IMPROVEMENT IN STEEL CLEANNESS IN LADLE AND SLAB CASTING PROCESSES BY ELECTROMAGNETIC FORCE[1]

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Abstract

Production of steel with high demands on cleanness requires good control of both chemistry and fluid flow in the ladle furnace and slab continuous casting processes. Electromagnetic stirring in the ladle furnace (LF-EMS) and the application of DC magnetic fields in the slab caster (EMBR and FC Mold) have consistently demonstrated to be reliable tools to improve steel cleanness. In this paper, the working principle of both technologies and plant results are presented.

Key words: Electromagnetic force; Ladle; Slab; Cleanness.

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1 INTRODUCTION

Fluid flow in ladle refining and continuous casting operations plays one important role in chemical mixing, temperature redistribution, steel cleanness, etc.
Various refining methods, such as RH, ASEA-SKF, VOD, CAS-OB, etc, have been developed with different metallurgical purpose. There are different ways to agitate and move liquid steel in the ladle, such as vacuum lift, gas stirring and electromagnetic stirring.
With the development of metallurgical knowledge, some common points on the ladle fluid control have been approached:

1. Strong turbulence or mixing at the slag/steel interface is required to achieve good desulphurization result.
2. Short mixing time in the bath melt can lead to chemical homogeneity, mixing time is influenced by flow pattern, ladle size, turbulence intensity, etc.
3. A relative calm flow is good for the inclusion floatation and avoiding re-oxidation, slag entrapment, etc.

As for flow control in slab mold, some common points have also been approached in recent years, such as

1. A low turbulence intensity in the slag/steel interface is favorable to avoid or reduce the slag entrapment.
2. A short penetration depth in the lower part of the mold is favorable to shorten the mixing zone length and enhance the inclusion floatation.
3. The impinging momentum of the jet flow from nozzle port shall be limited to avoid the local ‘hot point’ on the solid shell in the narrow face.

DC magnetic field has found wide application in slab casting operations due to its ability to stabilize the casting process and improve steel cleanness.
In this paper, the principles of electromagnetic stirring in ladle furnace will be presented, the advantage of electromagnetic stirring will be addressed through comparing its operational results with gas stirring. The fluid flow control philosophy in the slab casting mold will be discussed, which justifies the application of DC magnetic field in different slab configurations.

2 ELECTROMAGNETIC STIRRING IN LADLE FURNACE (LF-EMS)

The electromagnetic stirring of liquid steel in the ladle (also called LF-EMS) is done by the coil placed beside the ladle, one low frequency two-phase current is fed into the coil to generate the electromagnetic field. The ladle shell in front of the coil must be made of non-magnetic stainless steel so that the low frequency magnetic field can penetrate into the melt.
The low frequency traveling magnetic field induces current in the melt. A Lorenz force is then formed as a result of the co-existence of the two fields,

$$\vec{F} = \vec{J} \times \vec{B}, \tag{1}$$

where:

$\vec{J}$ is the induced current,
$\vec{B}$ is the magnetic field,
and $\vec{F}$ is the Lorenz force.

Figure 1 shows the calculated Lorenz force in the ladle, it is concentrated in the left side close to the coil, and its direction may be upward (as shown in the figure) or downwards by controlling current phase difference.

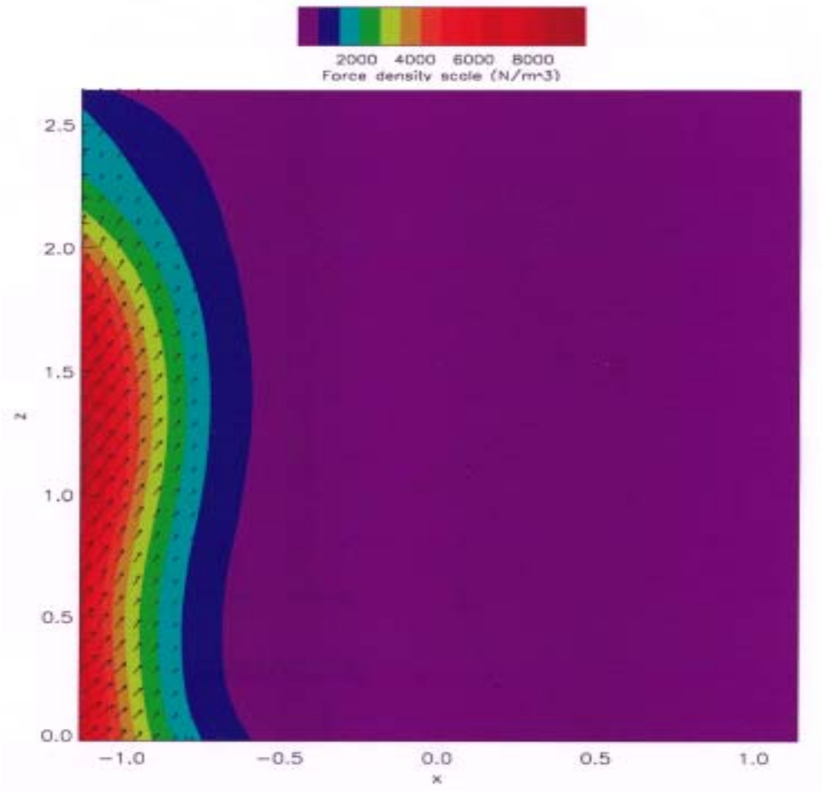


Figure 1. Calculated Lorenz force in the ladle

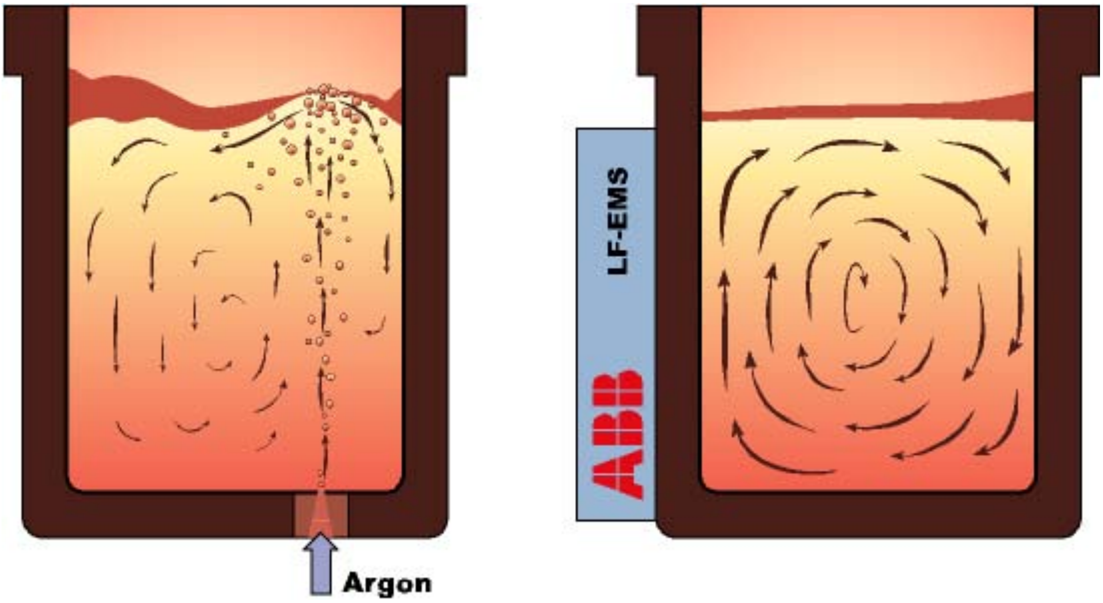


Figure 2. Fluid flow features of gas and electromagnetic stirring

Electromagnetic stirring produces a more homogeneously distributed steel velocity in the ladle, there is no significant difference between the velocities at the bottom and surface of the melt, as in the gas stirred ladle (Fig. 2). As with electromagnetic stirring the turbulence energy is more evenly distributed than in the gas stirred ladle, the ‘low velocity region’ in the center of electromagnetic stirred ladle is compensated by the high turbulent energy in this area (Fig.3). This will have one direct influence on the inclusions removal in the ladle as discussed later in this paper. Another important feature of electromagnetic stirring is that the slag layer is more quiescent than gas stirring, this makes gas stirring much more in favor of desulphurization.

(a) Electromagnetic stirred ladle (b) Gas stirred ladle

Figure 3. Distribution of turbulent energy in the ladle

The direction of the induction stirring, up or down, and the stirring power, can be easily changed. This means that an unbroken slag layer can be kept over the steel during the LF treatment but also that it is possible to open up a slag free steel surface (Open eye) for the time it takes to add alloys directly into the steel bath, without risking that the alloys get stuck in the slag.

3 CLEAN STEEL BY LF-EMS

3.1 Steel Re-oxidation

For clean steel production, it is of great interest in keeping down the steel re-oxidation during ladle treatment, aluminum and silicon are here of particular interest.

The minimization of aluminum oxidation loss is of important for several reasons. Firstly, the cost of aluminum is high. Secondly, the total oxygen content in the final product is generally higher from the heats with higher aluminum oxidation rate during ladle treatment. Thirdly, it is also essential to achieve the narrow composition ranges.

LF-EMS can keep an unbroken and calm slag layer on the top of the melt even with high stirring energy. While gas stirring causes a strong turbulence on the top of the melt, and the liquid steel gets direct contact with atmosphere at the slag ‘open eye’ region on the top of the gas plume. This mechanism makes the re-oxidation loss much higher in gas stirred ladle than in electromagnetic stirred ladle. Figure 4 shows aluminum oxidation loss vs. stirring energy of both types of stirring.

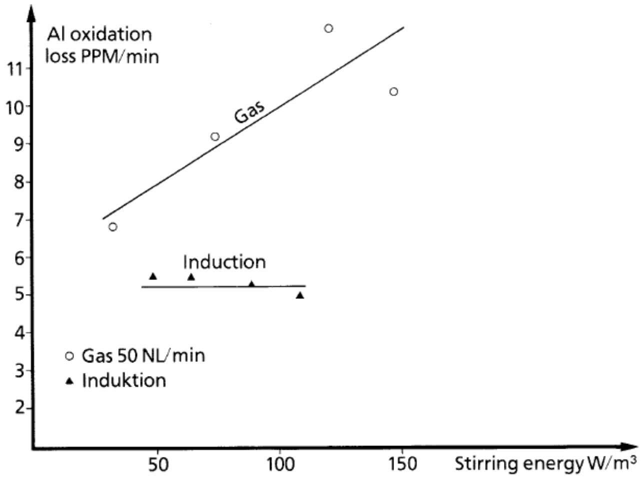


Figure 4. Aluminum oxidation loss in gas and EM stirred ladle (SSAB, Sweden)

3.2 Total Oxygen Removal

Total oxygen is a very important and common index of steel cleanness. Usually the total oxygen content is correlated with the total amount of oxide inclusions.

The growth of inclusions is mainly controlled by turbulent collisions, the separation of the oxides from the steel to the slag has been found to be enhanced by a buoyancy force, which is initiated from density differences between the oxide and the steel, and by the movement of small eddies in the turbulent flow. The rate of separation of inclusions might be increased using stirring which causes inclusions to collide as well as lifts the inclusions up to the top slag where they can separate and assimilate.

The stirring energy of LF-EMS is in common sense larger than gas stirring. LF-EMS generates one rotating flow in the melt from the bottom to the top. The homogenous distributed and high stirring energy in the melt is favorable to the formation of larger inclusions and can transport the inclusions to the steel-slag interface and steel-refractory interface and being captured.

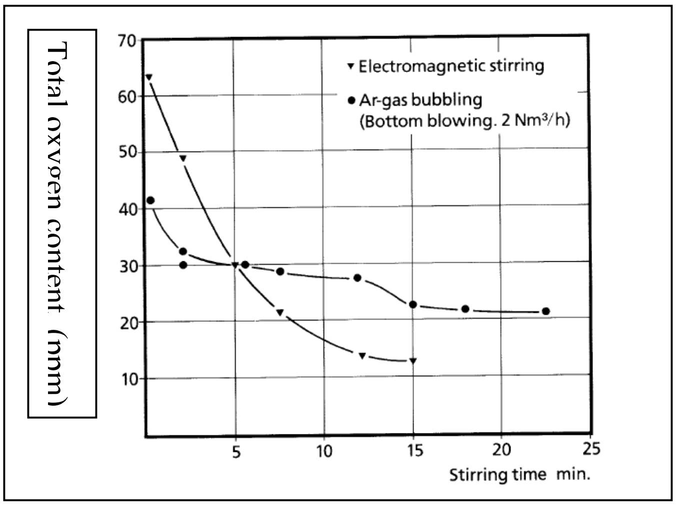


Figure 5. Total oxygen content in gas and induction stirred ladle (Kobe steel, Japan)

Figure 5 shows the total oxygen content decrease in gas and induction stirred ladle, electromagnetic stirring has a higher removal rate than gas stirring.

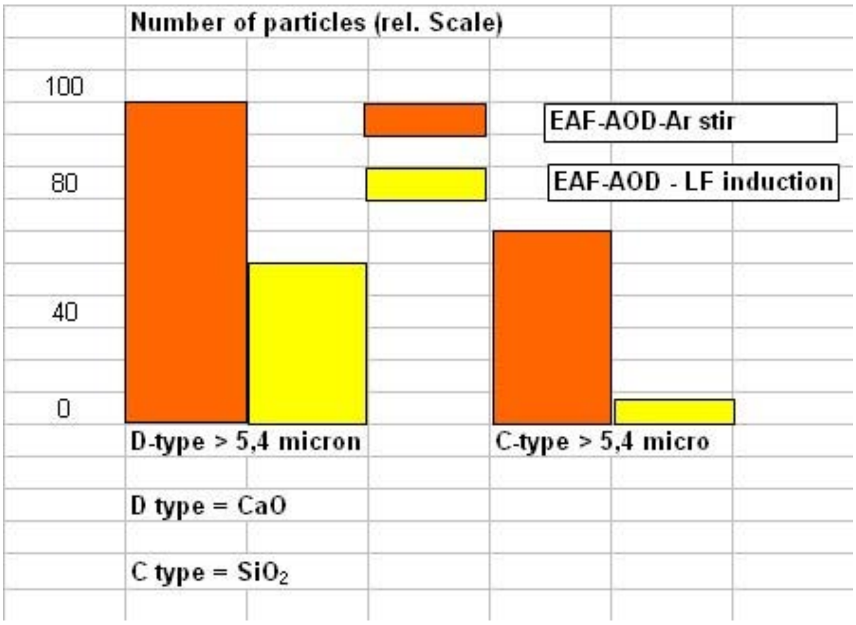


Figure 6. Number of non-metallic inclusions after electromagnetic respective gas stirring in the ladle furnace (Sandvik, Sweden).

Figure 6 shows the number of non-metallic inclusion after ladle refining by electromagnetic respective gas stirring, the cleanness of steel through electromagnetic stirring is much better than gas stirring. This is very important in producing the steel grades such as ball bearing steel, stainless steel etc, which have high demands on inclusion number and size.

4 FLUID FLOW CONTROL IN SLAB MOLDS

In the slab continuous casting mold, fluid flow can influence the final slab quality through several factors, such as temperature distribution, inclusion removal, mold powder entrapment, flow pattern stability, etc.

DC magnetic field has been implemented widely in slab casting process because of its essential features of braking down the jet flow momentum and damping the turbulence.

In the early 1990’s, EMBR, where a single static magnetic field covers the total width of the slab (Figure 7a), was applied. This configuration is today mainly used for thin slab casting to decrease the flow speed and turbulence at meniscus and avoid mold powder entrapments.

For the conventional thick slab casting, the removal of inclusions coming with the steel is an important feature. Consequently, two magnetic fields are required, one field at meniscus region to control the metal flow speed there and avoid mold powder entrapments and a second field at bottom of mold to decrease the penetration depth of the steel jets from the SEN (Submerged Entry Nozzle) facilitating the flotation of inclusions coming with the steel. This formed the background of the FC Mold (Flow Control Mold), see Figure 7b.

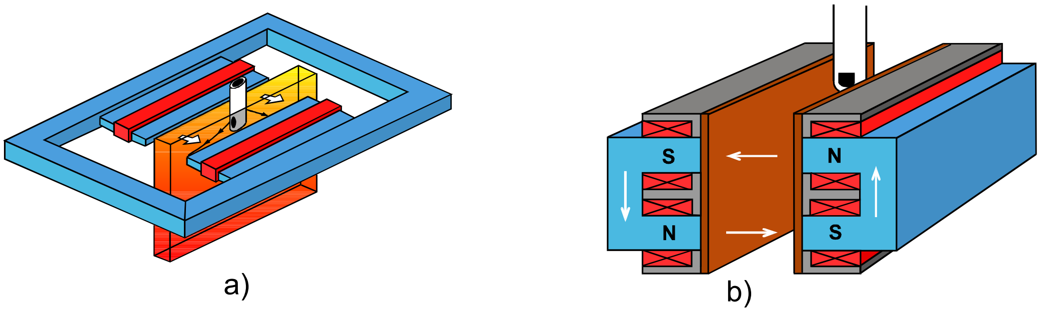
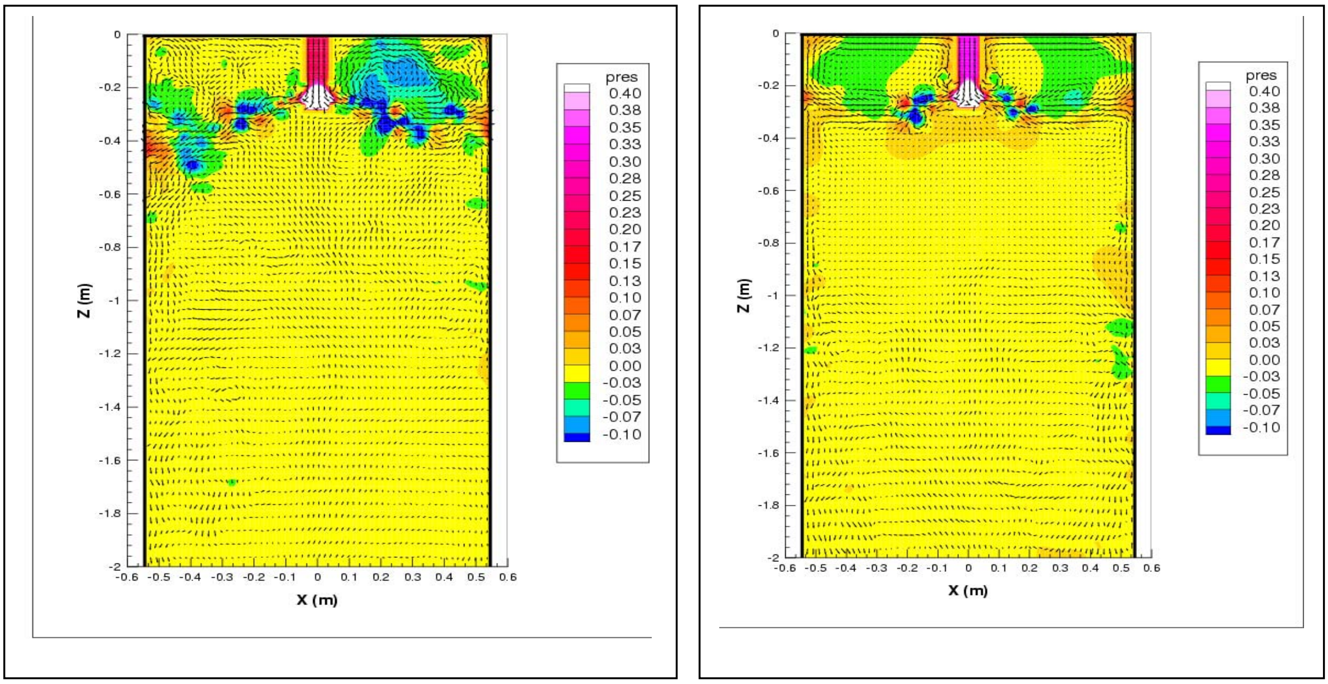


Figure 7. Schematic diagram of DC electromagnetic devices in slab casting mold. a) EMBR;   b) FC Mold



(a) Without FC Mold

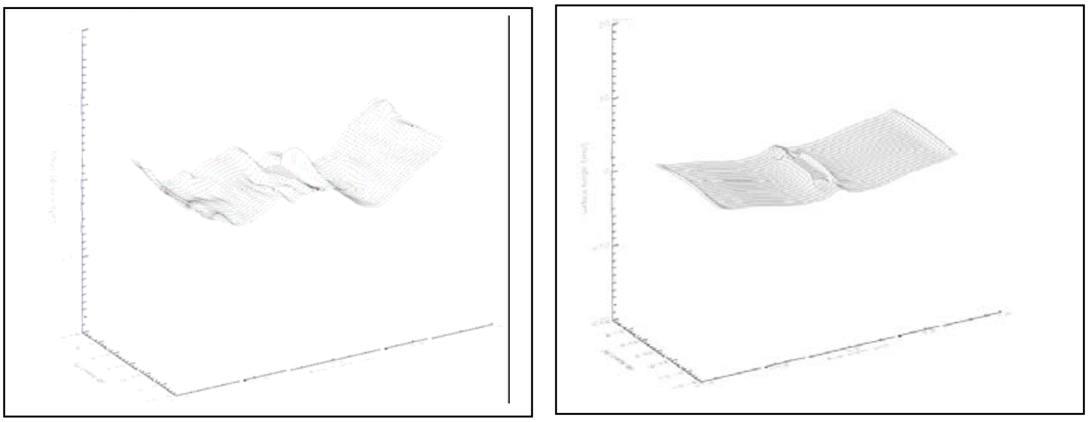
(b) With FC Mold

Figure 8. Simultaneous fluid flow in slab mold without/with FC magnetic field

Figure 8 shows the LES simulation of the fluid flow and pressure profiles in the mold with/without FC Mold.

Without FC Mold, the velocity profiles show quite strong turbulent characteristics which means that the velocity vectors change quickly with time. In this figure, the lower pressure zone indicates the vortex center. The high-pressure zone close to the narrow face is clearly shown which indicates the impinging region of the jet flow on the narrow face. In the upper region of the mold, we can see clearly the recirculation loops with lower pressure zones. And the flow pattern is not strictly symmetric even all the input parameters are in symmetry. In the center region below the SEN, the main stream of fluid moves upwards. Near the narrow faces of mold, there is a thin strong shear layer flowing down. Some vortices are formed by this thin shear layer. These small vortices may bring inclusions deep into the liquid pool, which is detrimental to the quality of the final product.

With FC Mold, the fluid flow in the mold is calmed down because DC magnetic field kills the turbulence. The short-wave length fluctuation region is suppressed. The large scale asymmetry and oscillation disappears. In the upper part of the mold, the flow is laminarized. The velocity below the top surface becomes quite horizontal and smooth, this is expected to result in a flat surface which will decrease the entrapment of top flux. In another word, the flow in the mold is redistributed.



(a) Without FC Mold

(b) With FC Mold

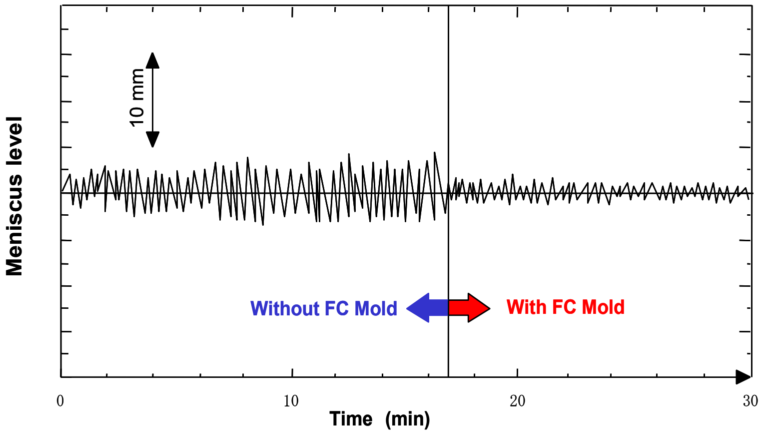
Figure 9. Simultaneous surface shape of the mold

Figure 9 shows the simultaneous surface shape of the mold, With out FC Mold, the surface shape is uneven and the vortices are clearly seen which will lead to the mold powder entrapment. With FC Mold, the surface is even along the slab width and thickness, the vortices are to a large extent diminished.

5 INDUSTRIAL RESULTS OF DC MAGNETIC FIELD

5.1 Meniscus Fluctuation and Temperature

Figure 10 shows that FC mold reduces meniscus fluctuations. the steel temperature at meniscus is increased (Figure 11) as a result of the lower turbulence, thus reducing heat convection and, additionally, due to the smaller penetration of the steel jets which keeps the hot steel from the SEN (Submerged Entry Nozzle) higher up in the strand.



Machine: Chiba 3CC
Slab Width: 1650 mm
Thickness: 260 mm

Casting Speed: 1.75m/ min
Through Put: 5.0t/ min

Electromagnetic MLC

Figure 10. FC Mold decreases meniscus fluctuations (JFE, Japan)

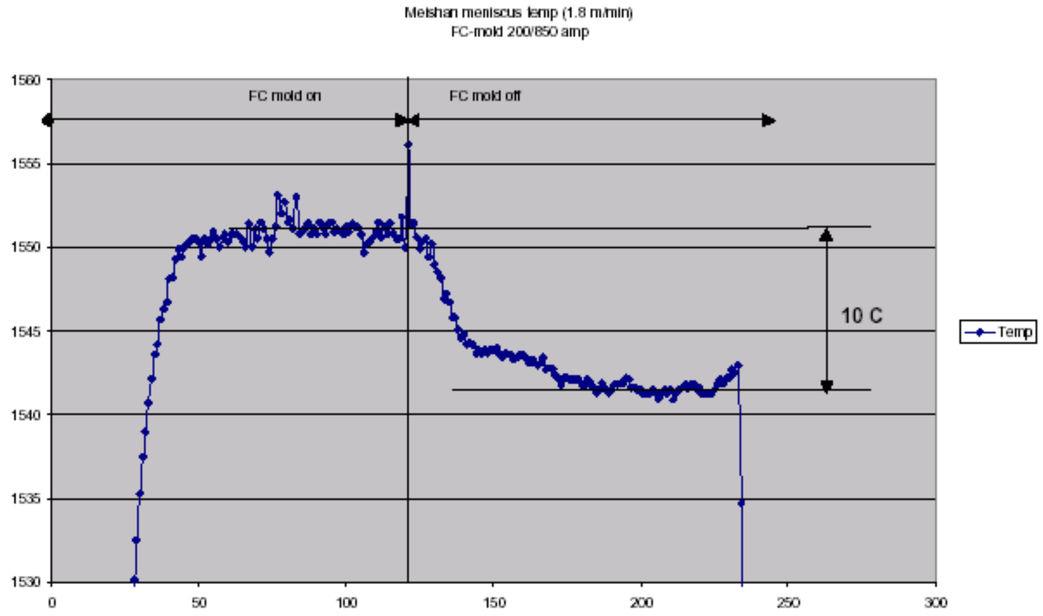


Figure 11. FC Mold increases meniscus temperature (Baosteel, China)

5.2 Meniscus Shape

The meniscus level along the slab width has been measured as a function of time with and without FC Mold, see Figure 12. The result is a very stable meniscus profile which is in accordance with the numerical simulations.

It shows a clear swelling towards the narrow sides, indicating that there is a controlled up-flow of hot metal, feeding sufficient heat to the meniscus for melting of the mold powder and maintaining a thick layer of molten mold powder. The fluctuating biased flow without FC Mold has been effectively eliminated.

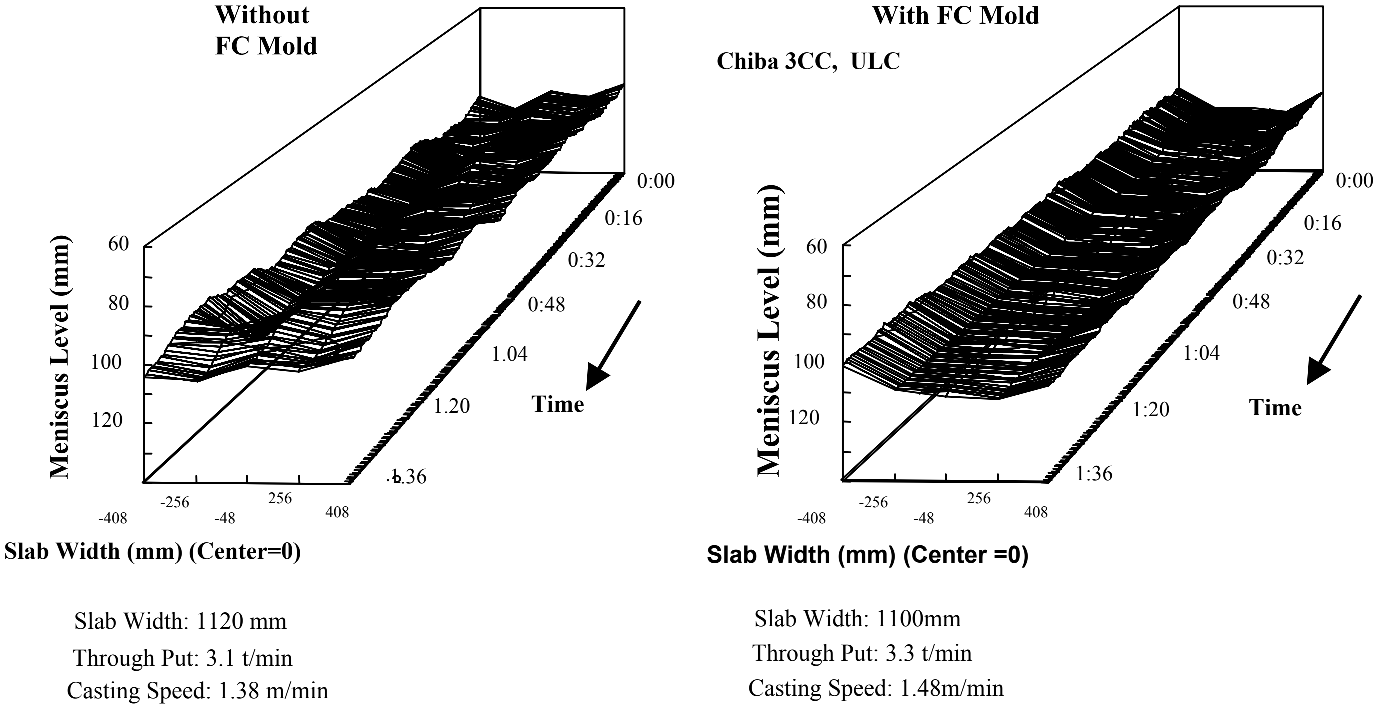


Figure12. Meniscus shape measured by thermocouples in the Cu plates (JFE, Japan)

5.3 Final Product Quality

A summary result from the production of hot rolled coils is given in Fig.13, where both surface and internal defects are presented. It is evident that when production rate reaches a certain limit, the end product quality is heavily impaired. The use of a FC Mold allows to increase the production without having to suffer from a quality downgrading. Alternatively, a dramatic increase in end product quality is reached while maintaining the production at the same level.

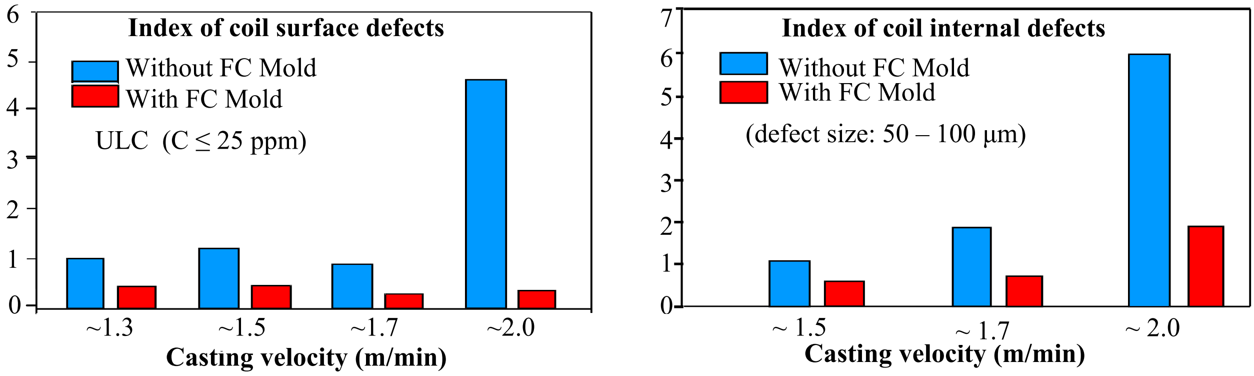


Figure13. Effect of FC Mold on coil surface and internal quality (JFE, Japan)

6 CONCLUSIONS

Electromagnetic stirring in the ladle furnace is one useful tool for the clean steel production in many aspects, such as minimizing steel re-oxidation and improving total oxygen removal. DC magnetic field has found wide application in controlling the mold fluid flow behavior in slab casting process. Turbulence damping and momentum brake of fluid flow by DC magnetic field contribute to slab quality improvement.

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