[Article ID] 1003 - 6326(2000)06 - 0726 - 06

Theoretical and experimental analyses of continuous casting with soft-contacted mould①
(Ⅱ) —EMF calculation and experimental analyses

DENG Kang(邓 康), REN Zhong-ming(任忠鸣), JIANG Guo-chang(蒋国昌)
(School of Materials Science and Engineering, Shanghai University, Shanghai 200072, P.R.China)

[Abstract] Coupling the quasi-3D numerical simulation of the electromagnetic field and the experiments with some metals, a series of phenomena in the processes of continuous casting with soft-contacted mould was analyzed. Some theoretical and experimental models were presented, from which following results were obtained. 1) The electromagnetic force is related with electric conductivity of billet as a power function to 0.4. 2) The heat transfer between billet and mould is related with the contacting pressure, and it is a linear function for tin billet approximately. 3) The distance between initial solidification point and meniscus in billet is related with the surface magnetic flux density as a fourth root function. 4) The temperature gradient in the initial solidifying shell is reduced, which can decrease the tendency of hot tearing on the surface of billet, and increase the equiaxed crystal zone in billet. 5) The stronger the magnetic flux density is, the more shallow and the thinner the oscillation mark on the surface of billet is. 6) The depth of oscillation mark on the billet cast by the soft-contacted mould can be reduced to about 10% in comparison with that on the billets cast by traditional mould. 7) In non-dimensional condition, the average depth of the oscillation marks on the billets cast by the soft-contacted mould decreases with increasing magnetic flux density on there as a complementary error function.

[Key words] electromagnetic continuous casting (EMC); soft-contacted mould; electromagnetic field (EMF)
[CLC number] TM154.21; TF19; TF748.423 **[Document code]** A

1 INTRODUCTION

The continuous casting with soft-contacted mould is a newly developing technology for steel and other heavy metals[1~3]. It can improve the surface quality and increase the equiaxed crystal region in billet efficiently, so it was paid great attentions in the world[4,5]. Now experiment is carried out on a half-industrial scale in Japan and Korea[6].

In this paper, based on the previous work[7,8] and the experiments of continuous casting with soft-contacted mould by some metals, such as gallium, tin, aluminum, copper and steel, following problems are studied, and some theoretical and experimental models are presented. Those problems are the relation of magnetic flux density, electromagnetic force and pressure in billet with electric property of metal, the heat-transfer coefficient with the contacting pressure, and the position of initial solidification point and oscillation mark with magnetic flux density.

2 ELECTROCMAGNETIC FIELD (EMF) CALCULATION AND CONTINUOUS CASTING EXPERIMENT

From the previous work[7], the calculation of EMF in the process of continuous casting with soft-contacted mould results from solving a group of complex linear equation:

$$([\boldsymbol{R}] + 2j\pi f[\boldsymbol{X}])\{\boldsymbol{I}\} = \{\boldsymbol{U}\} \quad (1)$$

where $\{\boldsymbol{I}\}$ is complex current column, $\{\boldsymbol{U}\}$ is complex potential column, $[\boldsymbol{R}]$ is resistance matrix, and $[\boldsymbol{X}]$ is inductance matrix. Hence the induction eddy in billet and mould can be calculated, and then, magnetic flux density, electromagnetic force and the pressure can be solved sequentially.

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

$$\boldsymbol{F} = \mathrm{Re}(\boldsymbol{J} \times \boldsymbol{B}^*) / 2 \quad (3)$$

$$p_m = (\boldsymbol{B} \cdot \boldsymbol{B}^*) / 2\mu \quad (4)$$

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

The experiment device of continuous casting with soft-contacted mould is illustrated in Fig.1, where the height of the mould is 150 mm, and both the outer and the inner diameters are 118 mm and 94 mm, respectively. The slit numbers are 4 ~ 10 and the length of slit is 100 mm. The inductor is 4 turns and the frequency of current within the inductor is 20 kHz. In the experiments, the pouring temperatures are 280 ℃ (for tin), 710 ℃ (for aluminum), 1150 ℃ (for copper) and 1560 ℃ (for steel) respectively, and all the drawing velocity is 100 mm/min. Also in the experiments, a group of thermal couples moving with the billet measures the temperature field

① **[Foundation item]** Projects (59574014) and (59734080) supported by the National Natural Science Foundational of China
[Received date] 1999 - 11 - 15; **[Accepted date]** 2000 - 05 - 08

in solidification, and a mini-coil measures the local induction electric potential in the system, from which the magnetic flux density is calculated by following equation from Faraday's law[9].

$$B_V = U/\sqrt{2}\pi f \cdot w \cdot S_c \qquad (5)$$

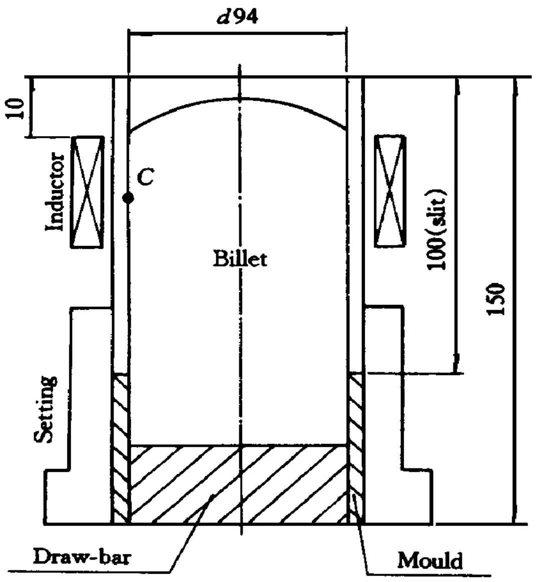

Fig.1 Device schetch of soft-contacted mould
(Units of length and diameter: mm)

3 RESULTS AND DISCUSSION

3.1 Effect of electric property of billet

The electric property of billet determines the induction and the coupling relation between the billet and EMF. The results of EMF calculation and continuous casting experiment with soft-contacted mould for tin, aluminum, copper and steel billets show that the higher the electric conductivity of billet is, the stronger the electromagnetic force induced in billet is, and the weaker the induction heat source generated is. And the varying amplitudes of previous contents are all decreased with increasing electric conductivity of the billets.

Fig.2 shows the comparison of electromagnetic pressure on aluminum billet with that on steel one. The result of EMF computation shows that the electromagnetic pressure on the surface of steel billet is decreased by 58 % compared with that on aluminum billet. And the electromagnetic force in aluminum billet is concentrated in the surface layer, whose gradient is 2.14 times higher than that in steel billet.

To take the point C on the surface of billet corresponding to the center point of inductor shown in Fig.1 as a reference point, the calculated and experimented results are described as following. For the billet with electric conductivity within 0.5 ~ 5.0 S/m, such as iron, titanium, nickel, copper, aluminum, zinc, tin and their alloys, the electromagnetic force F_C at the point C and the average one F_a on the surface of billet in the inductor region can be written as

$$F_C = 22.840\,\sigma^{0.373} \qquad (6)$$

$$F_a = 8.387\,\sigma^{0.401} \qquad (7)$$

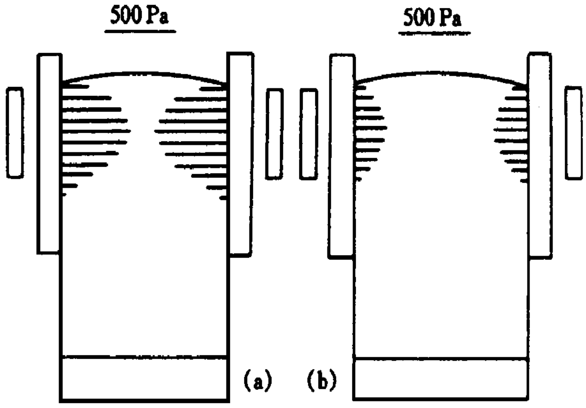

Fig.2 Electromagnetic pressure on aluminum billet and steel billet
(a) —Al; (b) —Steel

Therefore in continuous casting with soft-contacted mould, the electromagnetic force on the surface of billet is related with the electric conductivity as a power function with a power of 0.4 approximately.

Take the experiment process of continuous casting with soft-contacted mould by tin metal as an example, in which the topside of inductor is at the same location (height) with the contacting point of meniscus and the mould, and inductor current is 1.18 kA. The EMF numerical simulation result shows, in Fig.3, that at point C, electromagnetic pressure balances the static one of molten metal in the initial-solidifying shell by about 30 %. Also from Fig.3, it can be seen that the nearer the position to meniscus is, the larger

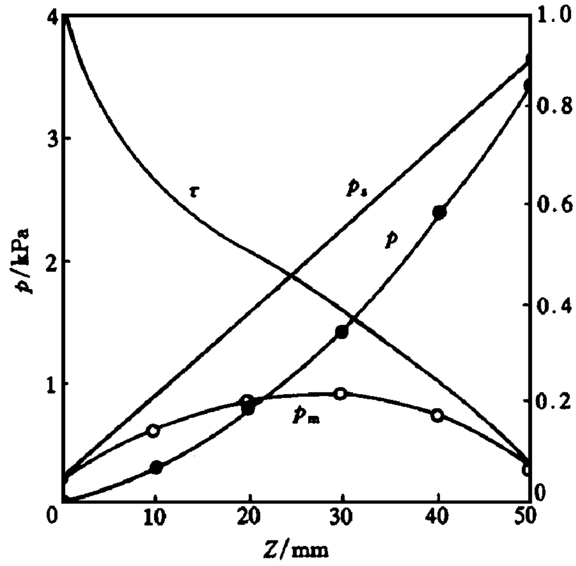

Fig.3 Distributions of static, electromagnetic and contacting pressure, and friction-reducing ratio (τ)
(coordinate Z is downward from edge of meniscus)

the amplitude of the static pressure balanced out by the electromagnetic one is. And up to the edge of meniscus, the friction between the billet and the mould disappears completely. Therefore in the initial solidification period, the contacting pressure and the oscillation friction between the billet and the mould is reduced by EMF, which makes the slag permeating be unobstructed and the surface quality of billet be improved (the oscillation marks on the surface of billet disappeared in the main).

3.2 Effect of contacting pressure on heat-transfer coefficient

In the process of continuous casting with soft-contacted mould, the contacting state between billet and the mould will influence the heat-transfer conditions. In this paper an experiment shown in Fig.4 is used to study the relation of heat-transfer coefficient between billets and the mould with the contacting pressure. In the experiment, the depth H of molten metal to 'mould' (copper) surface is changed to present the different contacting pressure between 'mould' and molten metal, and the temperatures at some points are measured by thermal couples continuously. The numbers in Fig.4 are the positions of the points of measuring temperature. From heat conduction equation the heat-transfer coefficient α between molten metal and 'mould' can be calculated by following equation:

$$\alpha|_{(p=\rho gH)} = \lambda(\theta_2 - \theta_1)/L(\theta_3 - \theta_2) \quad (8)$$

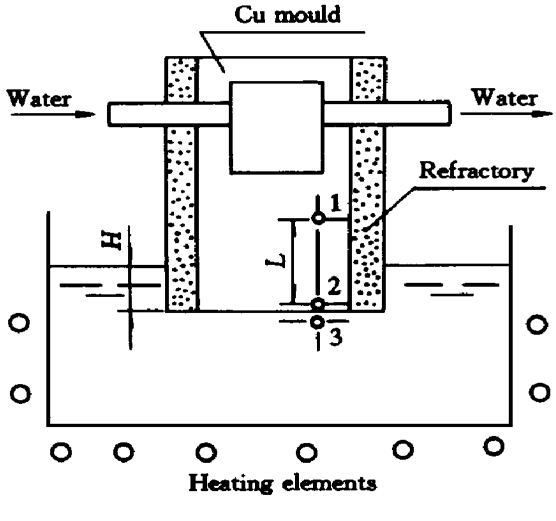

Fig.4 Sketch of experiment apparatus of heat-transfer between molten metal and mould

where λ is conductivity of 'mould' and L is the distance between thermal couples No.1 and 2.

The results measured from both metals gallium and tin are shown in Fig.5. It is shown that the bigger the contacting pressure between mould and molten metal is, the higher the heat-transfer coefficient is. This is the result of the liquid metal to overcome the surface tension and contact with the mould closely, which can decrease the thermal resistance between the billet and the mould effectively. And for the same reason, the balance of electromagnetic pressure against the static one on the surface of billet will reduce the heat-transfer coefficient between the billet and the mould.

For the above two metals, through mathematical regression and calculation of the data resulted from the experiment, the relation of heat-transfer coefficients with the contacting pressure between billet and the mould can be written as following:

$$\alpha = 1.35 p^2 - 0.01 p + 0.75 \quad \text{(For gallium)} \quad (9)$$

$$\alpha = 5.797 p + 7.5 \quad \text{(For tin)} \quad (10)$$

Therefore in design of continuous casting with soft-contacted mould, from the calculation of EMF, the increasing amplitude of temperature in billet and mould from induction, the electromagnetic pressure induced on the surface of billet, and the contacting pressure between the billet and the mould were gotten. Then coupling the conditions of flowing and solidifying of liquid metal, and the water cooling of the mould, the real heat-transfer coefficient between billet and mould can be analyzed and determined. Up to now, It can be obtained that in continuous casting with soft-contacted mould the electromagnetic pressure on the surface of billet reduces the heat-transfer coefficient to mould in the region of initial solidifying shell as linear or parabolic functions. It also reduces the billet temperature gradient. These make the equiaxed crystal zone increase, and the hot tearing tendency on the surface of billet decrease.

3.3 Effect of EMF on initial solidification position of billet

In continuous casting with soft-contacted mould, electromagnetic field reduces the heat-transfer coefficient between the initial solidifying shell and the mould, and in the same time it heats the billet inductively. These result in the initial solidification position of billet in the mould to be down, and the amplitude is related with the magnetic flux density on the surface of billet.

In the experiments of continuous casting with soft-contacted mould, some thermal couples are inserted to molten metal (billet) at different positions and moved down with the billet to measure the solidification process. Also in the experiments, some steel needles are inserted along the edge of meniscus to measure the location of initial solidification point of billet. Both above methods can be applied to correct each other for the initial solidification point of billet. The results from the measurements are shown in Figs.6 and 7. In Fig.6 the temperature curves from low to high are corresponding to the positions at the surface, 0.87 R, 0.57 R and the center of billet re-

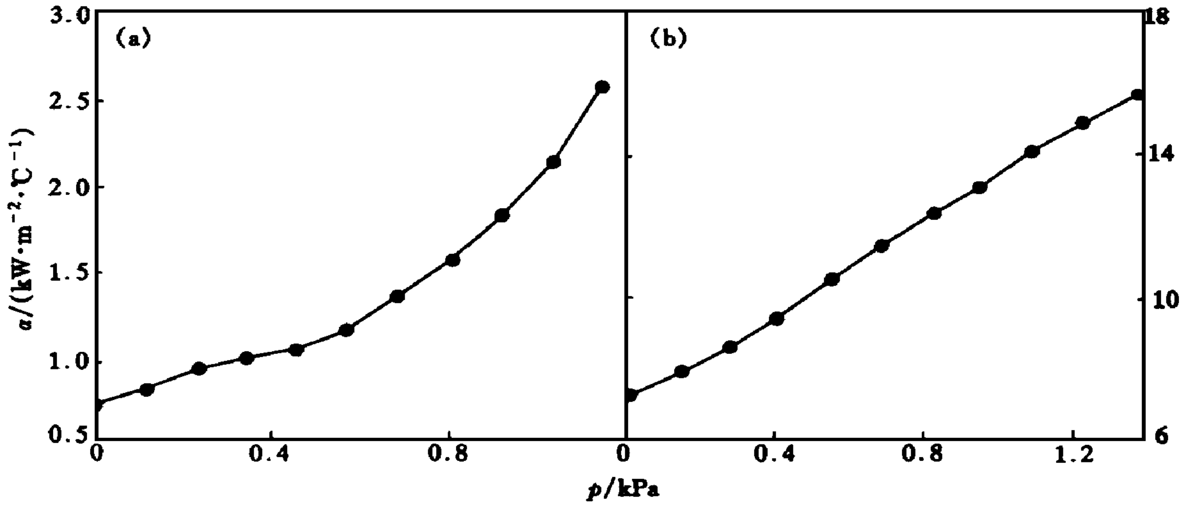

Fig.5 Effect of contacting pressure on heat-transfer coefficient
(a) —Ga; (b) —Sn

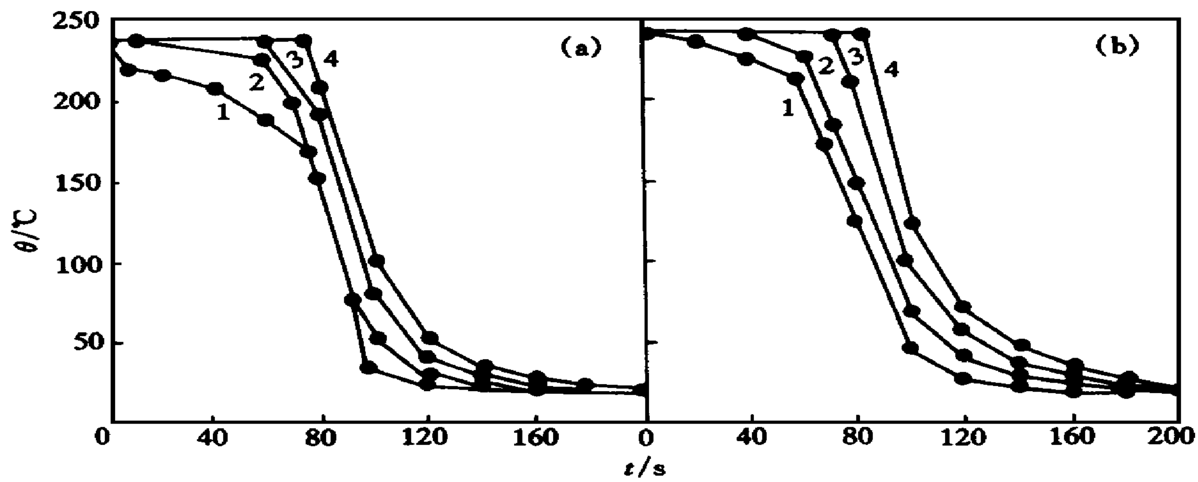

Fig.6 Temperature curves of tin billet in solidification with and without EMF
(a) — $B_C = 0$; (b) — $B_C = 40$ mT

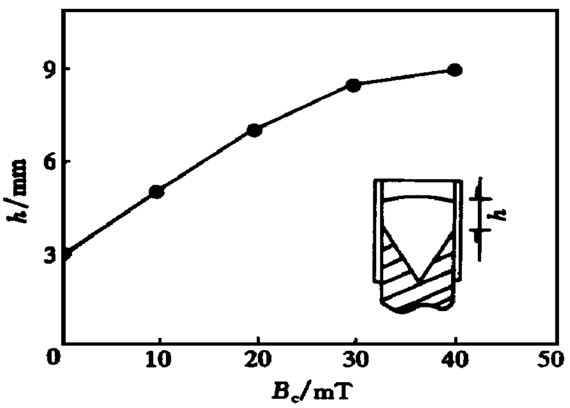

Fig.7 Effect of magnetic flux density on initial solidification position of tin billet

spectively, where R is the radius of billet.

In Fig.6 it is shown that comparing with the continuous casting of tin billet without EMF, the electromagnetic one with magnetic flux density 40 mT results in the temperature falling velocity in initial solidifying shell to be slowed in the region covered by inductor. Also the temperature gradient is reduced, and a solidification terrace in the surface temperature curve is generated. But at the center of billet, the temperature is the same as that one without EMF, and when the billet is out off the region covered by inductor, the temperature falling at the surface is the same as that in traditional continuous casting. These indicate that the influence of EMF on the billet is to decrease the growing velocity of the initial solidifying shell, and to homogenize the temperature distribution in liquid metal comparably in the domain covered by the inductor. These are benificial to decrease the tendency of hot tearing on the surface, and to increase the equiaxed crystal zone in the billet.

In Fig.7 it can also be shown that the position of initial solidification point in billet is going down with the increase of magnetic flux density on the surface of billet. This is the result of both the soft contact between billet and the mould, and the induction heating. This makes the influence of meniscus undulation on the initial solidifying shell being decreased, for this reason, the depth of oscillation mark on the surface of billet can be more shallow.

Coupling the measurements of both the temperature changing and the liquid metal depth in the billet with thermal couples and steel needles separately, and the calculations of EMF with finite elements, the initial solidification position at the edge of meniscus for tin billet is related with the surface magnetic flux density B_C as follows:

$$h = 2.431 B_C^{0.254} + 3 \quad (11)$$

On the other hand, coupling the calculations of both the induction heating in billet by EMF theoretical solution in 1-D[10] and the electromagnetic pressure on the surface of billet by numerical one in quasi-3D, the result shows that, the contributions of the induction heating in billet and mould and the decrease of contacting pressure between billet and mould on the declining distance h of initial solidification point in the mould, are respectively to be 10.5 %, 63.2 % and 26.3 % of the total one. Hence, the main factors of affecting the solidification processes of the billet cast by the soft-contacted mould are both the induction heating in the mould and the electromagnetic pressure on the surface of billet.

3.4 Effect of magnetic flux density on depth of oscillation marks

Applying the tolerance method, the depth of oscillation marks on the surface of billet cast by soft-contacted mould with different EMF intensity can be measured and studied. The result of coupling the material measurement of billets and the EMF calculation of the continuous casting processes is shown in Fig.8 that the average depth of oscillation marks in the continuous casting with soft-contacted mould is about one tenth of that in traditional continuous casting. It is also shown that the stronger the EMF is, the more shallow the oscillation mark is, and the smaller the fluctuating amplitude of the depth is. These indicate again that continuous casting with soft-contacted mould is of good effectiveness for improving the quality of billet.

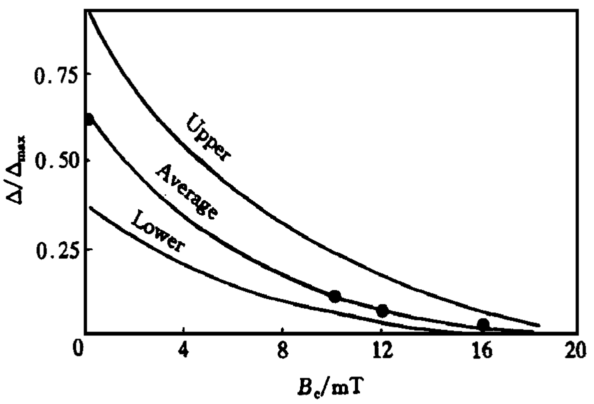

Fig.8 Effect of magnetic flux density at point C on oscillation mark depth

Fig.8 illustrates the relation of the oscillation mark depth with magnetic flux density at the point C. Applying the non-dimensional mathematical treatment, the average depth of oscillation marks on the billets cast by the soft-contacted mould is approximately related with the magnetic flux density at the point C as a complementary error function.

$$\Delta / \Delta_{max} = \mathrm{erfc}(B_C / B_{C,max}) \quad (12)$$

4 CONCLUSIONS

1) In the process of continuous casting with soft-contacted mould, the electromagnetic force generated in the billet increases with increasing electric conductivity of billet, but its amplitude decreases. And also, the electromagnetic penetration is decreased and the gradient of electromagnetic force is increased with increasing electric conductivity of billet. In the experiments, electromagnetic force is approximately related with electric conductivity of billet as a power function to 0.4.

2) The heat-transfer coefficient between the billet and the mould is related with the contacting pressure. The results of the experiment and the measurement for both billets of gallium and tin indicate that the heat-transfer coefficients of above metals to the mould are related with contacting pressure as a parabolic and a linear function respectively. In continuous casting with soft-contacted mould, the heat-transfer coefficient between the billet and the mould is declining compared with that in traditional continuous casting, which results in both the temperature and its gradient in initial solidifying shell decreasing. These are helpful to increase the zone of equiaxed crystal in the billet and to decrease the tendency of hot tearing on the surface of billet.

3) The position of initial solidification point of the billet is decreased on the effect of EMF, and the falling distance of that position is related with the magnetic flux density at the point C as a fourth root function. This makes the position be apart from the meniscus, thus initial solidifying shell of the billet is seldom influenced by undulation of the meniscus.

4) In continuous casting with soft-contacted mould the main factors of influence of EMF on the process of billet solidification are both the induction heating to the mould and the decrease of contacting pressure between the billet and the mould.

5) The experiments and the measurement show that the depth of oscillation mark on the billets is approximately decreased by 90 % compared with that in traditional continuous casting, which apparently improves the surface quality of the billet. And the average depth of oscillation mark on the billet cast by con-

tinuous casting with soft-contacted mould is related with the magnetic flux density at the point C as a complementary error function.

Signs and units

$\boldsymbol{B}$: magnetic flux density, T;
B_C: magnetic flux density at point C, mT;
$\boldsymbol{B}_V$: local magnetic flux density, T;
$\boldsymbol{E}$: electric field intensity, V/m;
$\boldsymbol{U}$: induction voltage measured by mini-coil, μV;
F: electromagnetic force, N/m^3;
f: electromagnetic field frequency, Hz;
F_a: average electromagnetic force on surface of billet covered by inductor, kN/m^3;
F_C: electromagnetic force at point C on surface of billet, kN/m^3;
h: initial solidification position, mm;
$\boldsymbol{I}$: current, kA;
$\boldsymbol{J}$: current density, A/m^2;
j: unity complex;
p: contacting pressure, kPa;
p_s: static pressure, kPa;
p_m: electromagnetic pressure, Pa;
L: distance of thermal couples, m;
S_C: cross section area of mini-coil, mm^2;
t: time, s;
w: turn number of coil;
α: heat-transfer coefficient, kW/(m^2·℃);
Δ: depth of oscillation mark, mm;
θ: temperature, ℃;
λ: heat conductance, kW/(m·℃);
μ: magnetic permeability, H/m;
σ: electric conductivity, S/m;
τ: friction-reducing ratio, $\tau = p_m/p_s$.

[REFERENCES]

[1] Vives C. Electromagnetic refining of aluminum alloys by the CREM process: (Ⅰ). Working principle and metallurgical results [J]. Metall Trans B, 1989, 20B(10): 623 - 629.
[2] Li T J. Motion of melt in continuously casting mold and surface quality of ingot under intermittent high frequency magnetic field [J]. Acta Metall Sinica, (in Chinese), 1997, 33(5): 524 - 528.
[3] Morishita M. Meniscus shape and flow in an electromagnetic mould [A]. Szekely J. Magnetohydrodynamics in Process Metallurgy [M]. California, TMS, 1991. 267 - 270.
[4] 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.
[5] Furuhashi S. Control of early solidification by the use of high frequency electromagnetic field in the continuous casting of steel [J]. Iron & Steel, (in Japanese), 1998, 84(9): 625 - 631.
[6] Ayata K. Scope of national project on electromagnetic casting of steel [J]. CAMP-ISIJ, (in Japanese), 1997, 10(4): 828.
[7] DENG Kang. Electromagnetic model of levitation melting with cold crucible [J]. Trans Nonferrous Met Soc China, 1996, 6(2): 12 - 16.
[8] Dong H F. Homogenization of the magnetic field in soft contact electromagnetic continuous casting [J]. J Iron & Steel Res, (in Chinese), 1998, 10(2): 5 - 8.
[9] Simpson P G. Induction Heating Coil and System Design [M]. London: Macgraw-Hill Book Company, 1960.
[10] REN Zhong-ming. Study of initial solidification in soft contact electromagnetic continuous casting [J]. Acta Metall Sinica, (in Chinese), 1999, 35(8): 851 - 855.

(Edited by HUANG Jin-song)