Application of static magnetic field to casting of steel

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Abstract
A magnetic field was applied in the continuous caster in steelmaking. A static magnetic field has advantages in the steelmaking processes, in that the apparatus for generating a static magnetic field is simpler than alternating magnetic coils, and stabilization of the flow is enhanced by a static magnetic field because a larger force acts on a faster steel flow. Therefore, application to industrial processes has been investigated.
In this presentation, two applications are discussed, as follows:
1) Steel flow control in mold
The steel flow is controlled in the mold to produce high quality steel products with high productivity. An unbalanced steel flow causes surface defects. A static magnetic field is effective for stabilizing the steel flow in the mold. Instability becomes more severe with larger throughput or a thinner mold. A static magnetic field is effective for reducing this instability. Furthermore, because an insufficient steel velocity causes entrapment of bubbles and inclusions on the solidified shell, optimization of the steel flow velocity by controlling the strength of the two domain magnetic fields is important.
2) Microstructure control of cast metal
A static magnetic field suppresses the liquid flow, and the microstructure can be controlled by this flow control. In a Sn-Zn alloy casting test, the columnar grain ratio increased when a magnetic field stronger than 0.1 T was applied.
These phenomena occurred because thermal convection was reduced by the magnetic brake, followed by less supercooling at the dendrite end. The equiaxed crystal size increases with a magnetic field. Since the magnetic field in the early stage has a larger effect, nuclear generation of equiaxed crystals is considered to be restrained by reducing the steel flow and the temperature gradient.

Keywords
Static magnetic field, casting, steel, surface defects, microstructure, control

1. Steel flow control in mold
It is important to optimize the flow velocity in a mold in order to reduce surface defects of cast steel. One cause of surface defects is the existence of an asymmetric unbalanced time-dependent flow. This means that the steel flow rate from one spout is not always the same as that from the other1).
To prevent penetration of molten steel and bubbles into the deep portion of the strands, the downward flow velocity along the narrow face is reduced by two types of electromagnetic flow control systems. The FC mold (Flow Control Mold) utilizes a static magnetic field, as shown in Fig. 1.
The FC mold, which consists of two magnetic coils, generates a homogeneous magnetic field over a large area. The upper field stabilizes the top free surface, and the lower field seems to be effective for suppressing the downward steel flow. Therefore, the effect of a static magnetic field on the time-dependent flow was also estimated by numerical simulation and measurement of cast slabs.
Because the dendrite angle changes depending on the steel flow at the solid/liquid interface, the flow velocity can be estimated by measuring the dendrite angle.
Fig. 2 shows the calculated results of the flow velocity with magnetic densities of 0.1 T or 0.2 T. The momentum of the steel jet from the nozzle spout is estimated by the flow velocity. The momentum is predicted by using the Stuart number, as shown at the right. The Stuart number, $N$, is the ratio of magnetic force to momentum force and is defined as follows.
Fig. 1 Schematic illustration of the FC mold.

Fig. 2 Reduction of momentum to narrow face by static magnetic field.

| Magnetic density | 0.1T | 0.2T |
|------------------|------|------|
| Center plane     |      |      |
| [kg/m²]          | 0.02 | 0.02 |
| 0.00             |      |      |
| Interface between solid and liquid (fs 0.2) | Probalility of entrapment (⁻) |
|                  | 5x10⁻⁵ | 5x10⁻⁵ |
| Calculated based on model experiment | 0 | 0 |

Fig. 3 Calculated probability of entrapment of 0.5 mm argon bubble in molten steel with static magnetic fields of 0.1 T and 0.2 T. (1500 mm width, 260 mm thickness, and throughput 4.5 t/min).

### Calculations

\[ N = \frac{B^2 \sigma L}{\rho v} \]

Where, \( B \): magnetic density, \( \sigma \): length, \( \rho \): density of steel, \( v \): flow velocity.

The measured value of the effect of the electromagnetic brake in decreasing the molten steel momentum was consistent with the calculated value. A correlation existed between this effect and the Stuart number under different throughput and magnetic flux density conditions. The molten steel momentum could be reduced by more than 50% when the Stuart number was more than 3.5.

Furthermore, since an insufficient steel velocity causes entrapment of bubbles and inclusions on the solidified shell, optimization of the steel flow velocity by controlling the strength of the two domain magnetic fields is important.
Entrapment of bubbles and inclusions can be suppressed by adjusting the magnetic flux density. Fig. 3 shows the calculated probability of entrapment of 0.5 mm argon bubbles in molten steel with static magnetic fields of 0.1 T and 0.2 T. In this case, entrapment is reduced with the higher magnetic density of 0.2 T.

2. Microstructure Control

The microstructure of cast steel affects the properties of final steel products. The microstructure also changes the efficiency of soft reduction to reduce center segregation.

Therefore, the effect of a static magnetic field on the solidification microstructure of a Sn-Zn alloy is examined in this study. A Sn-Zn alloy casting test was carried out using the apparatus shown in Fig. 4. Fig. 5 shows the microstructure on the vertical plane. The columnar grain ratio increased with a magnetic field stronger than 0.1 T. These phenomena occurred because thermal convection was reduced by the magnetic brake, followed by less supercooling at the dendrite end. The effect of the magnetic brake for steel was estimated by the Hartmann number. The result showed that a magnetic field stronger than 0.17 T is effective for increasing the temperature gradient and promoting the columnar grain formation. The experimental results of the columnar ratio shown in Fig. 6 can be explained by the above discussion.

The equiaxed crystal size increases with a magnetic field. The magnetic field in the early stage has a larger effect, so nuclear generation of the equiaxed crystal is considered to be restrained by reducing the steel flow and the temperature gradient.
References
1. Y. Miki and S. Takeuchi: ISIJ Int., 43 (2003)10, 1548-1555.
2. K. Furumai, Y. Matsui, T. Murai, Y. Miki: Tetsu-to-Hagane, 100(2014)4, 563-570.
3. Y. Miki, H. Ohno, Y. Kishimoto, S. Tanaka: Tetsu-to-Hagane, 97(2011)8, 423-432.
4. T. Odagaki, N. Aramaki, N. Kikuchi and Y. Miki: CAMP-ISIJ, 31(2017), 202.