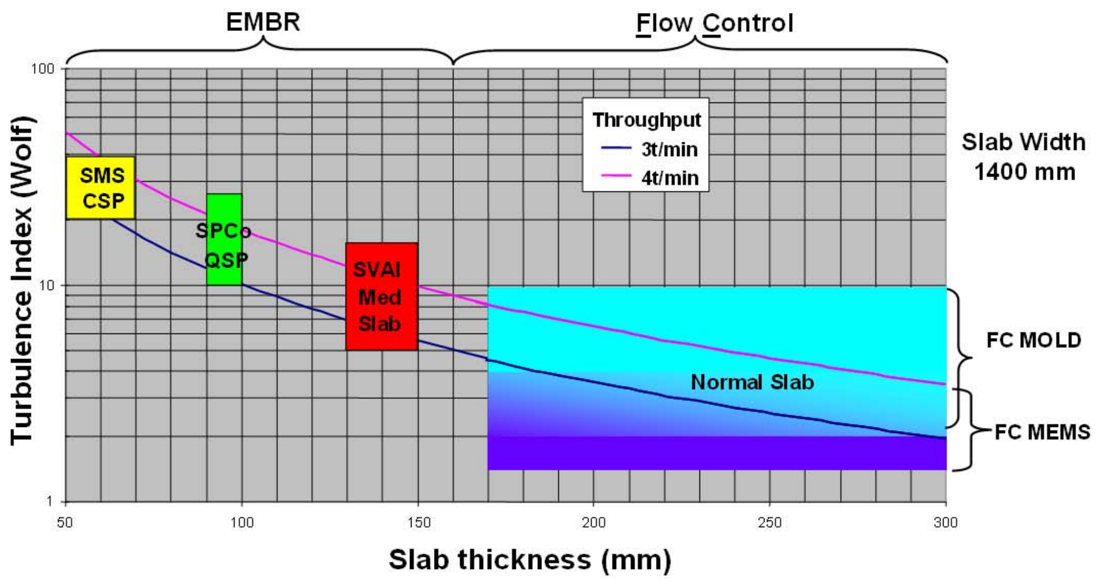

Figure 21 Guideline for product choice

It can be seen that for conventional slab casters either FC Mold or FC MEMS should be selected, depending on the turbulence index or the throughput. But the meniscus turbulence is also affected by SEN geometry. Further, steel grades and slab width are also important factors for the final choice of electromagnetic actuator. This guideline for product choice has therefore some overlapping area but FC MEMS should in general be selected for low to medium casting speeds and FC Mold for medium to high casting speeds.

CONCLUSIONS

The demands for higher quality and productivity in slab continuous casting are increasing and the need to use electromagnetic actuators to control the fluid flow in the mold has during recent years gained extensive interest. The aim is to optimize the meniscus flow velocity, minimize the penetration flow and to assure stable conditions in the mould. For low to medium casting speed FC MEMS is the preferred tool, and it is crucial that the stirrer is placed high in the mould. For medium to high casting speed FC Mold is the natural choice with superior flexibility to control the fluid flow and the stability in the mould.

REFERENCES

1 J. HERBERTSON et al., “Modelling of Metal Delivery to Continuous Casting Mould”, Steelmaking Conf. Proc, Vol. 74, Warrendale, PA, 1991, pp. 171-185.
2 J.F. DOMGIN et al., “Effect of Process Parameters Variations on CC Mould Hydrodynamics and Inclusions Behavior”, ECCC 2005, pp. 490-499.
3 S. KITTAKA, et al., “Nippon Steel in-Mold Electro-Magnetic Stirrer for Improving Slab Casting”, ECCC 2005, pp. 476-481.
4 H. HACKL et al., “Electromagnetics give Superior Slab Quality”, METEC InSteelCon 2007, pp. 736-743.
5 S. KUNSTREICH et al., “Multi-mode EMS in Thick Slab Caster Moulds and Effect on Coil Quality and Machine Performance“, ECCC 2005, pp. 482-489.
6 M. SUZUKI et al., “Recent Research and Technologies on Inclusion Removal in Ultra Low Carbon Steel”, ECCC 2005, pp. 508-515.
7 L. SANG-MIN et al., ”Electromagnetic Stirring in the Mould at the newly Rebuilt POSCO Pohang No. 3 - 3 Machine, ISSTech 2003 Conference Proceedings, pp. 505-518.
8 A. LEHMAN et al., “Fluid Flow Control in Continuous Casting using Various Configurations of Static Magnetic Fields”, International Symposium on EPM, 1994, Nagoya, ISIJ, pp. 372-377.
9 G. ABBEL et al., “Argon bubbles in slabs”, ISIJ Int., Vol. 36, Suppl., pp. S219-S222, 1996.
10 A. KAMPERMAN et al., “Curved versus straight mould, EMBR an alternative?”, Proceedings “3rd European Conf. on Continuous Casting, Madrid 1998, pp. 465-474.
11 P. NAVEAU et al., “An investigation on the mechanism of gas bubbles/inclusions entrapment in the solidified shell”, ECCC 2005, pp. 216-224.
12 M. WOLF, Iron & Steel International 1995, pp. 36-37.
13 O. WIDLUND et al., “Modeling of anisotropic turbulent transport in simulations of liquid metal flows in magnetic fields”, 3rd Int. Symposium on Electromagnetic Processing of Materials, EPM2000, Nagoya, Japan, 2000, ISIJ, pp. 97-102.
14 O. WIDLUND, “Implementation of MHD model equations in CFX 4.3.” Technical Report TRITA-MEK 2000:10, KTH, Stockholm, 2000.
15 K. YOKOTA et al., “Electromagnetic Coil Designed by Magneto-Hydro-Dynamic-Simulation”, Nippon Steel Technical Report No. 89, 2004.