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Theoretical and experimental analysis of continuous casting with soft-contacted mould ①

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Abstract: Coupling the quasi-3D numerical simulation of electromagnetic field and the experiments with some metals such as tin, aluminum, copper and steel, the electromagnetic characteristics of continuous casting with soft-contacted mould, especially the influences of power frequency, the mould structure, and the inductor position, size and current on the electromagnetic force and pressure on the billet, were analyzed. The result shows that, in continuous casting with soft-contacted mould, the electromagnetic pressure on the surface of billet increases with the rising of the power frequency as a logarithmically parabolic function and, with that of inductor current as a parabolic function. The design principle of the soft-contacted mould is that 1) the mould structure should be ' more segments and thin slits' ; 2) the topside of inductor should be at the same location with the meniscus of molten metal; 3) the inductor should cover the initial solidifying shell of billet.

Key words: continuous casting; numerical simulation; soft-contacted mould **Document code: A**

1 INTRODUCTION

The continuous casting with soft-contacted mould is a recently developing technology for near net shape billet of steel and(or) other heavy metals[1,2]. It is well known that electromagnetic continuous casting without mould (EMC) for aluminum and other light metals has been applied extensively[3,4]. In this process, electromagnetic confining for molten metal shaping is in place of the effect of traditional mould, and the phenomenon of electromagnetic stirring for molten metal occurs naturally. Hence high quality billets with smooth surface, fine crystals, homogenized composition and a large scale of equiaxed crystal organization can be produced. Now there is a tendency of replacing the conventional continuous casting technology with the electromagnetic one for light metals. Naturally, metallurgists hope to apply previous technology to that of steel and(or) other heavy metals for improving the quality of billets. But so far, it is hard to realize this aim. One reason stems from some physical properties of steel and heavy metals, such as high specific gravity, high melting point and (or) low electric conductance. The next one is that in EMC, the demands for measuring and adjusting the shape and the height of meniscus of molten metal, and the intensity and the distribution of electromagnetic force in billet are very strict and transient. It is very difficult to satisfy these demands in steel-making industry now. Therefore Vives[5] presented the idea of continuous casting with soft-contacted mould for steel and other heavy metals.

The principle of continuous casting with soft-contacted mould is similar to that of cold crucible, which is used to levitation melting and refining of metal and nonmetal materials[6]. The soft-contacted mould structure is the same as that of a straight cold crucible, in which it is slit into several segments, thus electromagnetic flux can penetrate through it. An inductor (coil) through high frequency current is set around the mould and it makes alternating electromagnetic field to the billet. Hence induction eddy is generated on the billet and then, the electromagnetic force is formed, which is perpendicular to the solidifying shell of billet and pointed to the liquid core. The electromagnetic force is inverse to the static pressure of liquid metal in direction, thus it reduces both the vertical pressure on the mould and the friction between the initial solidification shell of billet and the mould, from which the mould is called soft-contacted one. This technology can result in slag permeating to be unobstructed and, oscillation marks on the surface of billet to be shallow. Also, the molten metal in the mould can be stirred and the solidifying shell of billet can be heated electromagnetically. These make the composition of billet uniform, the crystals fine, the contacting angle of meniscus of molten metal and mould improved, the temperature gradient in the surface layer of billet covered by the inductor decreased, and then, the equiaxed crystal domain increased. All these matters can improve the quality of billet effectively, so it has drawn much attention of metallurgists[7,8]. Recently, it has stepped into the period of industrial experiment and development in Japan and Korea[9].

In this work, the quasi-3D numerical simulation

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for EMF with finite element method and the continuous casting experiments with some metals such as tin, aluminum, copper and steel are coupled. The processes of the continuous casting and some characteristics, especially the effects of the power frequency, the mould structure, and the inductor location, size and current on the electromagnetic force and pressure in the billet, are studied, also, some mathematical models from theoretical analysis and experimental results are provided. It is helpful to study and develop this new technology continually.

2 CALCULATION MODEL AND EXPERIMENT DESIGN

Fig.1(a) illustrates the principle and the structure of continuous casting with soft-contacted mould, and Fig.1(b) shows the surface quality of tin billet with and without EMF in continuous casting with soft-contacted mould. From electromagnetism, the traditional mould in continuous casting is shield for high frequency electromagnetic field, so that the soft-contacted mould is slit into some segments. It is just like that of a straight cold crucible, from which the high frequency electromagnetic flux can penetrate through the mould to work on the molten metal and the billet, and without strong eddy to be inducted in the mould.

According to electromagnetism, the electromagnetic field equations can be described as:

$$\nabla \times \boldsymbol{E} = -2\pi j f \boldsymbol{B} \quad (1)$$

$$\nabla \times \boldsymbol{B} = \mu \boldsymbol{J} \quad (2)$$

$$\nabla \cdot \boldsymbol{B} = 0 \quad (3)$$

$$\boldsymbol{J} = \sigma \boldsymbol{E} \quad (4)$$

$$\nabla \cdot \boldsymbol{J} = 0 \quad (5)$$

Applying the complex vector potential $\boldsymbol{A}$ to above equations and, holding $\mathbf{B} = \nabla \times \boldsymbol{A}$ and $\nabla \cdot \boldsymbol{A} = 0$, we can get[10]

$$J(x', y', z') = -\frac{j\sigma\mu f}{2} \cdot \int_{\Omega} \frac{J(x, y, z)\,\mathrm{d}\Omega}{\sqrt{(x-x')^2 + (y-y')^2 + (z-z')^2}} - \sigma \nabla \Phi \quad (6)$$

Utilizing the quasi-3D modified-coupled current method[11], the discrete calculation of EMF can be described to solve the following complex linear equation numerically:

$$([R] + 2j\pi f[X])\{I\} = \{U\} \quad (7)$$

where $\{I\}$ is the complex current column, $\{U\}$ is the complex potential column, $[\boldsymbol{R}]$ is a resistance matrix and, and $[X]$ is an inductance matrix.

From Eqn.(7), the induction eddy in billet and mould can be calculated. And then, the magnetic flux density and electromagnetic force in billet, and the electromagnetic pressure on the surface can be solved from the following equations:

$$\boldsymbol{B} = \frac{j}{2\pi f \sigma} \nabla \times J \quad (8)$$

$$\boldsymbol{F} = R_e (J \times B^*)/2 \quad (9)$$

$$\boldsymbol{P}_m = (B \cdot B^*)/2\mu \quad (10)$$

where R_e is the real part of the complex vector and, mark * means the conjugate complex.

In the experiments of continuous casting with soft-contacted mould, the mould is made of pure copper with height 150 mm, outer diameter 118 mm, and inner diameter 94 mm, slit numbers 4 ~ 10 and length 100 mm. The casting velocity for all the tin, aluminum, copper and steel billets is 100 mm/min, and the frequency of power source is 20 kHz. The temperature varying and distribution in the solidification of billet is measured using thermocouples moving with the billet together. The local magnetic flux density is calculated by following equation from Faraday's law with the inducted electric voltage measured by a mini-coil:

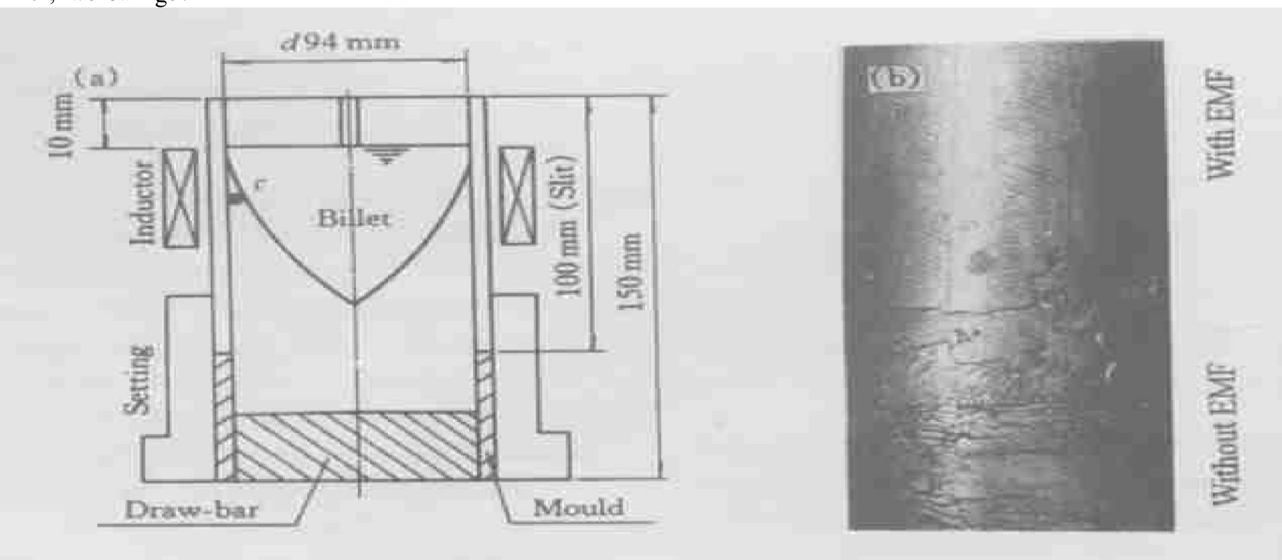


Fig.1 Principle of soft-contacted mould and tin billet
(a) —Structure of soft-contacted mould; (b) —Tin billet cast by mould

$$B_v = E_v / \sqrt{2}\pi f \cdot w \cdot S_c \quad (11)$$

3 RESULT ANALYSIS OF CALCULATION AND EXPERIMENT

In the processes of continuous casting with soft-contacted mould, the power frequency, the inductor current and the structure of the mould are the essential factors for the slag permeating unobstructed, the oscillation marks shallow, the composition uniform, the crystals fine and the equiaxed crystal domain increased. Hence the influences of above factors on the electromagnetic force and the surface quality of billet are studied in this paper.

3.1 Effect of power frequency

Power frequency determines the penetration depth of electromagnetic field in billet. The result of EMF calculation shows that with the frequency going up, the electromagnetic pressure on the surface of billet is increasing, and the electromagnetic stirring force in liquid core of billet is decreasing.

Fig.2 illustrates the effect of the power frequency on magnetic flux density at point c shown in Fig.1 in the process of the continuous casting. It is shown that with the frequency rising, the magnetic flux density is increasing comparatively quickly when the frequency is lower than 20 kHz, but when the frequency is higher than 20 kHz, the increasing tendency of magnetic flux density is slowing gradually. And when the frequency is over 100 kHz, the magnetic flux density is seldom increasing. This is the result of the shield phenomena of the mould for EMF to be increased with the rising of power frequency.

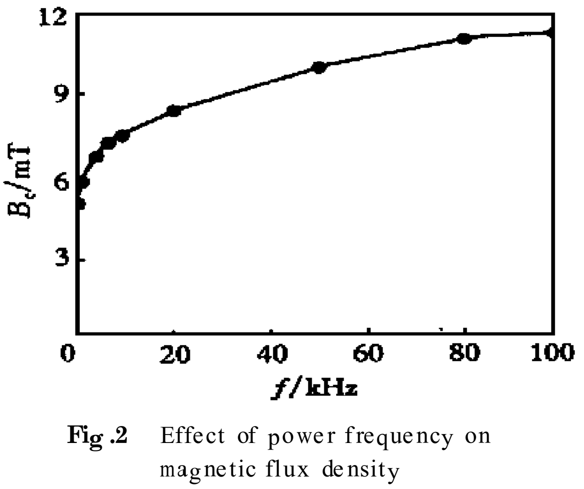


Fig.2 Effect of power frequency on magnetic flux density

In the processes of continuous casting with soft-contacted mould, the rising of magnetic flux density in billet makes the induction current and the electromagnetic force there increased. From EMF calculations and the experiments of the continuous casting, the relation of both the electromagnetic force at the point c and the average one on the surface region of billet covered by inductor with the power frequency ($50\ \text{Hz} \leqslant f \leqslant 100\ \text{kHz}$) can be written as follows:

$$F_c = 0.104 f^{0.514} \quad (12)$$

$$F_a = 0.162 f^{0.390} \quad (13)$$

And the electromagnetic pressure at the point c is

$$p_{mc} = 0.026 Q^2 - 0.054 Q + 0.318$$

$$(Q = \lg f) \quad (14)$$

Hence in continuous casting with soft-contacted mould, both electromagnetic force and pressure are related to the power frequency as a power function and a logarithmically parabolic function respectively.

3.2 Effect of segmented structure of mould

For the effectiveness of electromagnetic penetrating and low eddy loss in soft-contacted mould, the slit number is an important factor. The slit makes the electromagnetic field apply to the billet, and decrease the induction eddy in the mould; but they are easy to produce some technique problems in the casting, such as steel-leaking. Hence the slit number and width (gap) on the soft-contacted mould must be selected reasonably.

To take the point c shown in Fig.1 as an example, the relation of magnetic flux density, electromagnetic force and the pressure on the surface of billet with the slit number on the mould are given in Fig.3 from the calculation and the experiment. It is shown that the more the slit is, the stronger the magnetic flux density, the force and the pressure on the surface of billet are. When the slit is not more than 16, the previous variables are increasing quickly, but their tendency is slowed down. It can be seen that when the slit number is over a limited region, the magnetic flux density penetrated through the mould is tended to saturate. At this time, to re-increase the slits has not any effectiveness for magnetic penetration through the mould, and it can result in steel-leaking in the continuous casting processes on the contrary. So it is reasonable to the soft-contacted mould that the slit number is in the region from 12 to 20.

On the other hand, the EMF calculation shows that with slit gap in the mould increasing, the magnetic flux density on the surface of billet is rising, and the increment of that is concentrated on the domains of slits. To take the experiment of unloaded soft-contacted mould with 4 slits as an example, it is shown by EMF measurement that when the slit gap is 0.5 mm, magnetic flux density at slit is higher than that at the segment center point of the mould for 4% ~ 15% (sees Fig.4). This in-equalization of EMF in the mould can produce longitudinal concave marks on the surface of billet. In this paper, the numerical simulations of EMF in continuous casting with the soft-contacted mould with the slits number 0 ~ 35 and

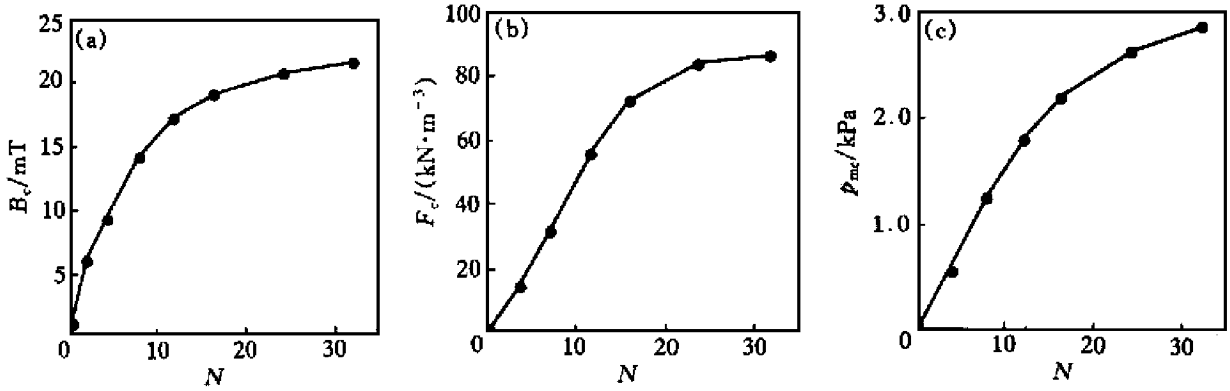


Fig.3 Relation of B_c, F_c and P_{mc} with slit number

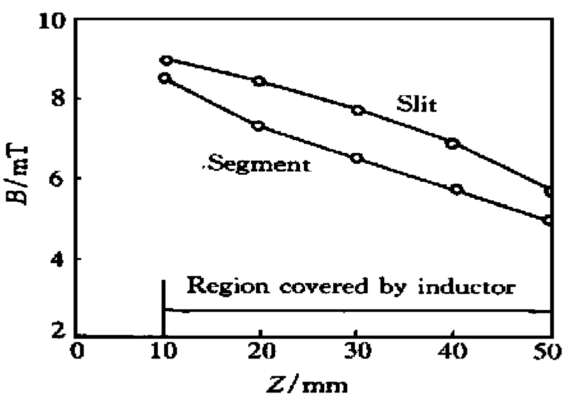


Fig.4 Magnetic flux density at different points in soft-contacted mould

the slit gaps 0.1 ~ 2.0 mm, and the casting experiments of tin billet with both the mould-slits 4 and 10, are researched. The result shows that the peak value of magnetic flux density at slit is rising with the increase of slit gap; and with the slits increased, this peak value of magnetic flux density at slit is decreased. And at the same time, the EMF in the mould tends to become well-distributed, and the longitudinal concave mark on the surface of billet tends to become thin and shallow also. In the previous work[12], we had used gallium (melting point 27 ℃) to study the shape and moving of the meniscus of billet in the continuous casting with soft-contacted mould, the result showed that when the slit gap is over 1 mm, it can be directly observed that the meniscus at slits is pushed inward and, on the surface of billet some longitudinal concave marks are formed, whose quantity is equal to that of slits. Up to now, the experimental result demonstrates that the depth and width of the longitudinal concave mark is related to the peak value of magnetic flux density at the mould-slit. Hence the optimization principle of soft-contacted mould is 'more segments and thin slits', and the slit gap is reasonable in the region of 0.5 ~ 1.0 mm.

3.3 Effect of inductor location and size

In the processes of continuous casting with soft-contacted mould, the location of inductor determines the soft-contacted condition between billet and mould, and the effectiveness of slag permeating, but the gap between inductor and mould then determines the magnetic leaking, induction capacity and the energy distribution in the system.

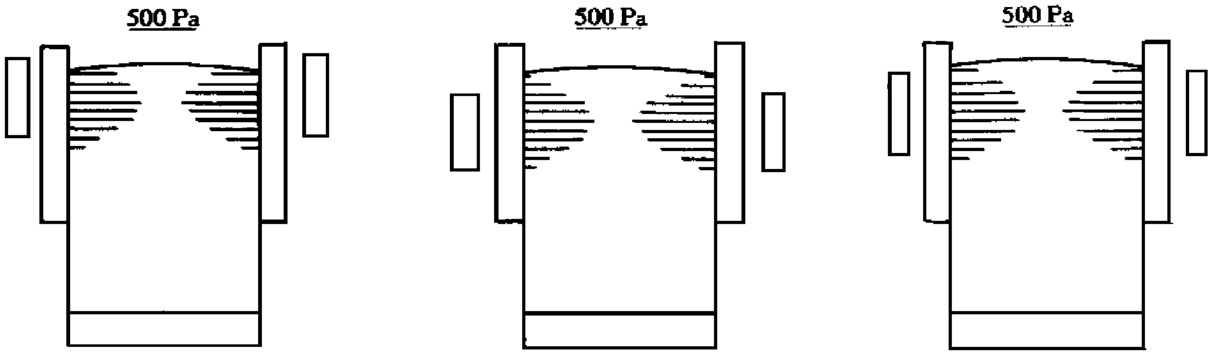
In this paper, take three positions (i.e. Δh = 10, 0, -10 mm) as the examples to study the effect of inductor location on electromagnetic force in the billet, where Δh is the location (height) difference of the topside of inductor to the contact point of the meniscus of billet and the mould. The calculation and experiment result is in Fig.5. It is shown that electromagnetic pressure is stronger only in the region covered by inductor, and it reduces quickly when billet moves out of this region. Hence the region of inductor must cover the initial solidifying shell of billet. From the calculation and experiment, it can be seen that when $\Delta h = 10$ mm, the electromagnetic force and pressure are strong in the meniscus region, which results in forced convection and undulation of liquid metal in this region; when $\Delta h = -10$ mm, the electromagnetic force and pressure are weak relatively in meniscus region and the meniscus is stationary, but which results in the stronger region of force and pressure not to work on initial solidifying shell of billet, so the effect of slag permeating is not to be good; and when $\Delta h = 0$, the initial solidifying shell of billet is covered by strong electromagnetic force and pressure on the whole, and the surface quality of billet is the best in all experiments (just like Fig.1(b)).

Also in this paper, EMF calculation and measurement study the effect of inductor size on electromagnetic pressure (Fig.6). The result shows that with the gap between inductor and mould to be reduced sequentially from $d = 21$ mm to 15 mm, 11 mm and 6 mm, the electromagnetic pressure at the point c on the surface of billet is related to the gap as follows

$$y = 0.72/d - 0.02d + 1 \qquad (15)$$

where $y = p_{mc}(d)/p_{mc}(d_{min})$.

Hence in continuous casting with soft-contacted



(a) $\Delta h = 10$ mm (b) $\Delta h = -10$ mm (c) $\Delta h = 0$

Fig.5 Effect of locations of inductor on electromagnetic pressure

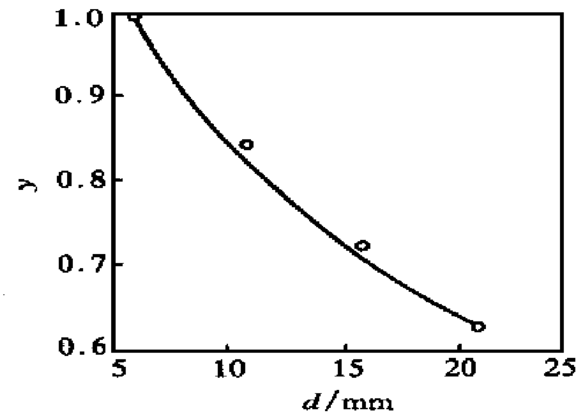


Fig.6 Relation of pressure with gap between inductor and mould

mould, the following conditions should be satisfied, so that the initial solidifying shell of billet can obtain the strong electromagnetic force and pressure, and the induction efficiency of the 'inductor-mould-billet' system is increased:

1) The topside of inductor is at the same position with the meniscus of billet.

2) The height of inductor can cover the initial solidifying shell of billet.

3) The gap between inductor and mould is small as far as possible.

3.4 Effect of inductor current

According to the domain of inductor current used in the continuous casting experiments, the electromagnetic field is calculated and measured to study the influences on the electromagnetic force and pressure in and on the billet.

Fig.7 illustrates the electromagnetic pressure on the surface of tin billet, when the inductor current is in the domain of 0.6 ~ 2.4 kA. The result of EMF calculation shows that with the inductor current increasing, the electromagnetic pressure on the surface of billet is rising as a parabolic function.

Also the relation of both electromagnetic force at the point c and the average one on the surface of billet

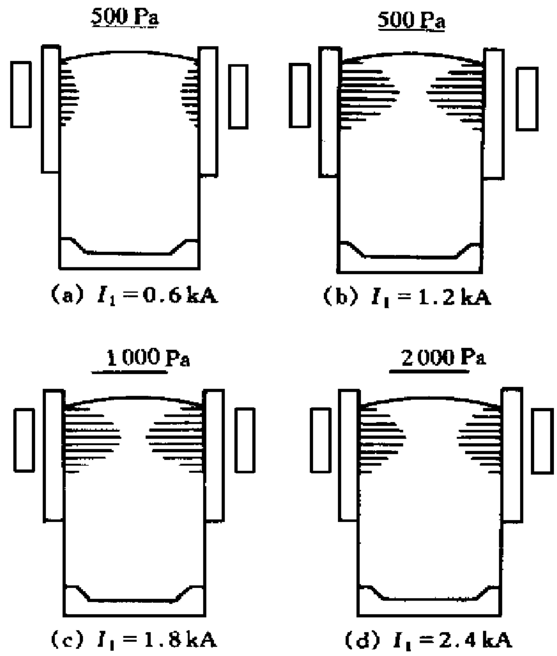


Fig.7 Effect of inductor current on electromagnetic pressure

(a) —$I_1 = 0.6$ kA; (b) —$I_1 = 1.2$ kA; (c) —$I_1 = 1.8$ kA; (d) —$I_1 = 2.4$ kA

in the region covered by inductor with the coil current can be written as

$$F_c = 9.722 I_1^2 - 0.278 I_1 + 0.556 \quad (16)$$

$$F_a = 3.80 I_1^2 - 0.38 I_1 + 0.88 \quad (17)$$

And for electromagnetic pressure at the point c, it can be written as

$$p_{mc} = 0.278 I_1^2 + 0.1 \quad (18)$$

In the experiments, the result shows that it is reasonable for coil current to be in the region of 4 500 ~ 5 000 Ampere-turns for the tin billet and, 8 000 ~ 9 000 for the steel one.

4 CONCLUSIONS

1) The electromagnetic force formed in billet increases with the rising of power frequency. In the experiments, when the power frequency is lower than

20 kHz, the magnetic flux density increases quickly. When the power frequency is higher than 20 kHz, the increasing amplitude of the density is decreased. And when the frequency is over 100 kHz, the density is seldom increased. The numerical and experimental results indicate that both the electromagnetic force and pressure formed on billet are related to the power frequency as a power function and a logarithmically parabolic one respectively.

2) In soft-contacted mould, magnetic flux density at slit is stronger than that at the center point of segment. This irr-equalization of EMF can result in the longitudinal concave marks on the surface of billet at the slits, and the depth and the width of these marks are related to the peak value of magnetic flux density at the slits. The wider the slit-gap is, the higher the peak value of EMF at the slits is. Also the more the slit in the mould is, the stronger the EMF in the mould is, and the less the irr-equalization of EMF between the slits and the segments is. In design of the slit structure of soft-contacted mould, the principle of 'more segments and thin slits' is reasonable. It is good that the slit number in the mould is in the region of 12 ~ 20, and slit gap is 0.5 ~ 1.0 mm.

3) In continuous casting with soft-contacted mould, the topside of inductor should be at the same position of the edge of meniscus. The height of inductor must cover the initial solidifying shell of billet. And the gap between inductor and the mould is small as far as possible, from which, meniscus and the initial solidifying shell of billet can obtain strong electromagnetic force and pressure relatively, and the magnetic leaking in the 'inductor-mould-billet' electromagnetic system can be decreased.

4) The electromagnetic force formed in the billet increases with the rising of inductor current. In the experiments, both the electromagnetic force and pressure are respectively relative to the coil current as parabolic functions, and the coil current is reasonable in the regions of 4 500 ~ 5 000 Ampere-turns for tin billet and 8 000 ~ 9 000 Ampere-turns for steel billet.

Signs and Units

B Magnetic flux density, T;
B_c Magnetic flux density at the point c on the surface of billet, mT;
B_v Local magnetic flux density, T;
d The gap between inductor and mould, mm;
E Electric field intensity, V/m;
E_v Measuring induction voltage, μV;
F Electromagnetic force, N/m^3;
f Power frequency, Hz;
F_a Average electromagnetic force on the surface of billet covered by inductor, kN/m^3;
F_c Electromagnetic force at the point c on the surface of billet, kN/m^3;
I_1 Inductor current, kA;
J Current density, A/m^2;
N The silt or segment number;
p_m Electromagnetic pressure, Pa;
p_{mc} Electromagnetic pressure at the point c on the surface of billet, kPa;
S_c Cross section area of mini-coil, mm^2;
w Turn number of mini-coil;
μ Magnetic permeability, H/m;
σ Electric conductivity, S/m.

REFERENCES

[1] LI Ting-ju. Motion of melt in continuously casting mold and surface quality of ingot under intermittent high frequency magnetic field [J]. Acta Metallurgica Sinica, (in Chinese). 1997, 33(5): 524 ~ 528.

[2] Morishita M. Meniscus shape and flow in an electromagnetic mould [A]. Szekely J. Magnetohydrodynamics in Processing Metallurgy [C]. California: TMS, 1991. 267 ~ 270.

[3] ZHU Xiao-ying. The study on electromagnetic casting [D], (in Chinese). Dalian University of Technology, 1991.

[4] Sakane J. Mathematical model of meniscus profile and melt flow in electromagnetic casters [J]. Metall Trans B, 1988, 19B(6): 397 ~ 408.

[5] Vives C. Electromagnetic refining of aluminum alloys by the CREM process: Part Ⅰ. Working principle and metallurgical results [J]. Metall Trans B, 1989, 20B(10): 623 ~ 629.

[6] DENG Kang. Cold crucible levitation melting and its electroheating characteristics [J]. J Shanghai Univ, (in Chinese), 1994, 15(1): 87 ~ 94.

[7] Cha P R. 3D numerical analysis on electromagnetic and fluid dynamics phenomena in a soft contact electromagnetic slab caster [J]. ISIJ Int, 1998, 38(5): 403 ~ 410.

[8] Furuhashi S. Control of early solidification by the use of high frequency electromagnetic field in the continuous casting of steel [J]. Iron and Steel, (in Japanese), 1998, 84(9): 625.

[9] Ayata K. Scope of national project on electromagnetic casting of steel [J]. CAMP-ISIJ, (in Japanese), 1997, 10(4): 828.

[10] Lavers J D. Computational model for the analysis of molten metal electromagnetic confinement system [J]. ISIJ Int, 1989, 29(12): 993 ~ 1005.

[11] DENG Kang. Electromagnetic model of levitation melting with cold crucible [J]. Trans Nonferrous Met Soc China, 1996, 6(2): 12 ~ 17.

[12] DONG Hua-feng. Homogenization of the magnetic field in soft contact electromagnetic continuous casting [J]. J Iron and Steel, (in Chinese), 1998, 10(2): 5 ~ 8.

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