Electromagnetic Field Distribution in Two-section Slitless Mold for Soft-contact Electromagnetic Continuous Casting

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Numerical simulations and orthogonal experiments were used to study the effects of electromagnetic and structural parameters on magnetic distribution in a two-section slitless mold for the SC-EMCC process. The results showed that magnetic flux density decreased as the electrical frequency ($f$) and the thickness of the mold ($d$) increased, but it increased as the resistivity of the top half mold ($\rho_v$), the coil current intensity ($I$), the length of the top half mold and the location of the coil increased. By dimensionless analysis, the relative equation among magnetic flux density and the parameters was given as $B(\mu_0/\sigma)=0.058 \times \left(\rho_v, f/d, d/f^2\right)^{0.29}$. Also the level of the initial meniscus should be controlled between the center and the top of the coil to attain better soft-contact effects. The total distribution of the electromagnetic field in the whole system of the two-section slitless mold was obtained. The magnetic flux density on the vertical direction mainly acted on the location of the initial liquid level, and the magnetic flux density was uniform along the circumferential direction but degenerated along the radial direction.

KEY WORDS: electromagnetic processing of materials; soft-contact electromagnetic continuous casting; two-section slitless mold; electromagnetic field; numerical simulation.

1. Introduction

Mold oscillation improves the lubricating condition during the continuous casting process. But the oscillation marks and cracks which can markedly affect the surface quality appear at the same time. In order to solve these problems as well as meet the demands of the higher surface quality strand, a soft-contact electromagnetic continuous casting process was introduced in the middle of the 1990’s. The soft-contact electromagnetic continuous casting (SC-EMCC) was a method using alternating electromagnetic field imposed from the outside of a mold to control the shape of the molten metal’s meniscus, to reduce the metallic static pressure between the mold and the molten metal, and then to improve the process of the initial solidification. Recently, the casting experiments showed that the quality of the billet surface became much better with SC-EMCC technology than with conventional continuous casting technology. However, one of the key factors is the mold design for applying this SC-EMCC technology in steelmaking. The mold used in the SC-EMCC should achieve high magnetic penetrability and suitable cooling ability. Therefore, there is great scientific interest in developing a new kind of mold which can be used in the SC-EMCC process.

Nowadays, the molds proposed in SC-EMCC of steel can be classified into two types, namely slit molds and slitless molds, according to their different structures. Slit molds like cold crucibles are usually proposed to penetrate magnetic field into the mold. However, the structural rigidity of this mold is lower and the design of the cooling water layout becomes more complex than the conventional one. Additionally, the inside values of the magnetic flux density at the slits and the segments are different. Thus there are major issues when it is applied to the large scale commercial caster. On the other hand, the slitless mold has better magnetic penetrability, and the distribution of the magnetic field is uniform and the design of the cooling water path is simple. However, the fabrication and connection of the copper tubes are difficult to implement. Therefore, these two molds mentioned above for SC-EMCC are not used in industrial production now.

The distribution of magnetic fields in the mold was very important in the soft-contact electromagnetic continuous casting processing because the electromagnetic pressure was mainly affected by this distribution. Many researchers carried out long-term studies on the distribution of the electromagnetic field in the soft-contact solidification process and obtained many important results. But up to now, the researches on the distribution of electromagnetic field have mostly concentrated on the case of the slit mold for SC-EMCC. Investigations on slitless mold for SC-EMCC are very lacking, except for the literatures that have introduced the structure of the two-section slitless mold, further research has not been reported.

In this paper, numerical simulations and orthogonal experiments are used to study the distribution of magnetic
fields in the two-section slitless mold for SC-EMCC. The effects of the factors such as thickness of the mold wall, the length and resistivity of the top half mold, electrical frequency, current intensity and coil location, liquid level on the magnetic field were investigated. The order of these factors affecting the penetration of the magnetic field in two-section slitless mold was also obtained. The suitable parameters and the relation equation among magnetic flux density and four parameters were given by dimensionless analysis. The electromagnetic field property in the whole system of the mold was also analyzed on the suitable parameters condition. Finally, the differences between the two-section slitless mold and conventional slit mold were compared. The results will provide theoretical reference for two-section molds to be used in industrial production in the future.

2. Governing Equations for Electromagnetic Field Distributions

The most radical governing equations for electromagnetic fields were Maxwell equations. In the SC-EMCC mold of the round billet electromagnetic system, the equations relating the various field quantities were constituted by the following subset:

\[ \nabla \times \vec{H} = \vec{j} + \frac{\partial}{\partial t} \vec{E} \] ........................................(1)

\[ \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \] ........................................(2)

\[ \nabla \cdot \vec{E} = 0 \] ........................................(3)

\[ \nabla \cdot \vec{H} = 0 \] ........................................(4)

The electromagnetic character equations of the medium were stated as:

\[ \vec{D} = \varepsilon \vec{E} \] ........................................(5)

\[ \vec{B} = \mu \vec{H} \] ........................................(6)

The Ohm law within conductor was given as:

\[ \vec{j} = \sigma \vec{E} \] ........................................(7)

where, \( \vec{H} \), magnetic field intensity (A/m); \( \vec{j} \), source current density (A/m²); \( \vec{E} \), induced current density (A/m²); \( \vec{E} \), electric field intensity (V/m); \( \vec{B} \), magnetic flux density (T); \( \vec{D} \), electric displacement vector (C/m²); \( \varepsilon \), dielectric constant (F/m); \( \mu \), magnetic permeability (H/m); \( \sigma \), electrical conductivity (Ω⁻¹m⁻¹), respectively.

The electromagnetic body force perpendicular to the surface of the strand and pointing to the inner of the conductor was described as:

\[ \vec{F} = \vec{j} \times \vec{B} = \left( \frac{1}{\mu} \nabla \times \vec{B} \right) \times \vec{B} = -\frac{1}{\mu} \vec{B} \times (\nabla \times \vec{B}) \]

\[ = -\frac{1}{2\mu} (\vec{B} \cdot \nabla) \vec{B} + \frac{1}{\mu} (\vec{B} \cdot \nabla) \vec{B} \] ........................................(8)

Introducing a vector potential function \( \vec{A} \) and scalar potential function \( \Phi \), the essential differential equations were as follows:

\[ \vec{B} = \nabla \times \vec{A} \] ........................................(9)

\[ \vec{E} = -\frac{\partial \vec{A}}{\partial t} - \nabla \Phi \] ........................................(10)

By introducing Lorentz limitative condition \( \nabla \vec{A} = -\mu \varepsilon \frac{\partial \Phi}{\partial t} \) into Maxwell equations, magnetic field and electric field were solved, respectively, to obtain the solution of the electromagnetic parameters. Finally, the analysis equation of the electromagnetic harmonic wave could be obtained as following formula:

\[ [K + j\omega C][\vec{u}] = \{F \} \] ........................................(11)

where, \([K]\), the coefficient matrix, \([C]\), magnetic damping matrix, \([F]\), external load (Voltage or Current load) and vector \( \{u\} \) is composed of the \( \vec{A} \) and \( \vec{V} \).

3. Boundary Conditions and Research Method

3.1. Boundary Conditions

The research object of the two-section slitless mold for SC-EMCC was designed according to the 178 mm mold used in conventional continuous casting. The structure of the two-section slitless mold is shown in Fig. 1, and its concrete size is shown in Fig. 2. The copper tube of the mold proposed in this study was composed of the two parts: the top half of the mold was copper alloy with high magnetic penetrability and the bottom half of the mold was copper with good thermal conductivity. Due to the symmetry of the round mold, a quarter of the mold was studied. A 3-D finite
element model was established according to the real structure of the mold, including mold, strand, coil and sufficient free space. In view of the rationality of the divisional elements, the width of the gap between the strand and the mold wall was set as 1 mm.

Basic assumptions\(^{11}\):

1) The liquid metal level was supposed to be plane, and the effect of the meniscus shape on magnetic field was neglected.
2) The liquid metal level was located at the middle of the coil.
3) The solidification process of the molten metal was not considered.
4) The oscillation of the mold was ignored.

Due to the symmetry of the model, parallel flux conditions were set as the boundary conditions of the symmetrical faces. The magnetic vector potential at the distance of 5 times mold height was set as zero. The resistivity of the related mediums appeared in numerical simulation model are shown in Table 1. The relative permeability of the materials used in two-section slitless mold was 1.

### 3.2. Research Method

Because the magnetic flux density in the mold is affected by the magnetic penetrability, and the shape of the meniscus is mainly affected by the magnetic flux density. Therefore, the penetration of the magnetic field into mold can be directly linked with the surface quality of strand. The magnetic penetrability of the two-section slitless mold for SC-EMCC is affected by many factors.\(^{10}\) The main factors are thickness of the mold wall, resistivity of the top half mold, electrical frequency and current intensity in coils. An orthogonal experiment was thus designed to find the regularity of the factors affecting the magnetic field to penetrate the mold. Orthogonal experiment is a statistical method by designing the orthogonal table to deal with the experimental data, using the fewer experimental times to find the better results. Under conditions of our research, the influence of the parameters such as thickness of the mold wall, resistivity of the top half mold, electrical frequency and current intensity in coils on the magnetic flux density in the two-section slitless mold was simulated.

In order to examine the effect of the above-mentioned four factors on the magnetic field penetrating into the mold, parameters as shown in Table 2 were selected to arrange the calculation. The selection of the parameters was based on the results of the reference literature.\(^{10}\)

### 4. Results and Discussion

#### 4.1. Comparison between Calculated and Experimental Results

To verify the accuracy of the calculated results, the distribution of the magnetic flux density in a standard three-dimensional electromagnetic test device\(^{14}\) was calculated using developed finite element program. The calculation condition was the same as that of Ref. 14). As shown in Fig. 3, the calculated electromagnetic flux density agrees very well with the experimental results. It shows that the developed finite element program could give a precise description for the distribution of the electromagnetic field in two-section slitless mold for soft-contact electromagnetic continuous casting.

#### 4.2. The Influence of the Parameters on Magnetic Field in Two-section Slitless Mold

The influence of the parameters on magnetic field was obtained by the orthogonal experimental method. The relationship between the magnetic flux density and factors was achieved as shown in Fig. 4 by using the range analysis to deal with the calculated results. From Fig. 4, the suitable parameters of the magnetic penetrability in φ78 mm two-section mold are found to be \(A_1, B_3, C_1\) and \(D_5\). The thickness of the mold wall \(A\), the resistivity of the top half mold \(B\), the electrical frequency \(C\) and the current intensity in coil \(D\) are 5 mm, \(8.8 \times 10^{-7} \Omega \cdot \text{m}\), 60 Hz and

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| Item                      | Steel (1520°C) | Cu (220°C) | Coil | Slag | Air |
|---------------------------|----------------|------------|------|------|-----|
| Resistivity, \(\Omega \cdot \text{m}\) | \(8.5 \times 10^7\) | \(2.4 \times 10^4\) | \(3 \times 10^4\) | \(1 \times 10^{18}\) | \(1 \times 10^{19}\) |

| Factors | Levels |
|---------|--------|
| A       | 1      |
| B       | 2      |
| C       | 3      |
| D       | 4      |

| Item | Value |
|------|-------|
| A    | 5 mm  |
| B    | 8.8 \times 10^{-7} \Omega \cdot \text{m} |
| C    | 60 Hz |
| D    | ISIJ International, Vol. 49 (2009), No. 1 |

Fig. 3. Comparison of \(B_z\) values measured and simulated for two-section mold.
2 000 A, respectively.

From Fig. 4, the influence regularity of these four factors on the magnetic flux density is also found. The magnetic flux density decreases with increasing electrical frequency and thickness of the mold wall, but increases with increasing mold resistivity and current intensity. This is because that the magnetic field is easier to penetrate into the mold and impose on the strand when the thickness of the mold wall is thinner. The penetration of the magnetic field is directly proportional to the skin depth. The skin depth increases with increasing mold resistivity, but decreases with increasing frequency.

The variance analysis was used to study the significance of the each factor on the magnetic flux density. The results show that the effects of the frequency, the resistivity of the top half mold and the current intensity in coils are highly significant, but the effect of the thickness of the mold wall is not significant. The order of the factors affecting the penetration of the magnetic field into the mold was electrical frequency, the resistivity of the top half mold, current intensity in coil and the thickness of the mold wall. Therefore, in order to improve the penetration of the magnetic field into the two-section mold, the frequency should be adjusted firstly, the next one is the resistivity of the top half mold and then current intensity in coils.

4.3. The Relation Equation among Magnetic Flux Density and Four Parameters

The quantitative relationship between the magnetic flux density and the four parameters including thickness of the mold wall, the resistivity of the top half mold, electrical frequency and coil current was examined. The dimensionless relation equation among the magnetic flux density and the four parameters mentioned above.

Defining \( B \) is the magnetic flux density in the bottom of the meniscus for two-section mold, then:

\[
B = f(\mu, I, d, \rho v, f, m_1, m_2, \ldots, m_n) \tag{12}
\]

where, \( \mu \), magnetic permeability (H/m); \( I \), current intensity in coil (A); \( d \), the thickness of the mold wall (m); \( \rho v \), the resistivity of the top half mold (\( \Omega \cdot \text{m} \)), \( f \), the electrical frequency (Hz), \( m_1, m_2, \ldots, m_n \) were other parameters related to the \( B \), and \( n \) was large enough. Using the dimensionless analysis, the following formula can be obtained.

\[
\frac{B}{\mu I / d} = c \left( \frac{\rho_v I^2}{\rho_v d^6 f^3} \right)^\alpha \tag{13}
\]

where \( c \) and \( \alpha \) are constants, \( \rho_v \) is the density of the top mold (kg/m\(^3\)).

The least square method was used to handle the simulated results obtained in the orthogonal experimentation. The dimensionless relation formula was obtained by simple linear regression, and the results were compared by the hypothesis testing. The dimensionless relation formula between the magnetic flux density and factors (the thickness of the mold, the resistivity of the top half mold, the electrical frequency and the coil current) can be given as:

\[
\frac{B}{\mu I / d} = 0.058 \left( \frac{\rho_v I^2}{\rho_v d^6 f^3} \right)^{0.29} \tag{14}
\]

Equation (14) shows clearly the relationship between the magnetic flux density and the factors. Theoretical reference can be provided for the optimal design of the two-section slitless mold for soft-contact electromagnetic casting.

4.4. The Influence of the Frequency on Magnetic Distribution

From Sec. 4.2, it can be found that the magnetic flux density in the two-section slitless mold increases with decreasing electrical frequency. Alternating magnetic fields have the functions of both shape controlling and stirring according to electromagnetic field theory. In SC-EMCC processing, the shape of the meniscus is controlled directly by the magnitude and orientation of the horizontal electromagnetic force. Therefore, the distributions of the electromagnetic force on strand with different frequencies were examined. The results are shown in Fig. 5. It can be found from the figure that the electromagnetic force direction under 60 Hz condition does not point to the strand center and thus can not favor the controlling of the shape of liquid steel. Also, the value of the electromagnetic force in horizontal direction is relatively low. So the frequency of 60 Hz can not meet the requirement of the shape controlling in SC-EMCC. At the frequency of 20 000 Hz, the effect on the shape controlling is obvious, but the penetration of the magnetic field is not very good due to the skin depth effect. Therefore, 20 000 Hz can not achieve the effect of the SC-
EMCC. At the frequency of 2,500 Hz, the horizontal magnetic force is the largest, and the effect on the shape controlling is also obvious, indicating that it is easier to achieve the effect of the SC-EMCC. Therefore, in order to achieve a satisfactory effect of the SC-EMCC, the selection of the frequency should consider the effect of both shape controlling and the magnetic penetrability. Figure 5 also shows the maximum value of the horizontal electromagnetic force on the strand with different frequencies. When the frequency is lower than 2,500 Hz, the horizontal electromagnetic force increases quickly with the increasing of frequency. But when the frequency is higher than 2,500 Hz, the horizontal magnetic force decreases gradually with increasing frequency. The value of the horizontal electromagnetic force reaches the maximum one when the frequency is 2,500 Hz. Therefore, for φ 178 mm two-section slitless mold for SC-EMCC in this research, the ideal frequency is 2,500 Hz according to the above-mentioned discussion.

Besides the above four parameters, the influence factors on magnetic field in mold include the length of the top half mold, the coil location and the liquid level. To multianalyze the regularity of the electromagnetic field in two-section slitless mold for SC-EMCC, the length of the top half mold, the coil location and the liquid level were studied as follows.

4.5. The Influence of the Length of the Top Half Mold on Magnetic Field

The length of the top half mold has an important influence on the magnetic field in the mold and then can affect the shape of meniscus. Under conditions of this work, the effect of the length of the top half mold on the magnetic field in the mold was calculated and the results are shown in Fig. 6, where L is the length of the top half mold. From Fig. 6, it can be found that the magnetic field and the range of the magnetic field increases with increasing length of the top half mold. The reason is that the skin depth is much larger in the top half of the mold than that in the bottom half of the mold. Therefore, the magnetic field acting on the strand is mainly penetrated from the top half of the mold. Then the magnetic field is easier to penetrate from the top half and act on the strand with increasing length of the top half of the mold. So the length of the top half of the mold should be increased in order to improve the penetration of the magnetic field if possible. On the other hand, the extent of the magnetic flux density was lower (the maximum value increased 10%) when the length of the top half of the mold was increased from 120 to 140 mm. Furthermore, the cooling effect would decrease with increasing length of the top half of the mold. Therefore, to meet the requirement of the penetration of the magnetic field and cooling effect, the suitable length of the top half of the mold is 120 mm for the φ 178 mm two-section mold for SC-EMCC.

4.6. The Influence of the Coil Location on Magnetic Field

Because the shape of the meniscus is controlled by the alternating magnetic flux density in the mold induced by the induction coil, the liquid level should be placed on the position at which the value of the magnetic flux density is larger to obtain a higher meniscus shape. In this study, the influences of the different coil locations on the magnetic flux density in two-section slitless mold for SC-EMCC such as H_{coil}=50, 65 and 80 mm were simulated, where H_{coil} shows the distance between the top of the coil and mold. As shown in Fig. 7, the maximum value of the magnetic flux density appears near the liquid level, and the maximum value of the magnetic flux density increases with increasing coil location. The reason is that the distribution of the magnetic field is affected by the magnetic flux density which comes from both mold inlet and mold wall. Therefore, in order to improve the usage rate of the magnetic flux density and achieve ideal effect of the SC-EMCC, the coil should be placed to approach the top of the coil as possible. The suitable coil location is H_{coil}=50 mm for φ 178 m mold for SC-EMCC.

4.7. The Influence of the Initial Liquid Level on Magnetic Field

The initial solidification starts at the bottom of the metal meniscus during SC-EMCC processing. The electromagnetic force can reduce the static pressure between the liquid steel and the initial strand, and expand the gap between the strand and the mold wall. This is important to keep the stability of the initial liquid level. The electromagnetic force is mainly affected by the magnetic flux density. Therefore, the magnetic flux density in initial liquid level should be studied under the different liquid level conditions. The results will provide theoretical reference for the optimal design of the two-section slitless mold for soft-contact electromag-
netic casting.

Figure 8(a) shows the distributions of the vertical magnetic flux density under different liquid level conditions. Figure 8(b) shows the maximum value of the magnetic flux density with different $h$. The $h$ in Fig. 8 is the distance between the liquid level and the mold top. From Fig. 8, it can be seen that the magnetic flux density has the maximum value when $h=80$ mm. Thus, at this location, i.e. $h=80$ mm, the effect of the liquid metal pushed from the mold is the largest, the gap of the flux is the widest, and the effect of the SC-EMCC is the best. The value of the magnetic flux density acting on the initial liquid region increases with rising meniscus location when $h<80$ mm. On the other hand, the magnetic flux density acting on the initial liquid region increases slightly with descending initial liquid level when $h>80$ mm. But the maximum value of the magnetic flux density changed little. Therefore, for the $\varphi$ 178 mm two-section slitless mold of the round billet for SC-EMCC, the liquid level should be controlled between the center and the top of the coil to get enough electromagnetic pressure and larger acting range, to ensure the surface quality of the billet and save energy.

4.8. The Total Distributions of Magnetic Fields

The distribution of electromagnetic fields and their uniformity were determinant to explore the metallurgical effect of the SC-EMCC. It is really necessary to simulate the 3-D distributions of the electromagnetic field in two-section mold for SC-EMCC.

According to the results mentioned above, the suitable parameters of the two-section slitless mold used in SC-EMCC processing are as follows: the thickness of the mold wall is 5 mm, the length of the top half of the mold is 120 mm, the resistivity of the top half of the mold is $8.8\times10^{-7}$ $\Omega \cdot$ m, the electrical frequency is 2 500 Hz, the current intensity in coil is 2 000 A, the distance between the top of the coil and mold is 50 mm, and the distance between the top of the coil and liquid level is 20 mm. The magnetic flux density on the longitudinal section and steel strand were simulated. Figure 9(a) shows the distributions of the magnetic flux density for the whole system in SC-EMCC region. As shown in this figure, the electromagnetic field is stronger and mainly concentrates at the region covered by the length of the top half of the mold. The magnetic flux density reduces quickly when the billet moves out of the region covered by the length of the top half of the mold. Hence, the region of the length of the top half of the mold should cover the initial liquid zone in order to obtain the stronger electromagnetic force. Under this condition, the magnetic field can penetrate from the top half of the mold. Therefore, the effect of the SC-EMCC can be achieved, and the magnetic flux density has its maximum of 0.162 T.

The simulated results of the magnetic field in steel strand are shown in Fig. 9(b). According to the two-section slitless mold for SC-EMCC, the magnetic flux density on vertical direction mainly acts on the location of the initial liquid level. The magnetic flux density on the top surface of the strand is higher than that of other regions in the strand, and mainly concentrates on the surface layer. The uniformity of the magnetic flux density is good in the circumferential direction, and degenerates monotonously into the charge. This is easier to keep the stability of the meniscus. Magnetic flux density has a maximum value of 0.043 T at the surface of the charge near meniscus.

![Fig. 8](image-url)  
Fig. 8. Distributions of vertical magnetic flux density (a) and maximum value (b) with different $h$ ($h$ is the distance of liquid level and mold top).

![Fig. 9](image-url)  
Fig. 9. Magnetic flux density distributions on the symmetrical section (a) and the surface of strand (b).
4.9. The Comparison of the Magnetic Fields in Two-section Slitless Mold and Slit Mold

In order to find the feasibility of the two-section slitless mold in soft-contact electromagnetic casting processing, the magnetic field distribution was compared with that in slit mold used in industrial experiment. The parameters of the two-section slitless mold are same as those in Sec. 4.8. The parameters of the slit mold according to the experiment done by our lab are: the thickness of the mold is 13 mm, the slit number is 32, the width of the slit is 0.5 mm, the length of the slit is 100 mm, the electrical frequency is 30 kHz, and the current intensity in coil is 2000 A, the distance between the top of the coil and mold is 50 mm and the liquid level is located in the centre of the coil. The results are shown in Fig. 10. Both of the two molds have good magnetic penetrability. The magnetic field in the two-section slitless mold is lower than that in the slit part of the slit mold, but stronger than that in the segment part of the slit mold. The circumferential magnetic field in two-section slitless mold is more uniform, indicating that it is better for the industrial use.

5. Conclusions

(1) Numerical simulations and orthogonal experiments were used to study the effects of the parameters on the magnetic field distribution in the two-section slitless mold. The results of the variance analysis showed that the order of the factors affecting the magnetic field penetrating into the two-section slitless mold was electrical frequency > the resistivity of the top half mold > current intensity in coil > the thickness of the mold wall. The effects of the electrical frequency on the magnetic field penetrating into mold were most significant.

(2) By dimensionless analysis, the relation equation among the magnetic flux density and the four parameters was given as \( B/(\mu_0 I/d) = 0.058 \times (p_1 r^2 / \rho d) + 0.29 \). Furthermore, the magnetic flux density in two-section slitless mold increased with increasing length of the top half of the mold and the coil location. The liquid level should be controlled between the center and the top of the coil to obtain better soft-contact effect.

(3) The suggested parameters of the two-section slitless mold used in SC-EMCC were obtained: the thickness of the mold wall was 5 mm, the length of the top half mold was 120 mm, the resistivity of the top half mold was \( 8.8 \times 10^{-7} \Omega \cdot \text{m} \), the electrical frequency was 2500 Hz, the current intensity in coil was 2000 A, the distance between the top of the coil and mold was 50 mm, the distance between the top of the coil and liquid level was 20 mm.

(4) The alternating magnetic field could penetrate through two-section slitless mold wall and impose on metal strand under suitable parameters conditions. The magnetic field on the vertical direction mainly acted on the location of the meniscus in the top half mold. The uniformity of the magnetic flux density was good in the circumferential direction and degenerated to the strand centre in the radical direction. Comparing the magnetic field in slit mold, the circumferential magnetic field in two-section slitless mold was more uniform than that in slit mold.

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REFERENCES

1) S. Asai: 129th–130th Nishiyama Memorial Seminar, ISIJ, Tokyo, (1989), 51.
2) T. Toh, E. Takeuchi, M. Hojo, H. Kawai and S. Matsumura: ISIJ Int., 37 (1997), 1112.
3) T. Tanaka, K. Kurita and A. Kuroda: ISIJ Int., 31 (1991), 350.
4) G. W. Yu, G. L. Jia, E. G. Wang and J. C. He: Acta Metall. Sin., 38 (2002), 208.
5) K. Iwai, K. Sassa and S. Asai: Electromagnetic Forces and Applications, Elsevier Science Publishers B.V, Amsterdam, (1992), 263.
6) J. Park, H. Jeong, H. Kim and J. Kim: ISIJ Int., 42 (2002), 385.
7) P. R. Cha, Y. S. Hwang, Y. J. Oh, S. H. Chung and J. K. Yoon: ISIJ Int., 36 (1996), 1157.
8) Y. Fuchigami, R. Suenaga and E. Takeuchi: Japanese Patent, JP3099753, (1991).
9) Q. Wang, J. C. He and E. G. Wang: Chinese Patent, 02132867.6, (2002).
10) B. G. Jin, Q. Wang, D. W. Cui, Y. Liu and J. C. He: Acta Metall. Sin., 43 (2007), 163.
11) X. Z. Na, X. Z. Zhang and Y. Gan: ISIJ Int., 9 (2002), 974.
12) T. Suzuki and H. Mori: Elect. Furn. Steel, 70 (1999), 133.
13) F. Jia, J. Z. Jin, X. G. Zhang, Y. M. Li and Z. Q. Cao: J. Dalian Univ. Technol., 43 (2003), 305.
14) B. G. Jin, Q. Wang, Y. Liu, D. W. Cui and J. C. He: China Nonferrous Metals, 11 (2006), 1931.
15) L. T. Zhang, E. G. Wang, A. Y. Deng and J. C. He: The Chinese Journal of Process Engineering, 6 (2006), 713.