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Hot-top electromagnetic casting research of Al thin slab①

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Abstract: The hot-top EMC (electromagnetic casting) method was put forward, namely, the shape of top liquid column was formed by the hot-top in the screen and the semi-suspended liquid column was formed by the electromagnetic force nearby the liquid-solid interface frontier. Using the numerical simulating technique, the temperature distribution was discussed, the effect of parameters such as upper-conduct distance (UCD), cooling water rate of flow, pouring temperature and liquid column height on casting velocity were studied, the relationship among them was confirmed finally. According to the calculated results, the hot-top EMC shaping system was designed and a lot of experiments were performed. The pure Al thin slabs of 480 mm × 20 mm × 850 mm were made successfully. The result showed that the casting velocity curve obtained experimentally almost coincides to the calculated one.

Key words: electromagnetic forming; casting velocity; thin slabs **Document code:** A

1 INTRODUCTION

Electromagnetic casting(EMC) is a mouldless continuous casting technology with which liquid metal is shaped by electromagnetic force and it has advantages such as: smooth ingot surface, compact, homogeneous tissue and higher casting velocity. EMC technology has been developing very quickly in the past 30 years. Firstly, the technique of producing simultaneously six ingots was invented[1] and was applied to copper and zinc alloys successfully[2,3]. Then up-leading EMC realized production of Al pipe castings[4]. Asai invented the horizontal EMC of Al thin plate[5], and American Energy Ministry applied for the similar patent[6], but didn't succeeded up to now. Numerical simulation of EMC process was widely researched. Prasso *et al* built three dimension temperature field model of Al slab, discussed the effects of casting velocity and cooling intensity on the solidification process as well as the shape and location of liquid-solid interface[7]. Cook and Evans put forward three dimension electromagnetic field calculating model, analyzed electromagnetic field, fluid velocity field, the shape of liquid column and proved by physical model[8]. Kurz and Fisher simulated and predetermined the micro-tissue of EMC ingot[9]. At present, research of Al thin slab EMC becomes one of the popular points. Al thin slab with 10 mm in thickness manufactured by EMC can be directly cold-rolled replacing the common hot rolling. This has more economic significance with not only reducing procedure and technological device, saving energy, but also developing merits of EMC of improving tissue and properties. Using finite element method, Cook and Evans calculated the location of the solidifying frontier while casting 10 mm Al thin slab by EMC and then analyzed the electromagnetic field and finally confirmed electromagnetic pressure supporting liquid column shaping[10]. Yamane *et al* proceeded the similar research[11]. Kanouya *et al* proceeded EMC technical experiment of Al alloy thin slab and manufactured a sample with 150 mm × 10 mm and the results showed the properties better than hot-rolled plate's[12]. This paper brings forward the hot-top EMC

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method of Al thin slab with confirming casting technical parameters under different conditions and relationships among them by numerical simulation. According to the calculated results and the lot of technical experimeats, the samples of 480 mm × 20 mm of pure Al thin slab were made out successfully.

2 HOT-TOP EMC METHOD

For the electromagnetic casting of Al thin slab, the control of pouring processing and shaping of semi-suspended liquid column are very important. Moreover, due to the small section of liquid column, the little changement of metal flow quantity can result in remarkable fluctuation of liquid column height while casting, so the size of thin slab is hardly stable. In order to solve above-mentioned problems, this paper puts forward the hot-top EMC method, its technology and principle are shown in Fig.1 and Fig.2. In contrast with the common EMC method, the hot-top EMC needs not to keep the electromagnetic force equilibrium with the liquid metal hydrostatic pressure, P_m everywhere along the liquid column height, h_z but separates the liquid column into two parts to fit the following conditions:

$$P_m \leqslant \rho g h \text{ when } h_z = h_2 \sim h_1 \quad (1)$$

$$P_m \geqslant \rho g h \text{ when } h_z = 0 \sim h_2 \quad (2)$$

When $h_z = h_2 \sim h_1$, the liquid column is shaped by hot-top lying on the screen. By reducing the height of electromagnetic inductor and

Fig.1 Hot-top EMC device of Al thin slab

Fig.2 Principle of hot-top EMC

forcing to restrain the top magnetic field by screen, the electromagnetic pressure of the top liquid column is decreased greatly so as to the section of the top liquid column being enlarged. On the other hand, this is easier for pouring processing, and also facilitates to eliminate the effect of metal liquid quantity change on liquid column height and to remain size of thin slab stable.

While $h_z = 0 \sim h_2$, the liquid column is still formed by electromagnetic force. Because metal liquid is remaining free surface before solidification, the method still has the virtues of EMC such as: smooth ingot surface, compact and homogeneous tissue, etc.

3 TEMPERATURE FIELD SIMULATION AND TECHNOLOGY PARAMETERS OPTIMIZATION

In order to determine technical parameters range of Al thin slab and to study the effect of each parameter on the casting velocity, this paper numerically simulated the temperature field of Al thin slab and optimized the technical parameters.

3.1 Basic equation

The simulation used the EMC temperature field model built by Prasso *et al*, the basic equation is as below:

$$\rho c_p\left[\frac{\partial \theta}{\partial t} + v_x \frac{\partial \theta}{\partial x} + v_y \frac{\partial \theta}{\partial y} + v_z \frac{\partial \theta}{\partial z}\right] =$$

$$\frac{\partial}{\partial x}(k\frac{\partial\theta}{\partial x})+\frac{\partial}{\partial y}(k\frac{\partial\theta}{\partial y})+\frac{\partial}{\partial z}(k\frac{\partial\theta}{\partial z})+q \qquad (3)$$

where c_p is specific heat, k is heat conduction coefficient, θ is temperature, v is casting velocity, t is time, ρ is density, and q is heat source.

3.2 Assumed condition

(1) The aspect ratio of Al thin slab is about 24, so the heat conduction in width direction is much less than in thickness direction, thus, heat conduction can be ignored and then $\partial\theta/\partial y = 0$.

(2) During calculation the liquid metal level and liquid column height are constant.

(3) The solidification latent heat is handled with temperature compensation method.

(4) The induction heat is treated as partial inner heat source and its heating velocity is 1.52 ℃/s determined experimentally.

(5) Only thinking about heat conduction during calculation, the convection heat exchange caused by melt flow in overheated region is handled with the method of amending coefficient of thermal conductivity, that is to say, using $k_{eff} = mk_{Al}$, $m = 1.2$.

According to above assumption, Eqn.(3) can be simplified as below:

$$\rho c_p\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial x}(k\frac{\partial\theta}{\partial x})+\frac{\partial}{\partial z}(k\frac{\partial\theta}{\partial z})-\rho c_p v\frac{\partial\theta}{\partial z}+q_{in} \qquad (4)$$

3.3 Differential equation

On the basis of law of conservation energy, using explicit differential method and during unit time, the energy changement Q of one-element amounts to the algebraic sum of which exchanged with around elements and induction heat, that is:

$$\Delta Q_{i,j} = \Delta Q_L + \Delta Q_R + \Delta Q_T + \Delta Q_B + \Delta Q_I \qquad (5)$$

where L is left element, R is right element, T is top element, B is bottom element and I is induction heat. Using above balance equation, the changed equation is as follow:

$$\theta_{i,j}^{p+1}-\theta_{i,j}^{p}=\frac{2\Delta t}{\rho c_p\Delta x_j}(k_L\frac{\theta_{i,j-1}^p-\theta_{i,j}^p}{\Delta x_{j-1}+\Delta x_j}+k_R\frac{\theta_{i,j+1}^p-\theta_{i,j}^p}{\Delta x_{j+1}+\Delta x_j})+\frac{2\Delta t}{\rho c_p\Delta z_i}(k_T\frac{\theta_{i-1,j}^p-\theta_{i,j}^p}{\Delta z_{i-1}+\Delta z_i}+k_B\frac{\theta_{i+1}^p-\theta_{i,j}^p}{\Delta z_{i+1}+\Delta z_i})+\theta_{in}(x,z)\Delta t \qquad (6)$$

where Δx, Δz is the length of element, Δt is time step, while calculating grid are divided into 600 elements and $\Delta x = \Delta z = 2$ mm, $\Delta t = 0.01$ s.

4 CALCULATION CONDITIONS

4.1 Initial conditions

The initial condition of calculating are as following: pouring temperature is 720 ℃, bottom mould temperature is about 80 ℃, cooling water temperature is 20 ℃ and casting velocity is 0 mm/s.

4.2 Boundary conditions

(1) The temperature of liquid column is stable because of metal liquid continuously pouring so it can be consider as heat insulation.

(2) The part of above spraying water is considered as atmosphere cooling boundary.

(3) The convection coefficient of heat exchange below spraying water is relevant to the cooling water quantity, flow velocity, water temperature and spraying method. This paper employs the empirical formula[13].

$$h = 2.25\times10^4\times w^{0.55}(1-7.5\times10^{-3}\theta_s) \qquad (7)$$

where $h = 1\,000 \sim 10\,000$ W/(m²·℃), w is spraying water density.

5 ANALYSES OF NUMERICAL SIMULATION RESULTS

The paper calculated the temperature field of Al thin slab during solidification and studied the influence of some parameters such as UCD (upper conduction distance), cooling water rate of flow and pouring temperature as well as height of metal liquid column on the casting velocity.

Fig.3 shows the change of isotherm and the shape of liquid/ solid interfaces while Al thin slab solidifying. Because the thin slab is only 20 mm in thickness, the center of thin slab even is cooled strongly. Moreover, because of induction heat, the solidification velocity in the surface decreases, so the isotherm of Al thin slab becomes much flatter than the large slab[14], and the liquid cave depth is only several micrometers. This coincided to Cook' s calculating result[8]. Fig.3 also indicated that the induction heating has not evident effect on the shape of liquid/ solid interface.

Fig.3 Isotherm of Al thin slab during solidification

The effect of induction heat on casting velocity is shown in Fig.4. It can be seen that when considering the induction heat, the initial velocity v_1 and the stable velocity v_2 is reduced from 0.95 mm/s and 2.90 mm/s to 0.85 mm/s and 2.20 mm/s separately. Moreover, the time of initial and transition period are both increased, so the effect of induction heat on the casting velocity can not be ignored.

Fig.5 illustrates the effect of UCD on the casting velocity. When UCD is very small, spraying point moves upward, the cooling effect is strengthened, therefore, the casting velocity must be raised to keep liquid/ solid interface stable. While UCD is less than 60 mm, the effect is notable, but when UCD is above 60 mm, the change of casting velocity tends to be stable. The effect of cooling water rate of flow on the casting velocity v_2 is shown in Fig.6. When cooling water rate of flow increases, the heat quantity being taken away in unit time increases and the spraying point is moved up a little, that is to say, UCD is reduced, and the solidification velocity increases. So as to remain the stability of liquid/ solid interface, the casting velocity must be raised. In contrast to UCD, the effect of cooling water rate of flow is smaller, therefore, UCD can be considered as coarse tuning and cooling water rate of flow is fine-tuning for casting velocity.

Tables 1 and 2 show the effect of liquid

Fig.4 Effect of inducting heat on casting velocity

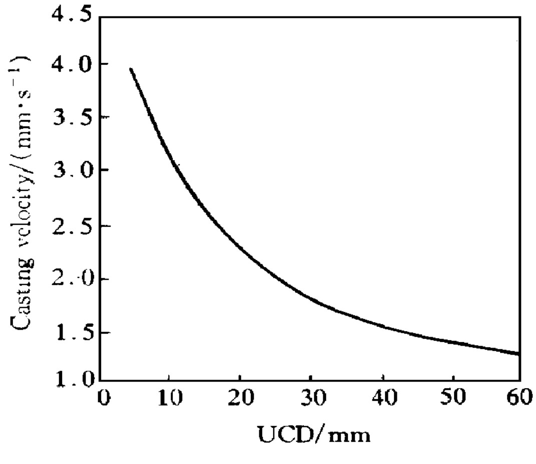

Fig.5 Effect of UCD on casting velocity

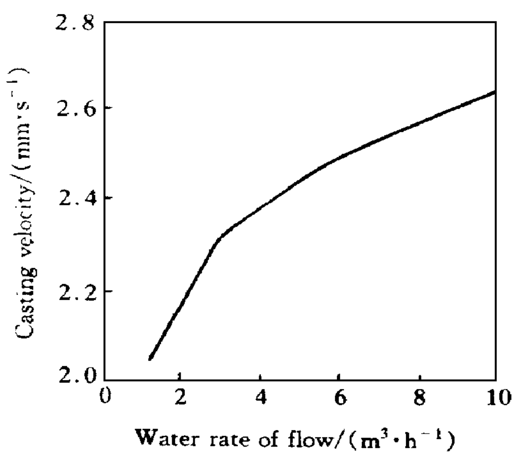

Fig.6 Effect of cooling water rate of flow on casting velocity

metal column height and pouring temperature on the casting velocity v_2 in stable stage. We can see that liquid column height change hardly affects the casting velocity, and casting velocity decreases with pouring temperature being raised but not notable. It can be concluded that for EMC of Al thin slab the pouring temperature can be raised in the range of technical permit to improve the fluidity of liquid metal to get the good formability.

Table 1 Effect of liquid metal column height on casting velocity

Item	Data				
h/mm	30	36	40	46	50
v_2/(mm·s^{-1})	2.30	2.31	2.32	2.32	2.32

Table 2 Effect of pouring temperature on casting velocity

Item	Data				
θ/℃	680	700	720	730	740
v_2/(mm·s^{-1})	2.47	2.39	2.32	2.28	2.25

6 RESEARCH OF Al THIN SLAB HOT-TOP EMC TECHNOLOGY

The hot-top EMC experiment device consists of melt furnace, electromagnetic inductor, screen, hot-top, pouring system, cooling water system, intermediate frequency power and casting machine. Inductor is made of single turn red copper plate, screen of stainless steel thin plate with 1.5 mm in thickness, and the width of hot-top is 100 mm in the top and 20 mm in the bottom and it is lay in the screen during casting experimental processing. Pouring temperature of pure Al is 740 ℃, pouring channel and split-flow channel are both preheated to 500 ℃. The power is 100 kW and frequency is 2 500 Hz. Casting machine is controlled by a serial of change velocity systems with velocity adjustable within 0 ~ 25 cm/min. According to the simulation results, the technical parameters are chosen as below: UCD is 20 mm, cooling water rate of flow Q_w is 3.0 m^3/h, liquid column height is 55 mm and inductor current is 5 600 A. Through a lot of experiments, the casting velocity-time curve is obtained as shown in Fig.7. We can see that casting velocity-time curve of Al thin slab still exists three stages, namely, initial, transition and stable stages. But in contrast to the large slab, the initial and transition stages are both shorten and the velocity reaches the stable stage very soon. Under the paper's technical condition, v_1 = 1.0 mm/s, v_2 = 2.6 mm/s and the transition stage time is about 10 s. Following this, the Al thin slab sample with section size of 480 mm × 20 mm is manufactured successfully as shown in Fig.8. It is necessary to point out that real casting velocity is higher about 10 % than the calculating one for the reason of ignoring the decrease of pouring temperature. However, the shape and value of calculated curve are roughly suitable to the experimental result, so we can conclude that numerical simulation is an available method with high precision for EMC technological analysis. On the other hand, calculating results indicate improving technological condition can further raise casting velocity.

7 CONCLUSIONS

(1) In addition to all merits of EMC, hot-top EMC is easier than common EMC in technical control, moreover, the liquid column height and size are more stable. Therefore hot-top EMC

method suits to the Al thin slab and other size's as well as alloy's EMC.

(2) Numerical simulation shows that the upper conduct distance (UCD) and the cooling water rate of flow affect notably on casting velocity, but the influence of the liquid column height and the pouring temperature are not obvious.

(3) Al thin slab sample with section size of 480 mm × 20 mm was made successfully using hot-top EMC method. The real casting velocity curve coincides to the calculated one, so the numerical simulation is valid for technical analysis of EMC.

Fig.7 Relative between casting velocity and time

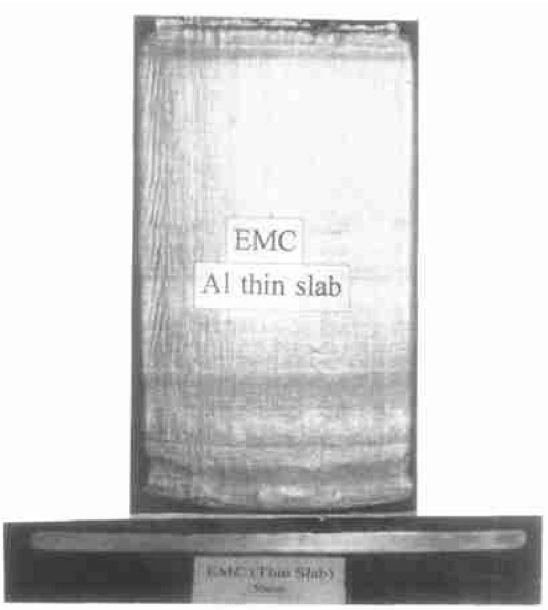

Fig.8 Sample of Al thin slab (480 mm × 20 mm × 850 mm)

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