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Improvement of Slab Surface Quality with In-mold Electromagnetic Stirring

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Abstract

The demands for surface quality assurance of sheets and plates have been increased in recent years, reflecting user requirements for higher grades of steel. To meet these requirements, a number of countermeasures, such as pursuing extremely clean molten steels and conditioning low-grade portions have been taken. These approaches, however, lead to a loss of profitability as a consequence of decreased productivity and the steel yield of prime-quality products. Therefore, the surface quality of commercial grade steel must be stabilized. In the continuous casting process, it is important to reduce the off-quality portion due to ladle changing or variation in process parameters. Based on these viewpoints, Kimitsu Works in Nippon Steel Corporation has been active in controlling slab surface quality by use of molten metal flow control, without by use of the nozzle stream, and consequently a new in-mold electromagnetic stirrer (hereinafter abbreviated to "EMS") was installed. This study reports the features and design concept of the new EMS, the resulting effects on slab quality, and theoretical considerations on the effects of initial solidification and cleanliness of slab.

1. Introduction

The required level of slab surface quality has become stricter in recent years as a result of user demands for defect-free coils allowing skipping of acceptance inspection at their plants and enhanced workability of steel materials. For the production of high quality and high performance steel materials, thoroughgoing purification of molten steel, heavy conditioning of cast slabs and various other measures have been taken in the steel-making process. On the other hand, these measures led to a lower prime yield, complicated materials handling, etc. and as a consequence, the deterioration of productivity in the entire production process, increase in quality control costs, etc. and in the bottom line, pressing the profitability of steel-makers. For these reasons, the stabilization of the surface quality of cast slabs is essential in the production of general use products and direct connection from the continuous casting process to downstream processes is required. In the continuous casting process, an important challenge is how to shorten product delivery periods and cut production costs at the same time while maintaining the market-oriented production scheme capable of quickly responding to our customers' requirements.

From this viewpoint, on the basis of the in-mold electromagnetic

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stirring technology[1-4] Nippon Steel Corporation had brought into practical use, Nippon Steel's Kimitsu Works proceeded with the development of a technology to utilize molten steel flow for improving the surface cleanliness and controlling the initial solidification of cast slabs, and established a new in-mold electromagnetic stirring technology[5-9]. This technology is characterized by not relying on the molten steel flow from the immersion nozzle, which is unstable by nature, for controlling the molten steel flow in the mold, but by having a control system independent from it. That is to say, the cleanliness of the surface layer of slabs and stable initial solidification are achieved by creating a molten steel flow independent of the flow from the nozzle spout along the solidification interface.

This paper explains the theory of relating to the mechanisms of the cleaning of the slab surface layer and the stabilization of the initial solidification and the quality improvement effects of the developed technology[6-9].

1.1 Philosophy of Slab Surface Quality Improvement

Firstly, the history of Nippon Steel's efforts for the improvement of slab surface quality is summarized. In 1980, the first in-mold electromagnetic stirring apparatus of Nippon Steel was installed at the Hirohata Works for the purpose of improving the surface quality of the slabs for thin strip products[1,2], and then in 1982, the second apparatus was installed at the Oita Works[3,4], but the casting seed of the casters was comparatively low. Then, as far as into the early 1990s, not only higher productivity but also improved surface quality was required of continuous casters, as the quality level of customer requirements became higher. The fact that the blowholes and non-metallic inclusions caught by and accumulated in the sub-surface layer of cast slabs could be decreased by washing the solidification interface with the molten steel flow from the immersion nozzle had been known empirically[10], the increase of production capacity and higher casting velocity were envisaged[11,12] to enhance the cleanliness of slab surface layers.

Meanwhile, local application of electromagnetic brake was tried for decreasing internal defects[11,12]. The techniques such as the above, however, were based on the utilization of the molten steel flow from the immersion nozzle and therefore, it was practically difficult to maintain stable functioning during long sequential continuous casting operation, because the shape of the nozzle changed from the initial state owing to the fusing damage or clogging as a result of accumulation of non-metallic inclusions inside it[11-14]. While various attempts to control the flow from the nozzle were reported[6,7], the stabilization of the flow from the nozzle was regarded as an important factor for improving the slab surface quality.

In the mid 1990's the growth of the production was slowed down and technical improvement efforts were directed not only to the enhancement of productivity but also to the stabilization of product quality and improvement of production yield through the enhancement of the quality capacity of the process. In this situation, from the viewpoints of (1) homogeneity in the slab width direction, (2) homogeneity in the slab length direction and (3) increase of tolerance for the fluctuation of operation conditions, Nippon Steel considered it important to create at the interface of solidification a molten steel flow independent of the flow from the nozzle spout for securing the surface layer cleanliness and stabilizing the initial solidification of cast slabs, instead of the conventional method relying on the steel flow from the nozzle, which is unstable by nature. Based on this philosophy, a new in-mold electromagnetic stirring technology was introduced.

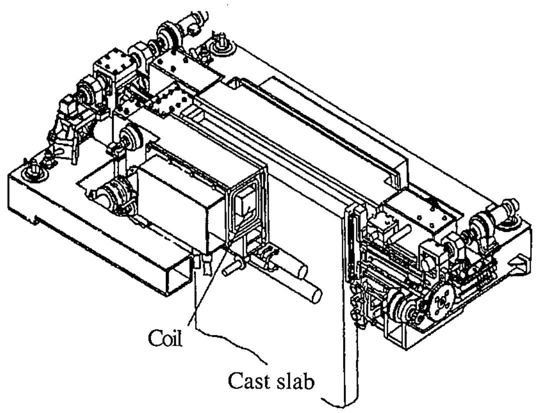
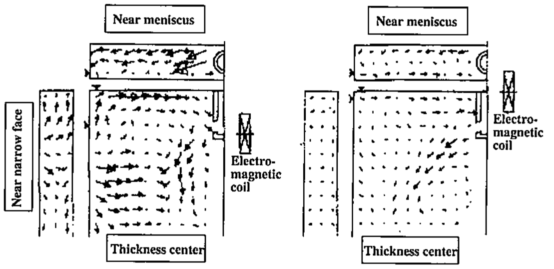


Fig. 1 Schematic illustration of in-mold electromagnetic stirring (EMS) equipment



(a) Case of magnetic field application at nozzle spout level (b) Case of magnetic field application at meniscus

Fig. 2 Result of 1/1 model test using fused metal

1.2 Outline of In-Mold Electromagnetic Stirring Equipment

The equipment of in-mold electromagnetic stirring (EMS) is shown in **Fig. 1**. For finding out an optimum operation condition of the equipment in commercial production, a series of tests were conducted using a real-size model and fused metal[5]. An example of the test results for determining the position of the magnet cores of the EMS equipment is shown in **Fig. 2**. It is clear in the figure that, in case (a) in which magnet cores were positioned at the level of the nozzle spout, a large downward flow was formed by the interference with the flow from the nozzle, and that, in case (b) in which the cores were positioned at the level of the meniscus, the loss of electromagnetic force was large and the velocity of the molten steel flow created by the force was small. The adequate position of the cores for commercial operation was decided based on these findings.

2. Experimental Method

Tests were carried out on a commercial caster for the purpose of clarifying the improvement effects of EMS on the initial solidification and the cleanliness of the surface layer of slabs. The condition of the test casting was as per **Table 1**.

2.1 Investigation of Influence of EMS on Initial Solidification in Mold[15]

To clarify the change of molten steel flow condition in the mold as a result of the application of EMS, the molten steel flow velocity was calculated using Okano's equation[16] from the measurement of

Table 1 Operation condition of tests on commercial caster

Steel grade	Low-C Al-killed steel : C = - 0.05% Middle-C Al-killed steel : C = 0.08 - 0.015%
Slab width	1,200 - 2,250 mm

dendrite angle and separately from this, the change of the molten steel flow velocity in the mold was directly measured using strain sensors[16]. In addition, to clarify the change of molten steel temperature resulting from the change of molten steel flow in the mold, the temperature distribution of the molten steel in the mold was measured using thermocouples[9], and the change of the shape of the initial solidification shell was evaluated by a sulfur addition test.

2.1.1 Measurement of Molten Steel Flow in Mold Using Dendrite

In the measurement of the dendrite angle, test pieces were cut out at a section in right angles to the direction of casting as shown in **Fig. 3**, etched with an acid and their solidification structure was photographed at a magnification of 5. The steel flow velocity was calculated on an assumption that Okano's equation[16] (equation (1)) obtained based on the figures of high carbon steels was applicable to the measured angle of primary dendrite arms to a normal line at a slab surface of any steel grade.

$$\ln V = (\theta + 9.73 \times \ln f + 33.7) / (1.45 \times \ln f + 12.5)$$
$$\text{provided } V < 50 \text{ cm/s} \qquad (1)$$

where, θ: dendrite angle (degree)
f: solidification velocity (cm/s)
V: molten steel flow velocity (cm/s).

2.1.2 Measurement of Molten Steel Flow in Mold by Flow Sensor

A molten steel flow sensor schematically shown in **Fig. 4** was used for directly evaluating the flow condition of molten steel in the mold. The sensor consisting of strain gauges and a refractory brick partially immersed in the molten steel measures the velocity and direction of the molten steel flow by detecting the load of the flow.

2.1.3 Measurement of Molten Steel Temperature in Mold[9]

For investigating the change of molten steel temperature in the mold caused by the application of EMS, molten steel temperature was measured at 9 grid points as shown in **Fig. 5**. The measurement was done using three thermocouples, immersing them together into the molten steel as seen in the figure, and switching EMS from on to off and vice versa.

2.1.4 Investigation of Initial Solidification Shell

A prescribed amount of sulfur reagent was added to the molten steel in the mold as shown in **Fig. 6** while continuing casting at a constant width (2,240 mm) and casting velocity (V = 1.02 m/min with EMS on; V = 1.03 m/min with EMS off). The shape of the initial solidification shell was evaluated by sulfur print method at the section surface of cast slabs shown in **Fig. 7**.

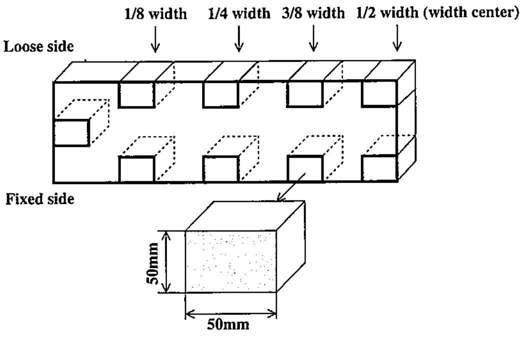


Fig. 3 Sampling position for dendrite angle measurement

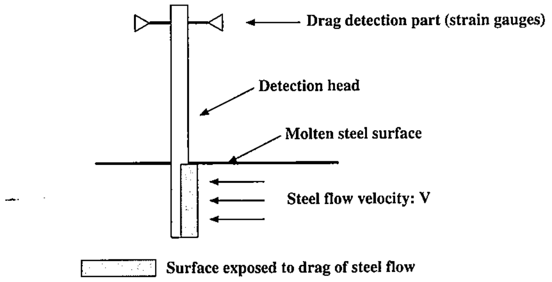


Fig. 4 Schematic illustration of flow velocity sensor

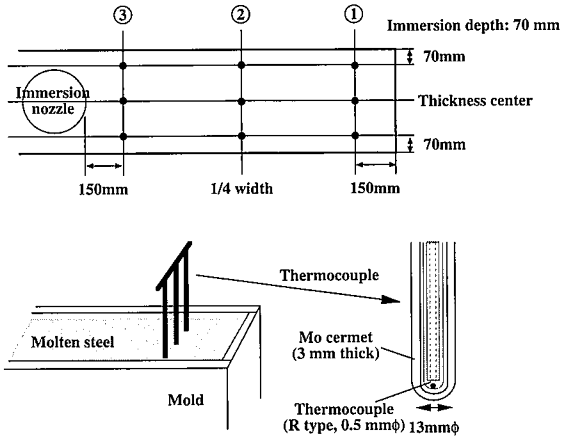


Fig. 5 Measuring method of temperature distribution in mold

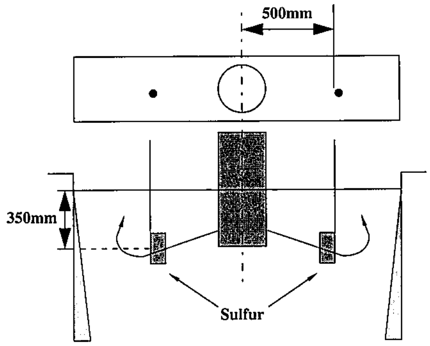


Fig. 6 Schematic illustration of sulfur addition test to steel in mold

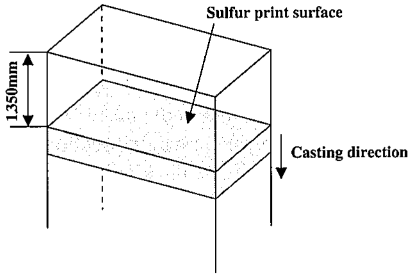


Fig. 7 Sampling position for measuring initial solidification shell thickness

2.2 Investigation of Influence of EMS on Cleanliness of Slab Surface Layer

The distribution of blowholes in the slab surface layer was investigated through sequential grinding test of slabs for the purpose of clarifying the influence of EMS on the cleanliness of the slab surface layer. The amount of non-metallic inclusions in the surface layer was also investigated by the slime method (an evaluation method of non-metallic inclusions by electrolytic extraction).

2.2.1 Investigation of Blowhole Distribution by Sequential Grinding

To evaluate the distribution of blowholes in the width and depth

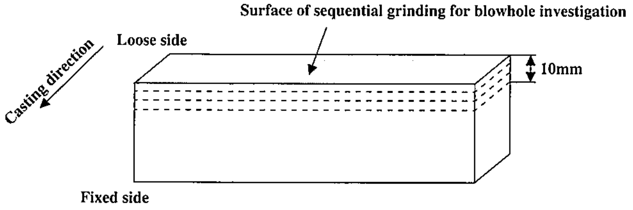


Fig. 8 Sampling position for sequential grinding test

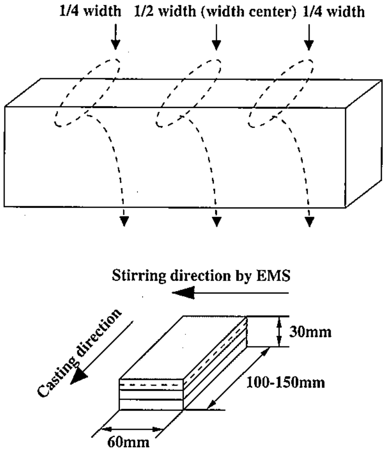


Fig. 9 Sampling position for slime method

directions in the slab surface layer, test pieces were cut out across slab width as shown in **Fig. 8**, and the number of blowholes 200 μm or larger was counted by grinding the test pieces in the thickness direction step by step.

2.2.2 Investigation of Cleanliness of Slab Surface Layer by Slime Method

The entrapment of non-metallic inclusions in the surface layer of slabs was evaluated by the slime method with respect to the non-metallic inclusions 38 μm or more in diameter. Test pieces were cut from three different positions in the width direction as shown in **Fig. 9** and at an interval of 10 mm in the thickness direction. The density of the extracted non-metallic inclusions was measured after classifying them by morphology into alumina clusters and spherical non-metallic inclusions and by diameter.

3. Experimental Results

3.1 Measurement Result of Molten Steel Flow in Mold

Fig. 10 shows the relation between the dendrite angle calculated using Okano's equation[16] and the molten steel flow velocity measured by the flow sensor. They were in considerably good agreement. Based on this result, the molten steel flow velocity was calculated thereafter by Okano's equation[16] from measured dendrite angle. As is shown in **Fig. 11**, it was made clear that, although the direction of flow was temporarily reversed at the positions where the stirring flow of EMS interfered with the return flow from the meniscus, a stable circulating flow was formed in the average of long terms. It is understood from Fig. 11 that, in terms of the flow velocity calculated from the dendrite angle measurement, an average, stable flow velocity of 20 cm/min or so in the slab width direction is obtained.

3.2 Measurement Result of Molten Steel Temperature in Mold

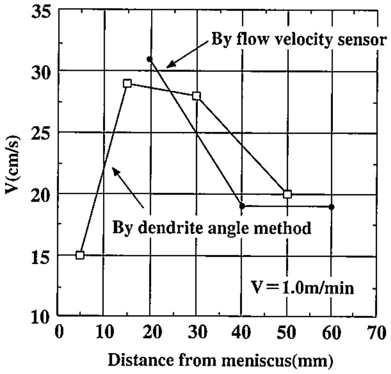


Fig. 10 Comparison of steel flow velocities calculated from dendrite angle and measured by flow velocity sensor

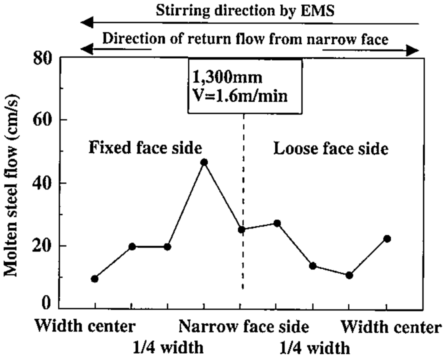


Fig. 11 Distribution of steel flow velocity calculated from dendrite angle

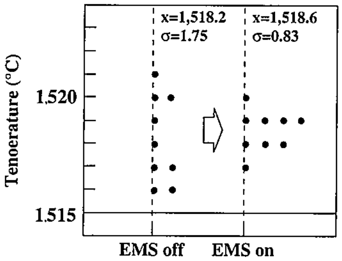


Fig. 12 Temperature fluctuation with and without EMS

Fig. 12 shows the temperature change at the 9 measuring points in the mold. By the use of EMS, it was confirmed, the molten steel temperature was changed by 1 to 2 °C or so at each point and while the temperature change was not the same in all the measuring points, the steel temperature was homogenized in the mold section as a whole.

3.3 Investigation Result of Initial Solidification Shell Thickness

Fig. 13 shows the solidification shell thickness in the slab width direction measured by the sulfur print method. As is clear from the figure, local delays in solidification were reduced, the fluctuation of shell thickness decreased and thus, uniform shell thickness was realized by the application of EMS.

3.4 Investigation Result of Blowhole Distribution in Slab Surface Layer

Fig. 14 shows the density of blowholes across slab width at different distances from the surface. The number of blowholes concentrated in the subsurface layer was significantly reduced by the application of EMS. No local concentration of blowholes in the width direction was observed, though not shown in the figure.

3.5 Investigation Result of Non-metallic Inclusions in Slab Surface Layer

Fig. 15 shows the change of steel cleanliness in the layer from the surface to a depth of 10 mm in the casting direction. The surface

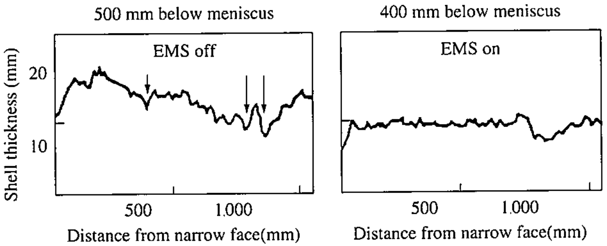


Fig. 13 Initial solidification shell thickness measured by sulfur print

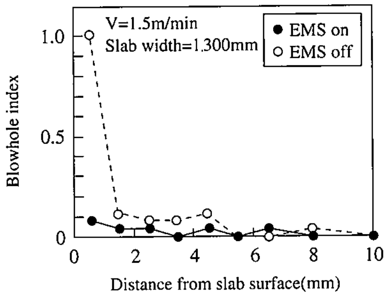


Fig. 14 Effect of EMS on distribution of surface layer blowholes

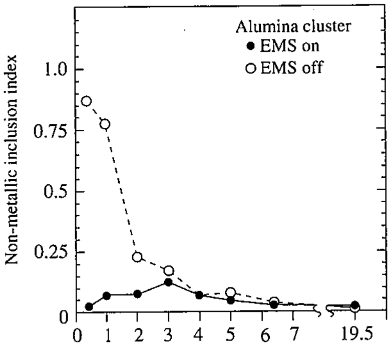


Fig. 15 Effect of EMS on distribution of non-metallic inclusions in casting direction

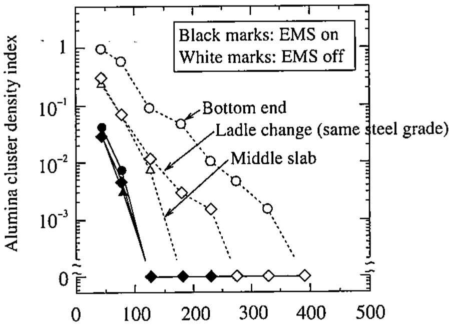


Fig. 16 Effect of EMS on diameter distribution of alumina clusters

cleanliness at the bottom end (casting start) was remarkably improved by EMS at the position roughly 0.4 m after the start of casting. A comparison of the surface layer cleanliness at the bottom end, a joint of same steel grade (ladle change portion) and a steady state portion (middle slab) is shown in **Fig. 16**. When MES was used, the steel cleanliness in the layer from the surface to a depth of 10 mm was significantly improved even at the bottom end: whereas non-metallic inclusions up to 400 µm in diameter were observed in the slab cast without EMS, no non-metallic inclusions 106 µm or more in diameter were found in the slab cast with EMS. It is clear form these results that, by the application of EMS, the steel cleanliness in the slab surface layer is improved all along the casting length of sequential continuous casting to the level of the steady state portion.

4. Discussions

4.1 Influence of Molten Steel Flow on Homogenization of Initial Solidification

As seen in Fig. 11, when EMS is applied, a homogeneous circulating flow is created at the interface of solidification all across slab width and throughout the casting time. This is considered to homogenize the steel temperature distribution in the mold as shown in Fig. 12, and stabilize the influx of the powder and as a result, make the heat transfer in the mold even as shown in **Fig. 17**, and reduce the fluctuation of the thickness of initial solidification shell as seen in Fig. 13. The influence of the molten steel flow on the homogeneity of the initial solidification shell has been verified through experiments by Yamamura et al.[17)]

Then, the mechanism that brought about the effect of homogenizing the solidification shell thickness from the viewpoint of the formation frequency of solidification nuclei[18)] was investigated. Since EMS proved effective for preventing longitudinal cracks of slabs, a middle carbon steel for plate products was selected as the subject of study, and its solidification structure at a depth 0.2 mm from the surface was exposed by etching with picric acid for observation with a microscope. In a micrograph of a magnification of 25, as shown in **Fig. 18**, the crystals having dendrite arms in the same direction were grouped as having grown from a common nucleus. Then, the number of the groups in a unit area was defined as the frequency of nucleus formation, and the frequencies with EMS and without were compared. In the above study, the nucleus formation frequency was 5.06/mm^2 with EMS, and 1.94/mm^2 without, proving that the application of EMS accelerated the nucleus formation. From this, it was made

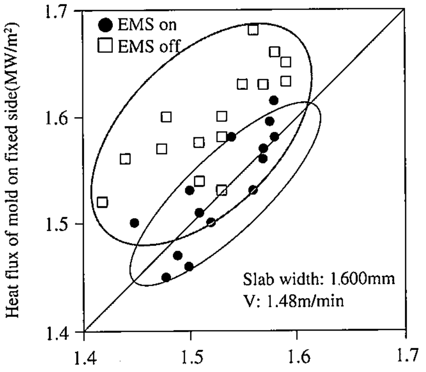
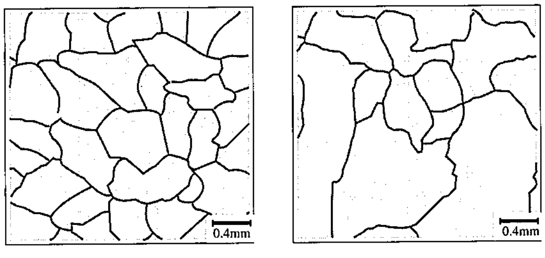


Fig. 17 Effect of EMS on heat flux of mold



(a)EMS on (a)EMS off

Fig. 18 Solidification structure at 0.2 mm from slab surface

clear that EMS accelerated the nucleus formation in the mold and contributed to the formation of a homogeneous initial solidification shell.

4.2 Influence of Molten Steel Flow on Cleanliness of Slab Surface Layer

With respect to the influence of molten steel flow on the cleanliness of slab surface layer, some papers had pointed out the washing effect of the steel flow at the interface between the shell and molten steel[1,2]. However, the influence of the steel flow velocity on the behavior of non-metallic inclusions in the slab surface layer had not been made clear. **Figs. 19 and 20** show the number of alumina clusters in the layer from 5 to 10 mm from the slab surface and the maximum diameter of the non-metallic inclusions entrapped in the layer in relation to the molten steel flow velocity calculated by the Okano's equation[16]. The number of alumina clusters entrapped in the slab surface layer decreases and the maximum diameter decreases as the steel flow velocity increases. As was shown in Fig. 16, the cleanliness of the slab surface layer with EMS is influenced more by the steel flow velocity at the solidification interface than the cleanliness of the steel coming into the mold. It was made clear from the above that it was possible to secure the cleanliness of the slab surface layer in a stable manner by creating at the solidification interface a stable steel flow independent of the flow from the nozzle spout through the use of EMS.

Next, the influence of the molten steel flow velocity on the diameter of the non-metallic inclusions captured in the solidification shell is examined, using the mathematical model Sawada et al. proposed[19] for the analysis of the dynamic behavior of non-metallic inclusions near the solidification shell. The concept of the model is shown in **Fig. 21**. According to the model, non-metallic inclusions in molten steel are subjected to two different forces: one is the force to trap it into the solidification shell caused by interfacial tension gradient; and the other is the force to expel it from the solidification shell caused by the washing effect owing to a pressure gradient in a boundary layer. The higher the steel flow velocity at the solidification interface, the larger the velocity gradient and pressure gradient in a velocity boundary layer become and as a consequence, the larger the force of the washing effect to expel non-metallic inclusions from the solidification shell becomes. Here, the larger the diameter of the non-metallic inclusions, the larger the washing effect becomes.

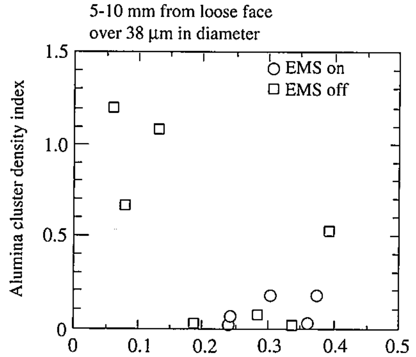


Fig. 19 Effect of steel flow velocity on alumina cluster density

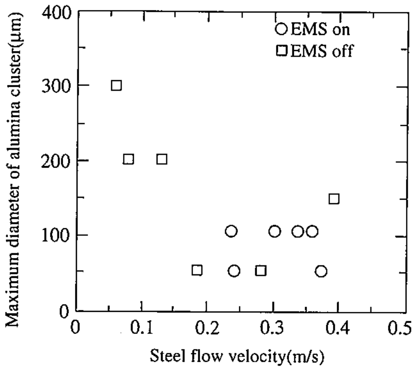


Fig. 20 Effect of steel flow velocity on maximum diameter of alumina cluster

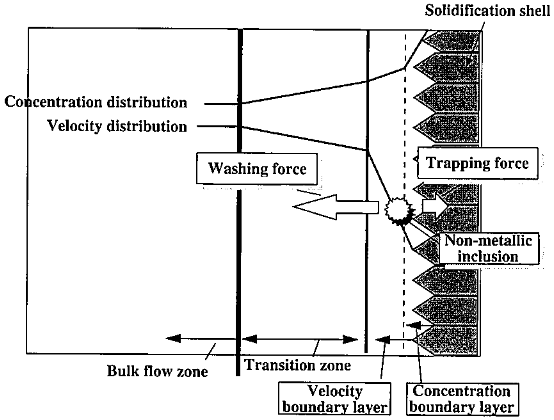


Fig. 21 Schematic illustration of forces working on non-metallic inclusion grain near solidification shell

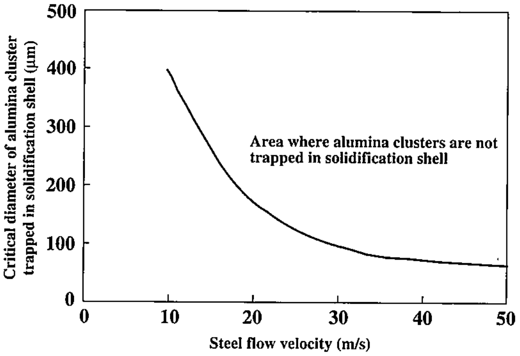


Fig. 22 Steel flow velocity and maximum diameter of non-metallic inclusions trapped in solidification shell

While it is true that the interfacial tension gradient increases as the steel flow velocity at the solidification interface increases, since the concentration boundary layer is smaller than the velocity boundary layer, the force to catch the non-metallic inclusions caused by interfacial tension gradient owing to the concentration gradient of the solutes in the molten steel is smaller than the force of the washing effect to expel non-metallic inclusions from the solidification shell. This is considered to be the reason why the diameter of the non-metallic inclusions caught in the solidification shell becomes smaller as the steel flow velocity at the solidification interface is increased by EMS, as shown in the model calculation result[19] of **Fig. 22**.

5. Product Quality Improvement Effects of EMS Application

Figs. 23 and 24 show the effects of EMS to decrease the surface defects of the slabs for sheet products and the longitudinal cracks of middle carbon steel slabs. Significant improvement is brought about

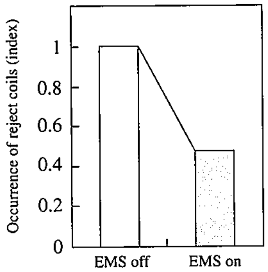


Fig. 23 Decrease in surface defects of low-C steels by EMS

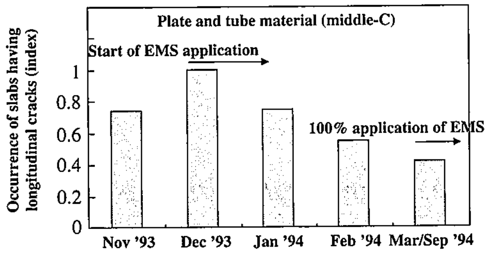


Fig. 24 Decrease in longitudinal cracks of slabs by EMS

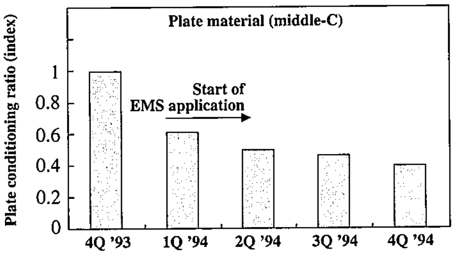


Fig. 25 Effect of EMS on plate conditioning ratio

by EMS in either of them. Since the installation of EMS, the occurrence of the alarm (casting anomaly alarm) of sticking-induced breakout using the information of thermocouples embedded in the mold has decreased dramatically[6] and the operation of casters has been much stabilized. As a consequence, the ratio of the plate products requiring conditioning has been greatly lowered as shown in **Fig. 25**.

6. Summary

For the purpose of improving slab surface quality, the flow of molten steel in a continuous caster mold was optimized by the application of in-mold electromagnetic stirring (EMS) technology, and the theoretical effects of EMS were made clear. Thus, it has been made possible to secure the cleanliness of the surface layer of slabs and to stabilize the initial solidification by the application of linear motor type EMS to the solidification interface as a means to directly control the molten steel flow in the mold, instead of the steel flow from the immersion nozzle, which is unstable by nature. As a result, not only product quality has been enhanced and stabilized at a higher level but also casting operation has been stabilized.

The EMS technology has been applied to commercial production at No. 2 continuous caster of Kimitsu Works of Nippon Steel since April 1994 and at No. 3 continuous caster of Kimitsu Works since August 1996, bringing about satisfactory results. The effectiveness of the technology for enhancing cast slab quality has been confirmed also at other steel-makers[20].

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