Steel Flow Control in Continuous Slab Caster Mold by Traveling Magnetic Field

Jun Kubota*, Noriko Kubo**, Toshio Ishii***,
Makoto Suzuki****, Norichika Aramaki* and Ryuzo Nishimachi*****

* Manager, Steelmaking Dept., Fukuyama Works
** Senior Research Engineer, Materials Solution Research Center, Materials & Processing Research Center
*** Team Manager, Materials Solution Research Center, Materials & Processing Research Center
**** Team Manager, Steelmaking Technology Development Dept., Materials & Processing Research Center
***** Assistant Manager, Steelmaking Dept., Fukuyama Works

Steel flow control in a continuous slab caster mold is effective for preventing mold powder entrapment and maintaining high slab quality. NKK has developed steel flow control technology that utilizes a traveling magnetic field to optimize the flow of steel in the mold from the start to the end of casting. This paper describes the features of this technology.

1. Introduction

Continuous casting is a liquid to solid phase transformation process. Fundamental characteristics of the final steel products are established during this process. Cleanliness of the steel is one of the critical variables that is determined in this process. In recent years, the casting speed has been continuously increased to raise production efficiency, but this has also increased the density of kinetic energy of the molten steel in the continuous caster mold. The increase in kinetic energy tends to cause non-uniform growth of the solidified shell in the mold and promotes entrapment of non-metallic inclusions into the molten steel. Accordingly, control of the molten steel flow in the mold has become an important technology to prevent operational problems such as breakout and to stabilize the continuous caster operation. Steel flow control is also important for reducing quality defects and improving the quality and yield of the final products.

Two types of technology are combined to control the molten steel flow in the mold[1),2)] : the first is technology for estimating or detecting the state of molten steel flow in the mold, while the second is technology for controlling and optimizing the state of the molten steel flow. The latter includes technology for controlling the fundamental parameters of the continuous caster operation, such as the casting speed, the shape and depth of the submerged entry nozzle[1),3),4)], and the argon gas flow rate. However, each of these parameters may influence operational variables beyond those of the molten steel flow[5)]. Therefore, the ranges in which these parameters can be changed are limited in many cases. In contrast, technology for using electromagnetic force on the molten steel in the mold provides the possibility for flexibly controlling the molten steel flow without being subjected to these limitations.

This paper describes the effect of controlling the molten steel flow in the mold of a continuous slab caster by using a traveling magnetic field generator and focuses on the results of a study where this technology was applied to a commercial facility.

2. Objective of controlling molten steel flow in mold

Mold powder that is trapped in molten steel during continuous casting becomes non-metallic inclusions in the steel. The main objective of the study was to find a way to prevent mold powder from being entrapped in the molten steel and caught in the solidified shell.

Mold powder tends to be trapped in the molten steel when the flow speed of the molten steel in the mold is increased. Many papers have been published with regard to this phenomenon[6)-9)]. Model experiments indicate that the meniscus of the molten steel may shave part of the molten mold powder, and that the vortexes generated at the meniscus may cause entrapment. The critical molten steel flow velocity under the meniscus (meniscus flow velocity) at which entrapment starts has been reported to be 0.13 to 0.20 m/sec[6)-9)].

Entrapped droplets of molten mold powder are ultimately exposed as sliver defects on the surface of rolled products. We identified slivers that originated from mold powder on cross-sections of rolled products by EDS (Energy-dispersive X-ray Spectrometry), and microscopically measured the distances from the product surface to these inclusions. These distances were then converted into distances from the slab surface to the molten mold powder droplets[10]. The study revealed that the molten mold powder droplets tend to penetrate deeper into the slab when the casting speed is increased. This is presumably because entrapped droplets of molten mold powder are carried by the flow of molten steel in the mold and transported downward along the strand.

In some cases, surface defects are generated in final products due to mold powder even when the molten steel flow velocity in the mold is low. In particular, these defects are often generated in ultra-low carbon steels. These surface defects frequently appear at positions corresponding to the slab corners. Microscopic observation of cross-sections of positions near slab corners along the casting direction showed that the inclusions were caught where the end of the solidified shell had grown in a hook-like shape along the meniscus[11]. The hook-like growth at the end of the solidified shell is probably enhanced by insufficient supply of heat to the meniscus[12].

Entrapment of mold powder in the molten steel causes product surface defects in both cases where the meniscus flow velocity is excessively high or low. **Fig.1** shows the result of an investigation by Teshima et al. on the relationship between an index of the molten steel momentum directly beneath the meniscus in the vicinity of the narrow side of the mold (the "F value"[1]) and the surface defect frequency of cold-rolled coils[2]. Since the F value represents the magnitude of the meniscus flow velocity[2], the relationship between the F value and the surface defect frequency indicates that surface defects can be prevented by controlling the meniscus flow velocity in an optimum range[2].

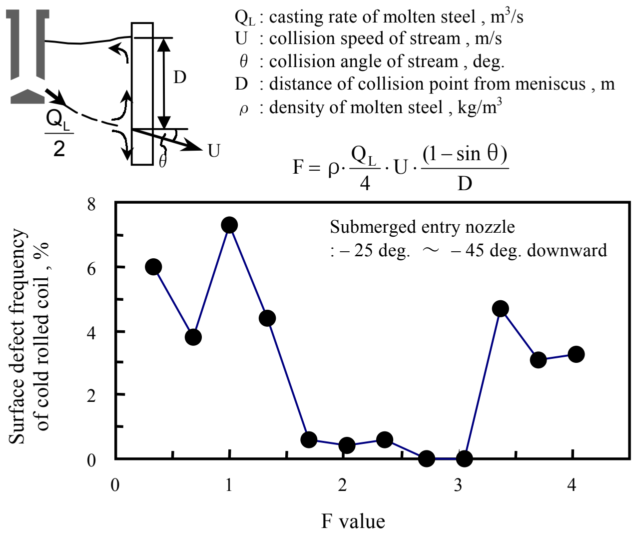

Fig.1 Relationship between F value and surface defect frequency on cold rolled coil [1]

3. Traveling magnetic field generator for controlling steel flow in mold

3.1 Basic concept

The traveling magnetic field generator discussed in this paper applies a magnetic field directly to the jet of steel spouting out of a submerged entry nozzle. **Fig.2** shows schematic drawings of the action. Two types of actions are applied to the spouting stream of molten steel by changing the traveling mode of the magnetic field. In the first mode, the magnetic field travels in a direction that is counter to the spouting stream of molten steel, thus decelerating it. This type of magnetic field traveling mode is referred to as EMLS (Electro-Magnetic Level Stabilizer). The second mode has the magnetic field that travels in the same direction as the spouting stream of the molten steel, thus accelerating it. This type of magnetic field traveling mode is referred to as EMLA (Electro-Magnetic Level Accelerator).

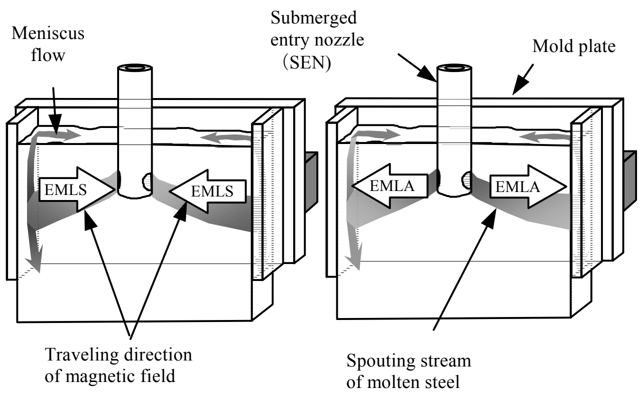

Fig.2 Driving force imposed upon molten steel by EMLS and EMLA

A linear motor type magnetic field generator was installed along the two wide sides of the mold to generate a traveling magnetic field. **Fig.3** is a schematic drawing of the magnetic field generator. A magnetic flux is generated by the two coils in the magnetic field generator placed at either side of the mold and penetrates the mold in the thickness direction, as shown in the figure. In the EMLS mode, the magnetic flux travels from the narrow side of the mold toward the submerged entry nozzle, while the flux travels in the opposite direction in the EMLA mode.

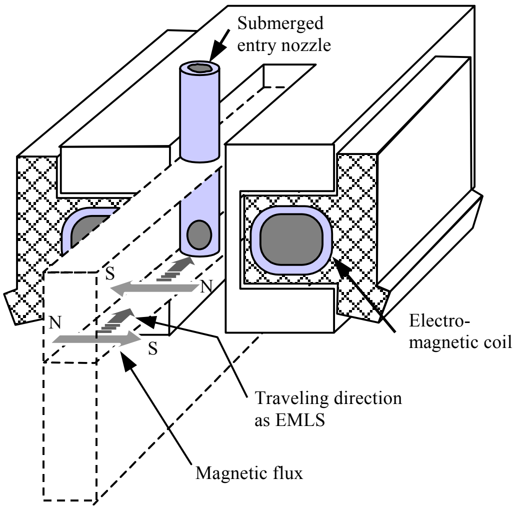

Fig.3 Schematic illustration of installation of the magnetic field generator for EMLS and EMLA

3.2 Specification of magnetic field generator applied to commercial facility

Table 1 shows specifications of the traveling magnetic field generator that was installed in a commercial facility. The rated value of the magnetic flux density is a maximum value over space and time measured in air when an electric current frequency of 0.5 Hz was applied to the magnetic field generator. The magnetic flux density is controlled by adjusting the applied current. **Fig.4** shows a steady-state distribution of magnetic flux density along the width and height directions, where the origin of distance measurement is set at the center point in the width, thickness, and height of the mold. The magnetic flux density was set to be maximum near the origin along the mold height direction and at about 0.35 m from the origin along the mold width direction.

Table 1 Specifications of the traveling magnetic field generator

Magnetic field mode	Linear traveling
Capacity	2000kVA-AC/strand
Voltage	430V/Max.
Current	2700A/Max.
Frequency	0Hz～2.6Hz

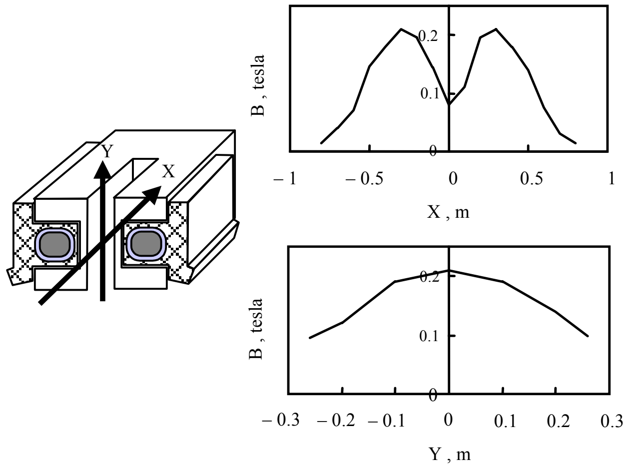

Fig.4 Magnetic field profile of the traveling magnetic field generator

4. Effect of controlling molten steel flow in mold

4.1 Effect on meniscus level fluctuation

First, the effect of control on the fluctuation of the meniscus level was studied at a commercial facility. An eddy current distance meter was used to measure the meniscus level at a cross point 0.058 m from both the narrow side and wide side of the mold. The measuring point is the position where the spouting stream of molten steel reaches the surface of the melt after colliding against the narrow side of the mold and ascending along the narrow side. **Fig.5**(a) shows an example of the measurements obtained when EMLS was applied. The meniscus level fluctuation was reduced to about one third of that where EMLS was not applied. The average level of the meniscus was also lowered. Considering that the amplitude of the meniscus level fluctuation in the vicinity of the narrow side of the mold is proportional to the molten steel flow velocity at that position[2], the fluctuation was probably reduced because the spouting stream was decelerated by the EMLS, and the steel flow was slowed down by the time it reached the measuring point. **Fig.5**(b) is an example when EMLA was applied. In this case, the meniscus level fluctuation increased because the spouting stream was accelerated.

4.2 Effect of control on meniscus flow velocity

4.2.1 Method of measuring meniscus flow velocity

Meniscus flow velocity was measured by two methods. In the first method, which is shown in **Fig.6**(a), the end of a rod, 0.02 m in diameter and 0.47 m in length, is dipped into the molten steel, while the other end is supported by a pivot where the rod can freely rotate. The drag induced on the rod by the molten steel flow balances against the weight of the rod when the rod is inclined at a certain angle. This angle of inclination is measured and converted to

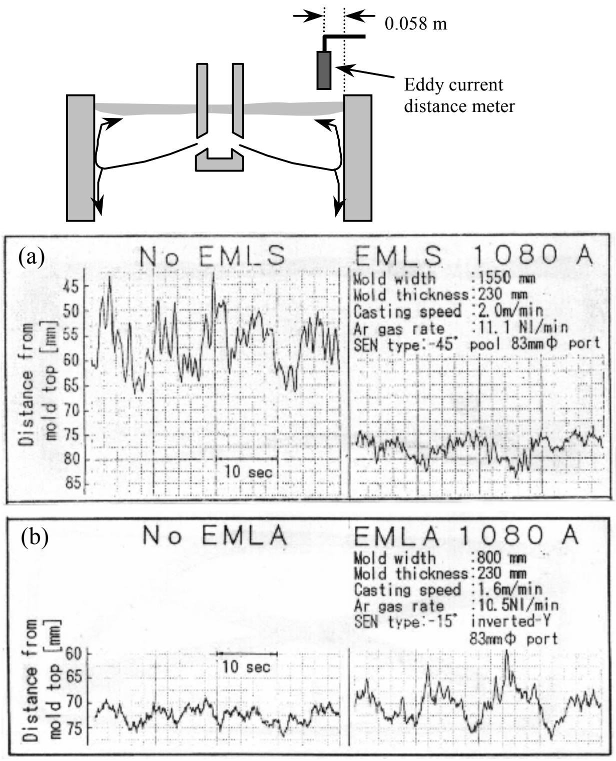

Fig.5 Change of meniscus level fluctuation in the vicinity of narrow side of mold by EMLS and EMLA

a molten steel flow velocity. This method is referred to as the "inclination measuring method." In the second method, which is shown in **Fig.6**(b), a load cell is attached to the rod to directly determine the drag induced on the rod by the molten steel flow. This method is referred to as the "drag measuring method." The rod is made from Mo-ZrO_2 cermet[13]. The dipping depth of the rod is 0.1 m.

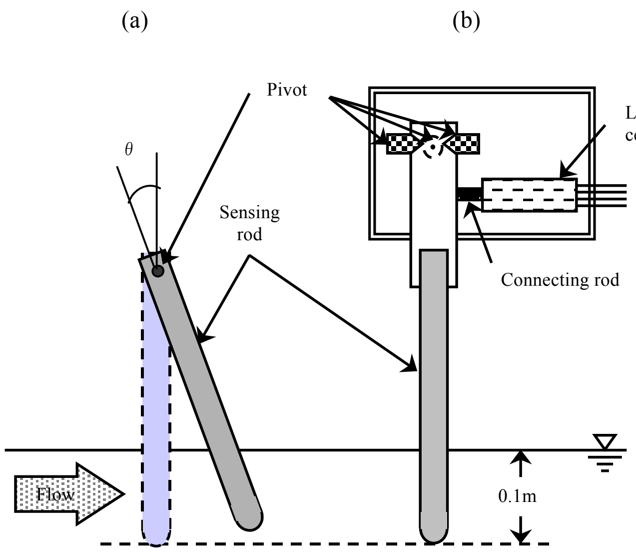

Fig.6 Schematic illustration of devices for meniscus flow tachimetry

4.2.2 Result of measuring meniscus flow velocity

Fig.7 shows the time-series variation of the meniscus flow velocity when EMLS was applied, as measured by the drag measuring method. The drag was reduced by the applied EMLS and stabilized in about 45 seconds. EMLS also reduced the oscillation width of the drag. The energy spectrum of the oscillation of the drag was proportional to about the –5/3 power of the oscillation frequency[14], suggesting that the oscillation was caused by turbulent vortex[15]. The result shows that the EMLS also attenuates the turbulent flow energy under the meniscus.

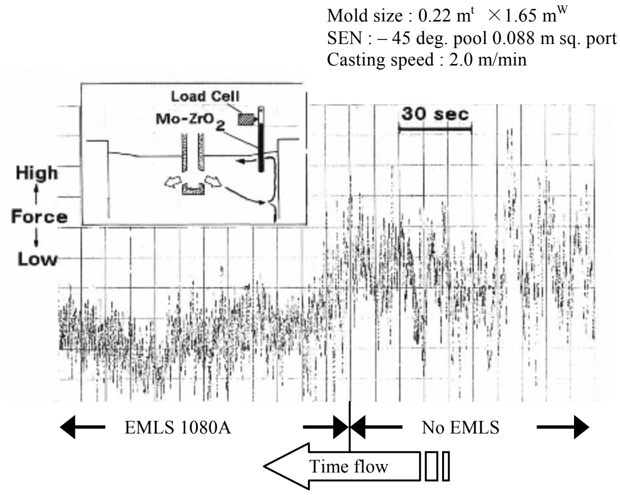

Fig.7 Time-series change of meniscus flow velocity by EMLS

Fig.8 shows meniscus flow velocities measured by the inclination measuring method when EMLS and EMLA were applied at various current levels. The measurement was carried out at a point on the centerline of the thickness of the mold and was 0.2 m from the narrow side of the mold toward the submerged entry nozzle. The vertical axis of the graph is the meniscus flow velocity. The flow direction was from the narrow side of the mold to the submerged entry nozzle (i.e., the "forward direction"). The horizontal axis of the graph is the applied electric current. The center position is a state where neither EMLS nor EMLA is applied, while the left side indicates the applied current for EMLA, and the right side for EMLS. In the EMLS condition, the meniscus flow velocity was continuously controlled to an arbitrary level down to 0.1 m/sec or less by adjusting the applied current. In the EMLA condition, the meniscus flow velocity is accelerated. This effect is particularly significant when the casting speed is low, and therefore the spouting stream flow velocity is low.

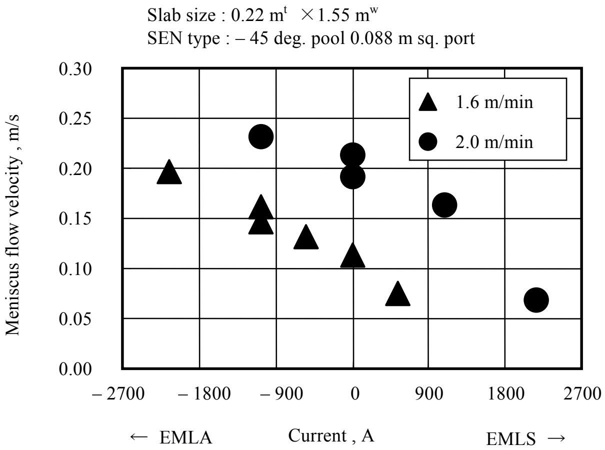

Fig.8 Change of time-averaged meniscus flow velocity in the vicinity of narrow side of mold by EMLS and EMLA at various intensities

Next, the measuring point was changed to the midpoint between the narrow side of the mold and the submerged entry nozzle (the "quarter width point"). **Fig.9** shows the meniscus flow velocity when EMLS was applied. The positive sign of the flow velocity on the vertical axis indicates that the flow is from the narrow side to the submerged entry nozzle, while a negative sign indicates that the flow is the opposite direction. In contrast to the measurement near the narrow side shown in **Fig.8**, the meniscus flow velocity decreased down to 0 m/sec when the EMLS current was increased. With further increases of the current, the flow direction was reversed (i.e., in the "backward direction"), and the flow velocity was increased in the backward direction. With regard to this phenomenon, a numerical electromagnetic fluid simulation[16] was applied

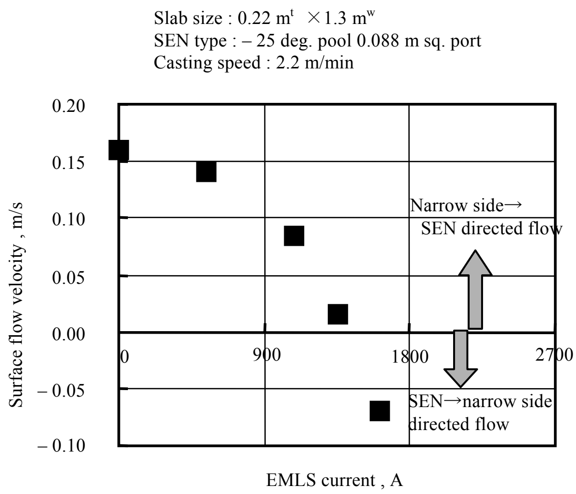

Fig.9 Change of time-averaged meniscus flow velocity at quarter-width point by EMLS and EMLA at various intensities

to obtain a profile of the meniscus flow velocity along the width of the mold under varied EMLS currents. **Fig.10** shows the result of the simulation. When EMLS with an intensity of 0.07T was applied, the flow velocity near the quarter width point from the submerged entry nozzle was significantly reduced, and part of the flow became backward. When the EMLS intensity was increased to 0.11T,

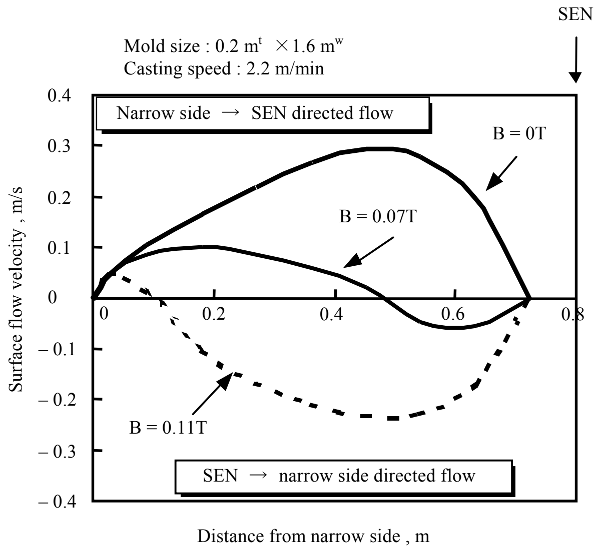

Fig.10 Calculated profile of meniscus flow velocity along mold width direction at different EMLS intensities

the flow became backward over the whole range. **Fig.11** shows the result of measuring the meniscus flow velocity at a commercial facility where an EMLS of 0.075T was applied. The figure shows an intermediate profile between those derived from simulations where magnetic fields of 0.07T and 0.11T were applied. Thus, it was found that the component of meniscus flow velocity heading from the narrow side to the submerged entry nozzle begins to attenuate in the vicinity of the submerged entry nozzle when

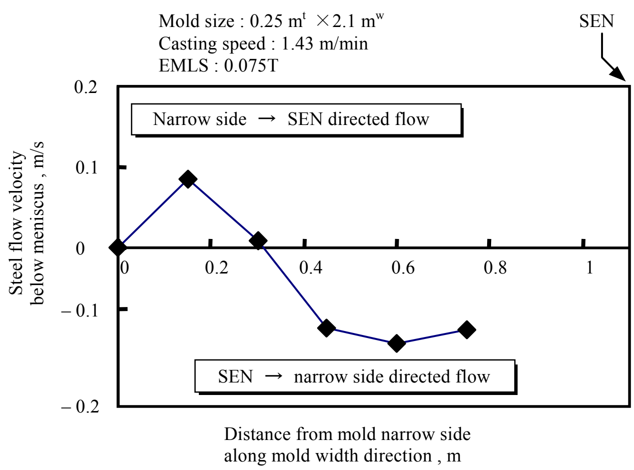

Fig.11 Measured profile of meniscus flow velocity

EMLS is applied. This is probably because the molten steel in the mold is driven by the traveling magnetic field of the EMLS to converge in the vicinity of the submerged entry nozzle, head upward to the meniscus, and then turn in a direction that is counter to the original meniscus flow.

4.2.3 Formulation of braking effect on meniscus flow

Next, the effect of decelerating the meniscus flow (braking effect) by applying EMLS was described mathematically. Based on flow velocity measurements taken at a commercial facility, deceleration of the meniscus flow by EMLS was considered to arise from the combination of the two types of braking effects. The first is caused by the magnetic field acting directly on the spouting stream, thereby decelerating the meniscus flow, as illustrated in **Fig.12**(a). Since EMLS is a traveling magnetic field, it not only slows the spouting stream, but also drives molten steel in the mold other than the spouting stream, as shown in **Fig.12**(b). As a result, the second braking effect is caused by the molten steel in the mold that is driven by the magnetic field in a direction that is counter to the original forward meniscus flow.

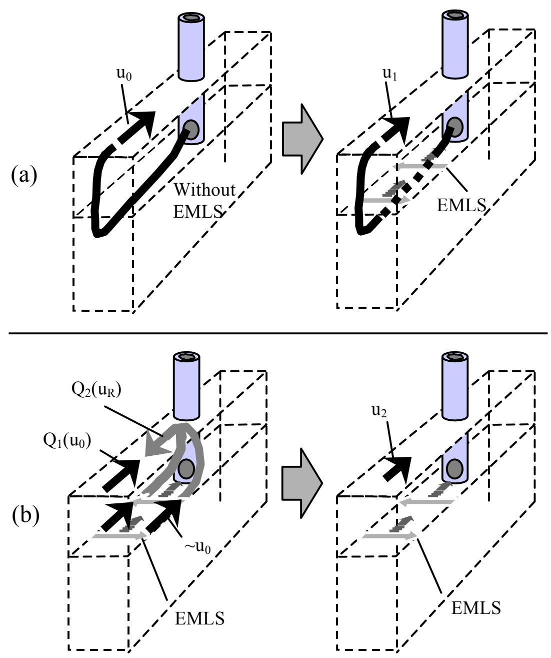

Fig.12 Schematic illustration of meniscus flow braking mechanism by EMLS

In general, when a magnetic field having a magnetic flux density B is applied to a conductor having a density ρ and conductance σ at a relative velocity u, the resulting electromagnetic force F per unit volume is expressed by Eq. (1).

$$F=\sigma \cdot u \cdot B^2 \qquad \cdots\cdots(1)$$

When this electromagnetic force is applied for a period of time Δt, the absolute value of the change in velocity Δu is expressed by Eq.(2).

$$\Delta u=(\sigma \cdot u \cdot B^2/\rho)\cdot \Delta t \qquad \cdots\cdots(2)$$

Regarding the first braking effect, the meniscus flow velocity and the spouting stream flow velocity when EMLS is not applied are expressed by v_0 and u_0, respectively, as shown in **Fig.12**(a). These velocities are expressed by u_1 and v_1, respectively, when EMLS is applied. The traveling velocity of the magnetic field of the EMLS is w, and the relative velocity of the magnetic field viewed from the spouting stream is $(v_0 + w)$. The velocity change rate r_1 of the meniscus flow induced by the EMLS is expressed by Eq.(3).

$$\begin{aligned} r_1 &= |u_1 - u_0|/u_0 \\ &\propto |v_1 - v_0|/v_0 = \Delta v/v_0 \\ &= (\sigma/\rho)\cdot(v_0+w)/v_0 \cdot B^2 \cdot \Delta t \end{aligned} \qquad \cdots\cdots(3)$$

Since v_0 and w have a similar magnitude, the term $(v_0 + w)/v_0$ can be eliminated as a constant. When (σ/ρ) is expressed as α, and Δt is represented by the ratio of the flow velocity of the spouting stream (v_0) to the mold width (L), Eq.(3) can be rewritten as Eq.(4).

$$r_1 \propto \alpha \cdot (L/v_0)\cdot B^2 \qquad \cdots\cdots(4)$$

The second braking effect is discussed referring to **Fig.12**(b). The original meniscus flow in the forward direction is expressed by Q_1. The meniscus flow in the backward direction, which is induced by the molten steel in the mold (other than the spouting stream) that is being driven by the EMLS traveling magnetic field, is expressed by Q_2, and its flow velocity is expressed by u_R. Here, the flow velocity of molten steel in the mold other than the spouting stream is assumed to be u_0. For an effective length of the magnetic field in the mold width direction of L_e, the velocity change rate r_R is expressed by Eq.(5) in the same manner as Eq.(4).

$$\begin{aligned} r_R &= |u_R - u_0|/u_0 = \Delta u/u_0 \\ &\propto \alpha \cdot (L_e/w)\cdot B^2 \end{aligned} \qquad \cdots\cdots(5)$$

The velocity change Δu_2 from u_0 to u_2, which results from the compounding of Q_1 and Q_2, is proportional to the impulse of the collision between Q_1 and Q_2. The collision time of Q_1 and Q_2 is assumed to be inversely proportional to the relative velocity $(u_0 + u_R)$, and the force is assumed to be a drag acting between Q_1 and Q_2 and proportional to $(u_0 + u_R)^2$. The impulse is then proportional to $(u_0 + u_R)$. Therefore, if u_0 is constant, the value of Δt is proportional to u_R. As a result, the velocity change rate r_2 resulting from the second braking effect is expressed by Eq.(6).

$$\begin{aligned} r_2 &= \Delta u_2/u_0 \\ &\propto u_R/u_0 \\ &\propto r_R \\ &\propto \alpha \cdot (L_e/w) \cdot B^2 \end{aligned} \quad \cdots\cdots(6)$$

Consequently, considering that both the first and second braking effects are simultaneously imposed by the application of EMLS, the combined braking effect R by EMLS is expressed by Eq.(7), where u_e is the meniscus flow velocity while EMLS is applied.

$$\begin{aligned} R &= 1-(u_0-u_e)/u_0 \\ &= 1-r_1 \cdot r_2 \\ &= 1-\alpha^2 \cdot (L \cdot L_e)/(v_0 \cdot w) \cdot B^4 \end{aligned} \quad \cdots\cdots(7)$$

The coefficient $(\alpha^2 \cdot L \cdot L_e)/w$ of the term B^4 has a value that is inherent to each continuous caster and magnetic field generator and is expressed by β. Then, Eq.(7) can be rewritten as Eq.(8).

$$R = 1-\beta \cdot B^4/v_0 \quad \cdots\cdots(8)$$

Using the result obtained from the measurements at the commercial facility as shown in **Fig.9**, the value R was plotted against the values of B^2/v_0 and B^4/v_0 on the horizontal axis, as shown in **Figs.13**(a) and (b). The value of v used here was obtained from the measurements of the 1/3-scale water model of the commercial facility that has Fluid number similarity. **Fig.13**(a) has the value of B^2/v_0 on the horizontal axis and assumes only the braking effect by r_1 derived from Eq.(4). The graph shows no proportional relation. It is easily foreseen that the relation will not be proportional even when the value on the horizontal axis is changed from B^2/v_0 to B^2/w. Therefore, the braking effect of EMLS on the meniscus flow velocity does not appear to be governed solely by either the first or the second braking effect. The braking effect is also not described by the simple sum of these two braking effects. On the other hand, plotting R against B^4/v_0 in accordance with Eq.(8) provides a good linear relation, as shown in **Fig.13**(b). Therefore, the braking effect of EMLS on the meniscus flow velocity can be expressed by the product of the first and second braking effects. Thus, measurements at the commercial facility confirmed that the EMLS meniscus flow braking effect is described by the product of the first and second braking effects and is proportional to the fourth power of the magnetic flux density of the applied magnetic field.

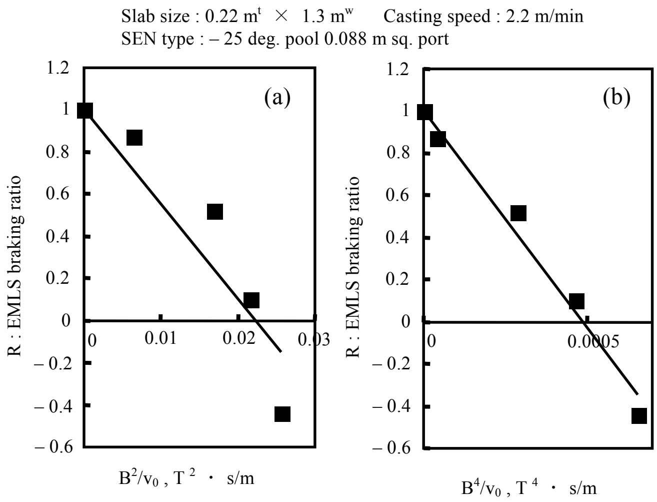

Fig.13 Relationship between EMLS braking ratio and two parameters for analyzing EMLS effect

Fig.14 shows values of the EMLS braking effect coefficient β derived from the measurements at the commercial facility where molds of various widths were used with different submerged entry nozzle spouting angles. The value of β is proportional to the mold width for a downward spouting angle of 25 degrees. This presumably comes from the fact that the length in the mold width direction (where the magnetic field generator faces the molten steel) increases with increasing mold width, thus enhancing the contributions of both r_1 and r_2. The value of β can be obtained for specific mold width and other casting conditions by using this proportional relation. The value of β is smaller when the spouting angle is 45 degrees than when it is 25 degrees for the same mold width. The likely reason is that, when the spouting angle is greater in the downward direction, the spouting stream proceeds farther downward along the strand. Hence, the period of time during which the EMLS magnetic field acts directly on the spouting stream becomes shorter, which reduces the contribution of r_1.

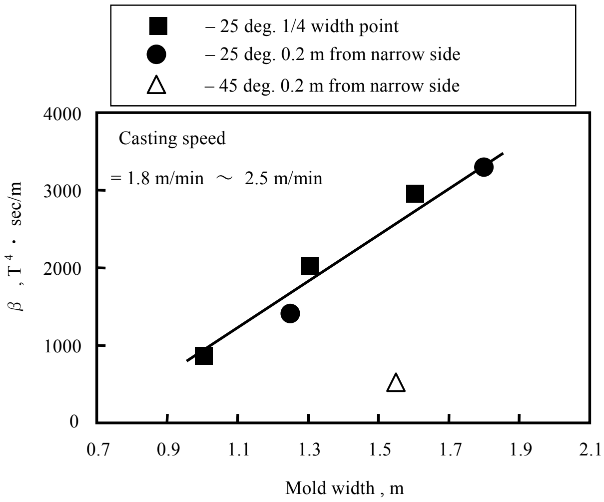

Fig.14 Relationship between mold width and coefficient of EMLS braking effect, β

5. Automatic control system for EMLS and EMLA

The casting conditions change constantly. Casting speed varies when casting is started or ended and when ladles are replaced. The mold width may also be changed during casting. In this regard, an automatic control system for EMLS and EMLA was developed to control the flow of molten steel in the mold. The developed system is an open control type. **Fig.15** shows a flow diagram of the system. First, the F value described in section 2 above is calculated from the mold width, casting speed, argon gas flow rate, and shape of the submerged entry nozzle. Next, electric current values necessary for EMLS and EMLA are determined from an operating table to control the meniscus flow velocity, which is estimated from the F value, to within an optimum range. The operating table is prepared in advance based on Eq.(7). The electric current values are then applied to the magnetic field generator as the set current values. These steps are repeated during the casting in regular cycles to detect variations of casting conditions, and thus the EMLS and EMLA operational conditions are automatically set.

6. Effect in commercial facility

Fig.16 shows the results of investigations on the frequency of mold-powder-caused surface defects of cold-rolled coils at the commercial facility before and after the EMLS and EMLA system was applied. The EMLS and EMLA magnetic flux densities were set to provide the optimum meniscus flow velocity, as described in section 2. Manual operation of the EMLS and EMLA reduced the surface defect frequency to one third, while automatic, computer control of the EMLS and EMLA further reduced it to half. In addition, occurrences of sticking type breakout were reduced to zero/year. The presumed reason is that excessive level fluctuations are suppressed by the use of EMLS, which also eliminates carburization of the solidified shell and variations over time and space of the lubrication between the mold and shell due to mold powder.

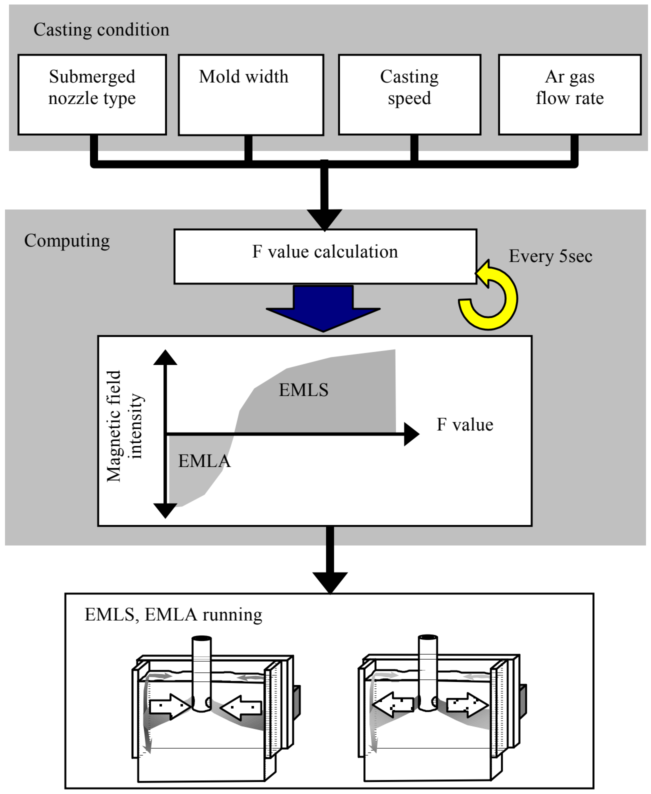

Fig.15 Schematic diagram of computer control of EMLS and EMLA

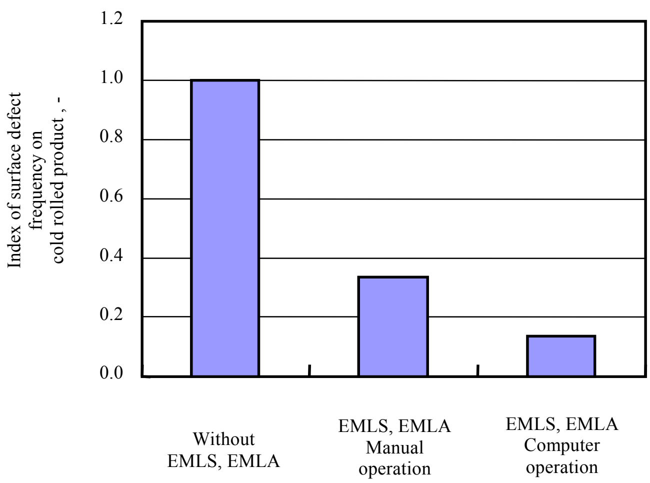

Fig.16 Effect of EMLS and EMLA on product surface defects

7. Conclusions

A traveling magnetic field generator was employed to control molten steel flow in the mold and to prevent mold powder entrapment in molten steel during high speed casting in a continuous slab caster. As a result, the following findings were obtained.

(1) The meniscus flow velocity can be continuously controlled to an arbitrary level by applying a traveling magnetic field to the stream spouting out of the submerged entry nozzle.

(2) When the EMLS braking force is applied to the spouting stream, the meniscus flow velocity along the mold width direction decreases with an increase in the magnetic flux density. After reaching 0 m/sec, the meniscus flow velocity increases in the backward direction.

(3) The braking effect on the meniscus flow velocity when EMLS was applied to the spouting stream was formulated assuming that it is proportional to the fourth power of the magnetic flux density. The braking effect is considered to arise from a combination of two effects. The first is the braking effect caused by the magnetic field acting directly on the spouting stream. The second is the effect caused by the molten steel in the mold that is driven by the traveling magnetic field and flows counter to the original meniscus flow.

(4) A control system was established that is based on conventional estimated indexes for molten steel flow in a mold and on the formula obtained in this study for calculating the effects of the magnetic field generator. The system incorporates the effect of variations in the operating conditions of a continuous caster. Automatic operation of EMLS and EMLA was carried out at a commercial facility. As a result, surface defects of cold-rolled products due to mold powder entrapment were significantly reduced.

This paper is cited from "Tetsu to Hagane, (Iron and Steel)", April, 2000.

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Jun Kubota
Steelmaking Dept., Fukuyama Works
Tel. 0849 (45) 3458
E-mail address : Jun_Kubota@ntsgw.fukuyama.nkk.co.jp