Evaluation of Defect Distribution in Continuously-Cast Slabs by Using Ultrasonic Defect Detection System and Effect of Electromagnetic Brake on Decreasing Unbalanced Flow in Mold

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In order to clarify the suppression mechanism of an unbalanced flow in the continuous casting mold under high molten steel throughput conditions, the relationship between the unbalanced flow and the distribution of defects entrapped on the solidified shell was measured by ultrasonic defect detection. The relationship between the unbalanced flow and the defect distribution in the mold with an electromagnetic brake was also investigated. The main results are summarized as follows.

(1) By using a new ultrasonic defect detection system, accurate measurement of defects was achieved for the defects' diameter of more than 0.6 mm in the range 2–10 mm from surface.

(2) The effect of the electromagnetic brake on decreasing molten steel momentum was measured. The measured value was consistent with the calculated value. Molten steel momentum could be reduced by more than 50% when the Stuart number (N) was more than 3.5 under molten steel throughput conditions of 4.7 and 5.3 ton/min.

(3) The position of entrapped defects on the solidified shell in the mold was influenced by the molten steel throughput condition and the magnetic flux density of the electromagnetic brake.

KEY WORDS: continuous casting; molten steel; unbalanced flow; inclusion; momentum; electromagnetic brake.

1. Introduction

Inclusions and bubbles which are trapped on the solidified shell during continuous casting may cause defects during cold or hot rolling. In recent years, higher surface quality under high throughput conditions has been required for the improvement of productivity.

High molten steel throughput conditions induce penetration of inclusions into the deep region¹⁾ and increase of mold level fluctuations followed by entrainment of mold flux.²⁾ These problems are harmful for slab quality. It is possible to reduce penetration of inclusions into the deep region and suppress mold level fluctuations by applying an electromagnetic brake in the mold.³⁾ It is also known that, especially under high molten steel throughput conditions, an unbalanced flow is induced by submerged entry nozzle (SEN) clogging or sliding gate movement.^{4–7)}

A large unbalanced flow causes distribution of the molten steel flow velocity in the mold. In the area of large upward molten steel flow velocity along with the narrow face of the

mold, mold flux is entrained by the large mold level fluctuations at the meniscus of the mold.⁸⁾ In the deep region of the mold, penetration of inclusions is caused by the large downward molten steel flow velocity.⁹⁾ In the area of small molten steel flow velocity in the mold, more inclusions and/or bubbles at the solid–liquid interface are entrapped due to the decrease of the washing effect.¹⁰⁾ Furthermore, the large unbalanced flow in the mold may cause breakout due to remelting of the solidified shell caused by the large discharge flow velocity from the SEN at the narrow face of the mold.¹¹⁾ To suppress this kind of the unbalanced flow in the mold, researches have been conducted on the shape of the SEN, electromagnetic stirring in the mold and application of an electromagnetic brake to the SEN.^{12–14)} However, the relationship has not been clarified yet between an unbalanced flow and the distribution of defects entrapped on the solidified shell in the mold. The effect of an electromagnetic brake on an unbalanced flow in the mold is also unclear.

In this study, the molten steel momentum in a mold with two static magnetic fields was investigated to evaluate the effects of the electromagnetic brake on the distribution of defects and an unbalanced flow behavior.

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2. Evaluation of Defect Distribution by Ultrasonic Defect Detection

As mentioned in the previous section, it is assumed that an unbalanced flow affects the distribution of defects entrapped on the solidified shell in the mold. To clarify the influence of an unbalanced flow, the defect distributions in the depth and width directions of slabs were measured by using an ultrasonic defect detection system. Since the thickness of the solidified shell in the mold is less than about 10–20 mm, it is necessary to measure the defect distribution within 10 mm from the slab surface. The local immersion method in the ultrasonic defect detection system was used for acoustic coupling (**Fig. 1**). In the conventional ultrasonic defect detection system, a dead zone of detection exists because of reflected waves on the surface (**Fig. 2**). Therefore, in the current study, a V-shaped receiving probe and a transmitting probe were used. It is possible to reduce the depth of the dead zone by installing acoustic shielding between the receiving probe and the transmitting probe. The actual defect depth and defect diameter were measured for the assurance of the ultrasonic defect detection system. **Figure 3** shows the accuracy of the values of defect depth measured by the ultrasonic defect detection system. Here, “defect depth” indicates the distance from the sample surface to the top of a defect. This result shows that defects could be detected in the range of about 2–10 mm from the

Fig. 1. Measurement principle of the ultrasonic defect detection system adopted in this research.

Fig. 2. Measurement principle of the conventional ultrasonic defect detection system.

sample surface. The results of microscopic observation in the cross section show that the minimum diameter of defect detected is about 0.6 mm. Thus, with the ultrasonic defect detection system, it is possible to measure the defect depth (in the range 2–10 mm from the sample surface) with high accuracy.

3. Experiments

Experiments were conducted in the No. 3 continuous caster (No. 3 CC) at JFE Steel East Japan Works (Chiba Area), which is equipped with the electromagnetic Flow Control (FC) mold.³⁾ A schematic diagram of the FC mold is shown in **Fig. 4**. Two coils are placed in the FC mold. The magnetic field generated by the upper coil controls the molten steel flow velocity around the meniscus, and the field generated by the lower coil controls the molten steel flow velocity in the lower part of the mold to minimize the penetration depth of the steel jets from the SEN.¹⁵⁾ In the FC mold, the discharge ports of the SEN are placed between the upper coil and the lower coil. The experimental conditions are summarized in **Table 1**. The casting speed was 1.2–1.7 m/min, and the maximum molten steel throughput was 5.3 ton/min.

The sliding gate used in this experiment was a three-layer

Fig. 3. Accuracy of the values of defect depth measured by the ultrasonic defect detection system.

 Fig. 4. Schematic diagram of the FC mold.³⁾

Table 1. Chemical composition of molten steel and casting conditions.

Slab width [mm]	1 600–1 700
Slab thickness [mm]	260
Casting speed [m/min]	1.2–1.7
Throughput [ton/min]	3.7–5.3
Index of magnetic flux density (T)	0.04–0.30

C	Si	Mn	P	Al
0.0015–0.0018	0.01–0.02	0.15–0.16	0.015–0.020	0.025–0.031

[Wt%]

type in which the opening and closing direction was width direction of the mold. Ar gas was blowing through the pool-type SEN with two ports⁴⁾ during casting. The magnetic flux density of the electromagnetic brake in the FC mold was changed under various casting conditions. To evaluate the effect of the molten steel momentum reduction by the electromagnetic brake, the angles of dendrites in the slabs were measured. The molten steel flow velocity in the mold was calculated by Eq. (1).¹⁶⁾

The solidification rate in Eq. (1) was calculated by Eq. (2). To determine the solidification constant, iron-sulfur alloys were added to the molten steel during casting. After casting, the thickness of the solidified shell was measured by the sulfur distribution in the slabs. The solidification constant was calculated by Eq. (3). To measure the upward molten steel flow velocity in the mold, samples were cut from the narrow face of the slabs. The samples were polished and etched with picric acid, the angles of dendrites were measured at 1 mm intervals by an optical microscope.

Fig. 5. Measurement procedure of the new ultrasonic defect detection system.

$$\theta = \left(\frac{0.35 \cdot C_0^2}{C_0^2 + 0.0005} + 0.65 \right) \cdot 11.5 \cdot V_F^{-0.177} \cdot \log \left(\frac{5.38 \cdot 10^{-1} \cdot V_F^{2.08}}{V} \right) \quad (1)$$

$$V = \frac{dD}{dt} \quad (2)$$

$$D = K\sqrt{t} = K\sqrt{Z/V_c} \quad (3)$$

Where, θ : angles of dendrites [degree], V_F : molten steel flow velocity [m/s], V : solidification rate [m/s], C_0 : carbon content in molten steel [mass%], D : solidified shell thickness [m], K : solidification constant [m/s^{1/2}], t : time [s], Z : distance from meniscus [m] and V_c : casting velocity [m/min].

For the investigation of the influence of an unbalanced flow in the mold, the positions of defects in the slabs were measured by the ultrasonic defect detection system. The slabs were cut to a thickness of 30 mm and polished by 1 mm from the slab surface in order to remove black scale (Fig. 5). The samples were then placed in the ultrasonic defect detection system, and the position of defects in the slabs was measured.

4. Calculation Method

The standard k- ϵ model in Fluent was employed to calculate the molten steel flows in the mold.^{17,18)} The equation of continuity, Navier-Stokes equation and the law of the conservation of energy in Fluent are expressed by Eqs. (4)–(6), respectively.

$$\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} = 0 \quad (4)$$

$$\rho \left[\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \nabla) \vec{v} \right] = -\nabla p + \eta \nabla^2 \vec{v} + \vec{F} \quad (5)$$

$$\rho \left[\frac{\partial T}{\partial t} + (\vec{v} \cdot \nabla) T \right] = -\frac{k}{C_p} \nabla^2 T + \frac{Q}{C_p} \quad (6)$$

Where, v : velocity of fluid [m/s], ρ : molten steel density, p : pressure [Pa], η : viscosity coefficient [0.0057 Pa·s],¹⁹⁾ F : external force [N/m³], T : temperature [K], k : thermal conductivity [34 W/K·m],²⁰⁾ C_p : specific heat at constant pressure [753 J/kg·K],²¹⁾ Q : flux of latent heat of solidification through solidification surface [J/m³/s], x : width direction in mold, y : thickness direction in mold and z : continuous casting direction.

Q was obtained from the temperature, viscosity coefficient

cient and results of the flow calculations.¹⁰⁾

The electromagnetic braking forces were calculated by Eqs. (7)–(8).

$$\vec{J} = \sigma(\vec{E} + \vec{V} \times \vec{B}) = \frac{1}{\mu} \nabla \times \vec{B} \quad (7)$$

$$\frac{\partial \vec{B}}{\partial t} + (\vec{v} \cdot \nabla) \vec{B} = \frac{1}{\sigma \mu} \nabla^2 \vec{B} + (\vec{B} \cdot \nabla) \vec{v} \quad (8)$$

Where, J : electric current density [A/m²], E : electric field [V/m], B : magnetic flux density [T], σ : electric conductivity [7.14×10^6 S/m]²²⁾ and μ : magnetic permeability [1.26×10^{-6} H/m].²³⁾

5. Experimental Results and Discussion

5.1. Effect of Electromagnetic Brake on Molten Steel Momentum

Figure 6 shows the relationship between magnetic flux density and decreasing ratio of molten steel momentum in the mold. The vertical axis is the ratio of measured or calculated molten steel momentum to momentum without magnetic field. The measured molten steel momentum ρV_m was determined from the angles of dendrites and the calculated molten steel momentum ρV_c was determined by calculation by Eqs. (4)–(6). ρV_e is the momentum in absence of the magnetic field and was calculated by Eqs. (9)–(13).²⁴⁾

$$V_d = \gamma \sqrt{(1 - \zeta_4)(1 - \zeta_3)} \cdot \sqrt{2g[c^2(h_{TD} + l_1) + l_2 + l_3]} \quad (9)$$

$$c = 0.364q^{0.65} \quad (10)$$

$$\zeta_3 = 1.1 \left(1 - \frac{a}{B'} \right)^2 \quad (11)$$

$$\zeta_4 = 1.16 - 0.015\varphi \quad (12)$$

$$\rho V_e = \rho V_d \left(\frac{X}{6.3d} \right)^{-1} \quad (13)$$

Where, V_d : discharge flow velocity from SEN [m/s], γ :

Fig. 6. Relationship between magnetic flux density and decreasing ratio of molten steel momentum in the mold.

ratio of average flow velocity and maximum flow velocity from discharge port of SEN [–], g : acceleration of gravity [m/s²], h_{TD} : molten steel depth in tundish [m], l_1 : length of upper nozzle [m], l_2 : length of lower nozzle [m], l_3 : distance between top of lower nozzle and molten steel surface level in SEN [m], c : discharge coefficient of free fall flow in the SEN [–], q : molten steel throughput [ton/min], a : cross-sectional area of falling flow in SEN [m²], B' : cross-sectional area in SEN [m²], φ : discharge port angle of SEN [degree], V_e : collision velocity on narrow face of mold [m/s], X : horizontal distance between discharge port of SEN and narrow face of mold [m] and d : diameter of discharge port in SEN [m].

When the magnetic flux density is less than 0.1 T, the measured momentum value is almost the same as that in absence of a magnetic brake obtained by Eq. (13). On the other hand, when the magnetic flux density is more than 0.25 T, the measured momentum value is about half of the maximum momentum compared with the case without the magnetic brake. The calculated values of molten steel momentum were in good agreement with the measured values at the molten steel throughputs of 4.7 and 5.4 ton/min.

Electromagnetic braking force F in a mold can be expressed by Eq. (14).

$$\vec{F} = \vec{J} \times \vec{B} \quad (14)$$

Figure 7 shows the Calculation results of Lorentz force and the molten steel flow velocity in the mold under the magnetic flux densities of 0.07 and 0.27 T. The Lorentz force on the molten steel increased with larger magnetic flux density. It decreased the collision momentum on the narrow faces of the mold. The Stuart number (N) was calculated to evaluate the effect of electromagnetic braking force. N , the ratio of inertial force and external force, is expressed by Eq. (15).²³⁾

Fig. 7. Calculation results of Lorentz force and the molten steel flow velocity.

$$N = \frac{|\sigma(\vec{v} \times \vec{B}) \times \vec{B}|}{|\rho(\vec{v} \cdot \nabla)\vec{v}|} = \frac{B^2 \sigma L}{\rho v} \quad \text{..... (15)}$$

Where, L : characteristic length [m].

Figure 8 shows the relationship between the magnetic flux density and N under different throughput conditions. In order to increase the effect of the electromagnetic braking force and overcome inertial force with large throughput, it is necessary to apply a larger magnetic flux density compared with the case of low throughput conditions. Therefore, it is important to apply an adequate electromagnetic braking force corresponding to the increased throughput. **Figure 9** shows the relationship between N and $\rho V_m / \rho V_e$ or $\rho V_c / \rho V_e$. A good correlation can be observed between N and $\rho V_m / \rho V_e$ or $\rho V_c / \rho V_e$. The reducing effect of momentum by the electromagnetic brake in the mold becomes larger with increasing N . When N is more than 3.5 under molten steel throughput conditions of 4.7 and 5.3 ton/min and different magnetic flux density, it is considered that the molten steel momentum in the mold can be reduced to more than half of that without an electromagnetic brake.

5.2. Unbalanced Flow in Mold

Figure 10 shows a scanning electron microscope (SEM) image of a defect in a slab which was detected by the ultra-

Fig. 8. Relationship between the magnetic flux density and N .

Fig. 9. Relationship between N and $(\rho V_m / \rho V_e)$ or $(\rho V_c / \rho V_e)$.

sonic defect detection system and energy dispersive X-ray (EDX) spectroscopy. Two types of defects were observed. One was mold flux in Ar bubbles and the other was Al_2O_3 in Ar bubbles. In this experiments, a large number of defects in slabs were observed under the conditions where the fluctuations of mold level were large. It is assumed that these defects were caused by mold flux entrained in the molten steel by a large fluctuations of mold level or Al_2O_3 in molten steel introduced through the SEN. The defect depths from the slab surface were converted to the distance from the meniscus in the mold by using Eq. (16) and the converted values were plotted on the schematic diagram of the mold shown in **Fig. 11**. The dashed arrows in the figure indicate the discharge direction of the molten steel from the SEN.

$$Z = V_c \left(\frac{D}{k} \right)^2 \quad \text{..... (16)}$$

The experimental results of molten steel throughput conditions of 4.2 ton/min and 4.6 ton/min with the same magnetic flux density were compared. The positions of defects

Fig. 10. Results of the defect investigation by a SEM image and EDX.

Fig. 11. Position of the defects in the mold.

entrapped on the solidified shell in the mold depended on the molten steel throughput conditions, and there was a large uneven distribution of defects under the 4.6 ton/min throughput condition. From these results, it is assumed that the molten steel flow greatly affects the position of defects entrapped on the solidified shell in the mold. As shown in **Fig. 12**, there was a difference of the molten steel momentum on the left and right narrow faces of the mold. The difference has a positive dependence on the molten steel throughput under a constant magnetic flux density condition (0.17 T). It is known that the sliding gate induces an unbalanced flow in the mold. **Figure 13** shows the calculated result of the unbalanced flow caused by the three-layer-type sliding gate and pool-type SEN with two ports, which were the same conditions as in these experiments. From the results of this calculation, the flow velocity from the discharge port is large on the sliding gate opening direction side. This is the same result as in the present study. To investigate the degree of the uneven distribution of defects entrapped on the solidified shell in the mold, the difference

of the numbers of defects on the left and right sides of the mold was defined by Eqs. (17)–(18).

$$A = \frac{|N_R - N_L|}{N_{R+L}} \cdot 100 \quad (17)$$

$$N_{R+L} = N_R + N_L \quad (18)$$

Where, A : degree of uneven distribution of defects entrapped on solidified shell in mold [%], N_{R+L} : defect density in mold [number/m³], N_R : defect density of right side in width direction in mold [number/m³] and N_L : defect density of left side in width direction in mold [number/m³].

The number of defects within 200 mm from the meniscus in the casting direction was measured by the ultrasonic defect detection system. **Figure 14** shows the relationship between the difference of the upward molten steel momentum on the left and right narrow faces of the mold and the degree of uneven distribution of defects A under a constant magnetic flux density. When the difference of the upward

Fig. 12. Difference of the molten steel momentum on the left and right narrow faces of the mold.

Fig. 14. Relationship between the difference of the upward molten steel momentum on the left and right narrow faces of the mold and the degree of uneven distribution of defects.

※ In this paper, the right narrow face of the mold corresponds to port B and the left narrow face corresponds to port A.

Fig. 13. Schematic diagram of the SEN and velocity profile at discharge ports of the SEN.⁴⁾

Fig. 15. Relationship between N and index of mold level fluctuations.

molten steel momentum on the left and right narrow faces of the mold increases, A also increases. This indicates that the uneven distribution of defects is related to the difference of the molten steel momentum in the mold.

5.3. Effect of Electromagnetic Brake on Mold Level Fluctuations

Figure 15 shows the relationship between N and index of mold level fluctuations caused by an unbalanced flow in the mold under different magnetic flux density conditions. Mold level fluctuations decreases with increasing N . These results are the same as those in Fig. 9. Based on these results, it can be stated that the uneven distribution of defects and increased mold level fluctuations are suppressed by applying an electromagnetic brake with the optimum magnetic flux density, even under high molten steel throughput conditions.

6. Conclusion

The effect of an electromagnetic brake on decreasing molten steel momentum and suppressing an unbalanced flow in the mold was investigated. The results are summarized as follows.

(1) A new ultrasonic defect detection system enabled accurate measurement of the depth of defects with diameters of more than 0.6 mm in the range 2–10 mm from the

sample surface.

(2) The effect of the electromagnetic brake on decreasing molten steel momentum was measured. The measured value was consistent with the calculated value. Molten steel momentum could be reduced by more than 50% when the Stuart number (N) was more than 3.5 under molten steel throughput conditions of 4.7 and 5.3 ton/min.

(3) The uneven distribution of defects and increased mold level fluctuations caused by an unbalanced flow in the mold were suppressed by applying electromagnetic brake with the optimum magnetic flux density.

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