The Linear-motor Type In-mold Electromagnetic Stirring Technique for the Slab Continuous Caster

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Conducting downward longitudinal stirring by the use of linear-motor type In-mold Electromagnetic Stirrer (M-EMS), it was possible to control the molten steel flow within the mold and to reduce inclusions and pinholes at the inside t/8 accumulation zone of the curved-type slab continuous caster.

The reason have proved from the investigation of flow pattern in the mold and three-dimensional flow analysis; that is the M-EMS downward longitudinal stirring reduces the penetration depth of outlet molten steel flow from the nozzle and de-celerates the flow-rates at the meniscus.

KEY WORDS: linear-motor type in-mold electromagnetic stirring (M-EMS); downward longitudinal stirring; non metallic inclusion; pinhole; curved-type slab continuous caster; three-dimensional magnetic field analysis; flux entrainment three-dimensional fluid flow analysis; penetration depth.

1. Introduction

As the need increases for steel sheet of higher workability and upgraded quality, it is critical to find ways of reducing slab defects such as non-metallic inclusions and blowholes.

These defects occur primarily at the inside t/8 position of slab produced with a curved continuous caster, and increase the possibility of surface defects when the sheet undergoes critical material working or when the sheet thickness decreases.

To overcome this problem, two techniques have been applied to the curved-type slab continuous caster: the electromagnetic brake technique,\(^1\) utilizing a direct-current magnetic field in the continuous-casting mold; and the electromagnetic stirring technique,\(^2\) which imparts a circular flow to molten steel in the mold through use of an alternate current magnetic field which reduces pinholes and inclusions at the slab surface layer equivalent to rimmed steel.

At Kakogawa Works, we have developed a technique for controlling the molten steel flow within the mold using a linear-motor type electromagnetic stirrer which improves the inside t/8 accumulation zone of the curved-type slab caster.\(^3-7\)

In developing the technique, flow patterns within mold and slab were simulated using a three-dimensional magnetic field and flow analyses. At the same time, the stirring direction and intensity were varied by the linear-motor type electromagnetic stirrer installed in the mold of our No. 3 slab caster, and optimum conditions for improving slab quality were investigated. Downward longitudinal stirring was found to significantly improve inclusions and blow holes at the inside accumulation zone. This paper outlines the findings obtained from these tests.

2. Concept of Fluid Flow Control in the Mold

Accumulation behavior of inclusions in the slab is affected to the great extent by fluid flow in the mold. When molten steel flow within the mold is considered from the viewpoint of reducing slab inclusions, the following controls are necessary:

(1) The downward outlet stream of molten steel from the immersion nozzle must be prevented from penetrating too deeply into the mold.

(2) Molten steel meniscus level must be stabilized and flux entrainment must be prevented by reducing the flow rate at the meniscus of the reverse outlet stream of molten steel which rises along the narrow side of the mold.

With these controls made, the in-mold electromagnetic stirrer was designed and tested with actual production equipment and molten steel flow was simulated.

3. In-mold Electromagnetic Stirrer (M-EMS) and Experimental Procedure

A mold with a built-in electromagnetic stirrer (hereafter called M-EMS) was installed to a strand of Kakogawa Works' No. 3 slab continuous caster, and the experiment conducted. Fig. 1 shows a cutaway view of the mold incorporating M-EMS. Table 1 shows principal specification of the slab caster and
M-EMS. The inductor is of the two-phase linear-motor type, and the frequency range is 1–5 Hz. In order to prevent magnetic flux density attenuation, an ultra-thin 12-mm copper mold sheet was used.

Fig. 2 shows a width-wise cross-sectional view of the mold. The M-EMS coil box can be rotated parallel to the copper mold sheet, allowing the stirring direction to be varied from horizontal to upward and downward longitudinally.

In this experiment, braking directions of the nozzle outlet stream, the horizontal (opposite), and upward and downward longitudinal stirring directions were investigated. The steel grades subjected to this experiment were low-carbon aluminum-killed and ultra-low-carbon titanium-killed steels. The mold was approximately 240 mm×1260 mm in size, and the casting speed was about 1.0–1.45 m/min.

4. Experiment Results

4.1. Effects of M-EMS Stirring Direction

4.1.1. Inclusions at the Accumulation Zone

To determine the effects of M-EMS on inclusion reduction at the accumulation zone, inclusions greater than 100 μm existing in the area of 22–32 mm from the slab inside were investigated by C-scope ultrasonic testing throughout the slab width, as shown in Fig. 3.

Fig. 4 shows the relationship between stirring force and number of inclusions with each stirring direction (upward longitudinal, downward longitudinal, horizontal, and toward the molten flow) when M-EMS is used. The stirring force was the value 20 mm from the mold wall surface, and was calculated using the value found from magnetic flux density calculation. The inclusion index of 1.0 indicates the level of without M-EMS stirring, and lower value of the index means favorable level of inclusions. The results indicated that upward longitudinal and toward the molten flow stirring have no positive good effect on inclusion reduction, and may even increase the number of inclusions. Horizontal stirring exhibited considerably wide variation in effects, both favorable and unfavorable. In contrast, downward longitudinal stirring showed consistent and positive effects on inclusion reduction.
4.2. Investigation of Molten Steel Level Fluctuations in the Mold

Fluctuations of the molten steel level, which were measured by eddy current type mold level detector, caused by application of electromagnetic stirring force are illustrated for each stirring direction. As Fig. 5 shows, the mold level fluctuation rate increases with upward longitudinal and horizontal opposite stirring. It is believed that unstable streams, such as drift flows of outlet molten steel, are accelerated by electromagnetic stirring.

It was surmised that the increase or instability of the inclusion level in upward longitudinal and horizontal stirring can be attributed to aggravated mold level fluctuation. On the contrary, downward longitudinal stirring provides a stable mold level.

4.2. Investigation Results from Downward Longitudinal Stirring

4.2.1. Inclusion Distribution Inside of the Slab

This section discusses the investigation results of downward longitudinal stirring and the favorable improvements on inclusions which were demonstrated in the investigation of M-EMS stirring.

Fig. 6 shows the investigation results of the inclusion distribution against distance from the slab inside surface as shown by C-scope ultrasonic testing in a cross-sectional direction. Reduction of inclusion due to M-EMS downward longitudinal stirring is observed throughout the slab and is especially conspicuous at the inside accumulation zone.

Pinosles in the slab interior occur when argon gas, blown into the nozzle to prevent inclusions from adhering to the immersion nozzle inside, is carried into the mold. In low tensile strength steels such as ultra-low-carbon steel, it is thought that pinholes in the slab interior cause the defects known as “blister” during annealing in the cold rolling. In the curved-type slab caster, pinholes, like inclusions, are likely to be concentrated at the accumulation zone.

Fig. 7 shows the number of pinholes larger than 1 mm in the slab counted at a 10-mm pitch from the slab bent inside surface. M-EMS downward longitudinal stirring markedly reduced the number of pinholes at the accumulation zone in particular, and it is expected that this will have the effect of also reducing blisters.

4.2.2. Relationship between Number of Inclusions and Pinholes and Through-put

In general, as the casting rate (through-put) per unit of time increases, the penetration depth of the immersion nozzle's outlet stream also increases, and thus inclusions increase.

Fig. 8 shows the effect of through-put on the number of inclusions (200–300 μm) at the accumulation zone. The inclusion quantity is kept stable at a low-level by M-EMS downward longitudinal stirring even when the through-put is increased, allowing a higher casting speed without aggravating the inclusion level.

As with inclusions, pinholes in the slab accumulation zone increase as through-put increases. Fig. 9 shows the relationship between the number of pinholes in the accumulation zone larger than 1.0 mm and the through-put. M-EMS downward longitudinal stirring keeps the number of pinholes in the slab consistently low even if through-put increases, making it possible to loosen operational restrictions such as the

![Fig. 5. Relationship between stirring force of M-EMS and mold level fluctuation.](image)

![Fig. 6. Effect of M-EMS on inclusions.](image)

![Fig. 7. Effect of M-EMS on pinholes of cross section of the slab.](image)
5. Discussion

5.1. Discussion Based on Investigation of Molten Steel Flow in the Mold

The experiment proved that M-EMS downward longitudinal stirring reduces the number of inclusions in the slab. The possible reasons were investigated by studying the molten steel flow patterns within the mold.

5.1.1. Investigation of Flow Patterns within the Mold

The flow patterns were estimated by measuring dendrite deflection angles in the slab. Fig. 10 shows the investigation results of dendrite deflection angles at shell thickness of 10 mm (200 mm from the meniscus) and at 30 mm (1900 mm from the meniscus). At this point, the deflection angle was seen from the widthwise corner to w/2, where θ>0 shows a downward flow.

The experiments showed that an intense downward flow is created near the narrow-side corner when M-EMS is not applied, but that M-EMS downward longitudinal stirring decreases the downward outlet molten steel flow from the immersion nozzle, and thus reduces the penetration depth.

5.1.2. Investigation of the Meniscus Profile

In general, as the outlet flow rate from the nozzle increases, the reverse flow from the outlet stream striking the mold narrow side also increases intensity, thus increasing the rising level ("d" in Fig. 11) of meniscus at the mold narrow side.

Fig. 11 shows the relationship between throughput and the narrow-side meniscus rising level. As shown, M-EMS downward longitudinal stirring helps in keeping the narrow-side meniscus rising level ("d") low even if throughput increases. It is believed that M-EMS downward longitudinal stirring reduces the nozzle outlet stream and thus decreases the narrow-side reverse flow.

The investigation results on molten steel flow patterns within the mold indicated that M-EMS downward longitudinal stirring provides the following improvements in molten steel flow patterns:

1. Intense downward outlet molten steel flow along the mold narrow side is reduced.
2. Reverse outlet molten steel stream flow to the meniscus is decreased.

5.2. Discussion Based on Three-dimensional Molten Steel Flow Simulation

Following the aforementioned molten steel flow investigation, three-dimensional magnetic field analysis and molten steel flow analysis were conducted to determine the relationship between the behavior of inclusions and molten steel flow when electromagnetic stirring is conducted.8-10

5.2.1. Three-dimensional Magnetic Field Analysis

The effects of molten steel flow on the magnetic field are small enough to be neglected, and in this kind of low-frequency region the transfer of electric current can also be neglected. Therefore, the fundamental equation for three-dimensional magnetic analysis is expressed as follows with vector potential (A) and scalar potential (ϕ) (see Appendix).

\[ \nabla \times (1/\mu_0) \nabla \times A + \sigma \partial A/\partial t + \nabla \phi = J_0 \] \hspace{1cm} (1)

\[ \nabla \cdot \sigma \partial A/\partial t + \nabla \phi = 0 \] \hspace{1cm} (2)

where, \( \sigma \): conductivity
\( \mu_0 \): permeability
\( J_0 \): source current density vector.

Spatial discretization was done by the Galarkin procedure of the finite element method. To solve Eqs.
Mold size: \(240^\circ \times 1260^\circ\)

\(V_c: 1.4 \text{ m/min}\)

Stirring direction: downward

![Fig. 10. Estimation of the molten steel flow from the deflection angle of dendrite.](image)

<table>
<thead>
<tr>
<th>Thickness of the shell</th>
<th>(\theta (\deg))</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 m/m (2000 m/min)</td>
<td>corner</td>
</tr>
<tr>
<td>30 m/m (1800 m/min)</td>
<td>corner</td>
</tr>
</tbody>
</table>

![Fig. 11. Relationship between through-put and difference of meniscus level.](image)

![Fig. 12. Numerical model.](image)

\(J_e\): density of eddy-current flowing in the molten steel

\(J \times B\): Lorentz force vector

\(P\): pressure

\(u\): velocity vector

\(\mu\): viscosity coefficient

\(\rho\): molten steel density.

Eqs. (3) and (4) were solved by the finite volume method.

Fig. 13 shows the calculation model used in the molten steel flow analysis. Because the Kakogawa No. 3 slab continuous caster is of the curved type, calculation was carried out up to 4 m from the meniscus in view of the curved profile. For the boundary conditions, free-slip conditions were given to the free surface and solidification wall surface. In order to consider a turbulent flow, calculation was made with a laminar flow with the viscosity coefficient of 100 times.

5.2.2. Three-dimensional Molten Steel Flow Analysis

The fundamental equation for unsteady incompressible viscous flow analysis was based on the Navier-Stokes equation and continuity condition.

\[
\rho \frac{\partial u}{\partial t} + \rho (u \cdot \nabla) u = -\nabla p + \mu \nabla^2 u + J \times B \\
\nV \cdot u = 0
\]

where, \(B\): flux density vector

\(\frac{\partial u}{\partial t} + \rho (u \cdot \nabla) u = -\nabla p + \mu \nabla^2 u + J \times B\)

\(V \cdot u = 0\)

Eqs. (3) and (4) were solved by the finite volume method.

5.2.3. Calculation Results and Findings

For the magnetic field results, as shown in Fig. 14, the distribution of magnetic flux density in the mold thickness direction was measured when casting was not being conducted, and the simulation's was confirmed.

Fig. 15 shows the Lorentz force vector plots when \(t=0\), found from the three-dimensional magnetic field analysis results.

Then, the Navier-Stokes equation was solved using the body force, which was found from the time average of the Lorentz force vector. Fig. 16 shows the calculation results where the casting speed is 1.4 m/min, the mold size is 240 mm \(\times\) 1260 mm, and the nozzle directs at 25° downward.

When M-EMS was not applied, the outlet stream from the nozzle struck against the narrow side of the mold, separating the stream into two flows: one penetrating deeply into the mold and the other turning over and ascending to the meniscus. The following effects were confirmed from the simulation results of M-EMS downward longitudinal stirring:

1. The nozzle outlet stream flow rate reduces,
2. Ascending flow generates at the center of mold thickness, especially just below the nozzle, and
3. The intensity of the flow striking against the mold narrow side is weakened. As a result, the flow descending along the mold narrow side which pene-
Fig. 13. Numerical model of molten steel.

Fig. 14. Magnetic field in the mold.

Fig. 15. Lorentz force vector at the moment (t=0).

Fig. 16. Effect of M-EMS on fluid flow.

Conducting downward longitudinal stirring with a linear-motor type in-mold electromagnetic stirrer (M-EMS) has made it possible to reduce inclusions and gas bubbles especially at the inside accumulation zone of the curved-type slab caster.

Investigation of molten steel flow patterns in the mold and three-dimensional magnetic flux and flow analyses have proved that M-EMS downward longitudinal stirring reduces the nozzle outlet stream penetration depth and decelerates the molten steel flow rate at the meniscus, resulting in stabilization of the meniscus.

We will continue our efforts to establish techniques for proper control of the molten steel flow in the mold in accordance with various operating conditions.

REFERENCES

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Appendix

Assuming that effects of molten steel flow on the magnetic field are negligible, the basic equations of eddy current found from Maxwell’s equation can be expressed as the following:

\[ \nabla \times H = \partial D/\partial t + J \]  \hspace{1cm} (A-1)
\[ \nabla \times E = -\partial B/\partial t \]  \hspace{1cm} (A-2)
\[ \nabla \cdot B = 0 \]  \hspace{1cm} (A-3)

where, \( H \) : magnetic field intensity
\( B \) : flux density
\( J \) : current density
\( E \) : electric field intensity
\( D \) : electric displacement.

These have the following relationship:

\[ J = \sigma E \]  \hspace{1cm} (A-4)
\[ B = \mu H \]  \hspace{1cm} (A-5)

where, \( \mu \) : permeability
\( \sigma \) : conductivity.

Because divergence of flux density is zero in Eq. (A-3), the magnetic vector potential \( A \) as shown in the following equation can be defined:

\[ B = \nabla \times A \]  \hspace{1cm} (A-6)

Substitution of Eq. (A-6) into Eq. (A-2) gives

\[ E = -\partial A/\partial t - \nabla \phi \]  \hspace{1cm} (A-7)

The eddy current density \( J_e \) is expressed as

\[ J_e = -\sigma (\partial A/\partial t + \nabla \phi) \]  \hspace{1cm} (A-8)

where, \( \phi \) : electric scalar potential.

Substitution of Eqs. (A-5) and (A-6) into Eq. (A-1) gives Eq. (A-9).

\[ \nabla \times 1/\mu_e \nabla \times A = \partial D/\partial t + J \]  \hspace{1cm} (A-9)

Because the first term of the right side of Eq. (A-9) \( (\partial D/\partial t) \) can be ignored in the low-frequency region, Eq. (A-9) can finally be expressed as follows:

\[ \nabla \times 1/\mu_e \nabla \times A = J \]  \hspace{1cm} (A-10)

and since in a conductor \( J \) can be divided into source current density \( J_s \) and eddy current density \( J_e \), substitution of Eq. (A-8) into Eq. (A-10) gives

\[ \nabla \times 1/\mu_e \nabla \times A + \sigma (\partial A/\partial t + \nabla \phi) = J_s \]  \hspace{1cm} (A-11)

Then, according to the continuity condition of eddy current in the conductor, the following equation must hold

\[ \nabla \cdot (\sigma \partial A/\partial t + \nabla \phi) = 0 \]  \hspace{1cm} (A-12)