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Technical parameters in electromagnetic continuous casting of aluminum alloy①

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Abstract: The temperature field of aluminum ingot during electromagnetic continuous casting was calculated by the numerical method, and the effects of cooling water strength, position of the cooling water holes and pouring temperature as well as induction heat on casting speed, were studied. The results show that among the technical parameters the distance from the position of the cooling water holes to the bottom of the mold is the most important factor, whose change from 20 mm to 15 mm and from 15 mm to 10 mm causes the setting rate increasing respectively by 0.14 mm/s and 0.3 mm/s. The calculated results also agree with the experiment well. The simulation program can be used to determine technical parameters of electromagnetic casting of aluminum ingot effectively.

Key words: continuous casting; electromagnetic field; temperature field; casting speed; aluminum alloy.

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1 INTRODUCTION

Electromagnetic casting (EMC) is an advanced material processing technique invented by Getselev[1] and has been widely used in the world because its products have the advantages of smooth surface, homogeneous microstructure and good workability[2, 3]. Electromagnetic continuous casting of steel is a new type method brought forward by Vives[4-6] that combined the electromagnetic field with continuous casting technique. It is also a new idea to apply this method into the shaping process of aluminum alloy to improve the surface and inner quality of the ingots. However, few reports on this topic were found as so far.

As the basic study, the relative process parameters should be investigated. Because only when the casting speed keeps consistent with the setting rate can the electromagnetic continuous casting process be realized successfully, it is essential to determine the casting speed of the ingot during solidification using computer numerical simulation which can forecast the temperature field of the ingot quickly and effectively.

In the present study, the effect of the key parameters such as the position of water jet holes, pouring temperature, cooling water strength and inducting heat on the setting rate have been calculated and discussed to provide the guides for the optimum design of the other technical parameters.

2 MATHEMATICAL MODEL

2.1 Heat transfer equation

For the numerical simulation of electromagnetic casting process, Prasso et al[7-9] had brought forward an excellent mathematical model as shown in Eqn. (1):

$$\rho c_p\left(\frac{\partial T}{\partial t}+V\cdot\nabla T\right)=\nabla\cdot(k\nabla T)+\dot{q} \qquad (1)$$

where c_p, k, ρ are specific heat capacity, thermal conductivity and density of the metal respectively, V is the casting speed, T is the temperature, t refers to time and $\dot{q}$ is the inner heat source, including the latent and induction heat.

To solve the heat transfer equation, the following assumptions are introduced:

1) Inside the ingot, only the heat conduction is taken into account, and the effect of heat transfer caused by convection is dealt with the equivalent heat conduction coefficient k_{eff}.

2) The latent heat of solidification is not regarded as inner heat source and is dealt with the equivalent special heat method.

3) The inducting heat is regarded as inner heat source and the value and distribution of it can be determined experimentally[10].

4) The ingot moves down at casting speed V, at the same time, the $V\Delta t$ length at the upper should be filled with liquid metal. So the process of continuous casting can be treated as a moving, but relative stable temperature field problem[11].

Thus, the heat transfer in Eqn. (1) becomes

$$\rho c_p\left(\frac{\partial T}{\partial t}\right)=\nabla\cdot(k\nabla T)+\dot{q} \qquad (2)$$

For round billet, the heat transfer equation in cylindrical polar coordinate system can be transformed

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into:

$$\rho c_p\left(\frac{\partial T}{\partial t}\right)=\frac{1}{r}\frac{\partial}{\partial r}\left(rk\frac{\partial T}{\partial r}\right)+\frac{1}{r^2}\frac{\partial}{\partial \varphi}\left(k\frac{\partial T}{\partial \varphi}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+q \quad (3)$$

2.2 Boundary conditions

1) For the free-surface: $T = T_p$.

2) For the symmetry face: $\frac{\partial T}{\partial z} = 0$.

3) At the interface between mould and ingot, the heat transfer coefficient is dealt with the funtion of the mould height because the heat-resistant of air gap changes at different height of the mould.

4) Below the water jet hole, the heat transfer coefficient can be obtained according to the experimental equation[12]:

$$h = 2.25\times10^4\omega^{0.55}(1-7.5\times10^{-3}T_w)$$

where T_w is cooling water temperature, ω is the density of cooling water flow rate.

5) At the interface between the ingot and the bottom mould, a simple model of equivalent heat-resistant is used.

3 EXPERIMENTAL

In order to verify the accuracy of the simulating calculation program, the temperature field of the ingot was measured during electromagnetic continuous casting of Al alloy. The schematic diagram is shown in Fig. 1, the mould with size of 125 mm in diameter is made of copper-plate and is cooled by the cooling water. The inductor is placed outside the mould. The power is 60 kW and the frequency is 2 500 Hz.

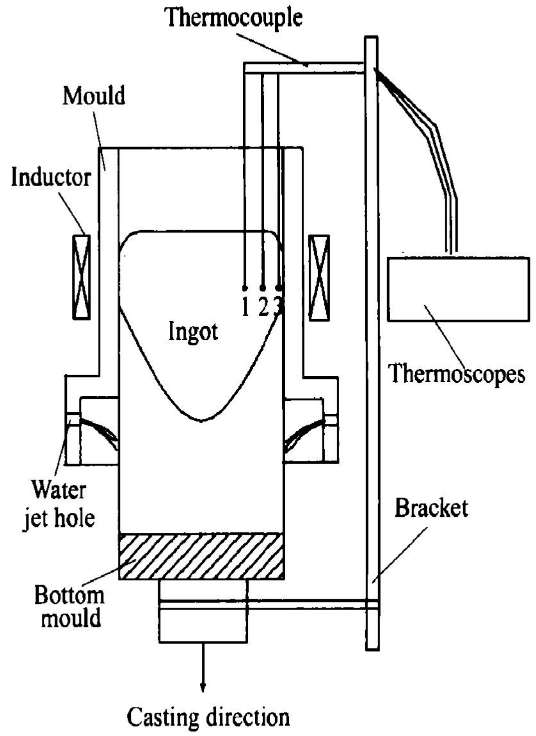

Fig. 1 Schematic diagram of temperature measuring

3.1 Measurement of temperature field

The temperature of three points in ingot were measured as shown in Fig. 1 using NiCr-NiSi thermocouples and recorded by Molytek-32 during the electromagnetic continuous casting of Al alloy. The resinous plate with thermocouples arranged on it was fixed at the bottom mould and downed with the mould simultaneously. The technical conditions of temperature measurement experiment are shown in Table 1.

Table1 Conditions used in experiment

Casting parameter		Alloy parameter	
Pouring temperature	720 ℃	Alloy	AA1201
Water temperature	20 - 30 ℃	Density	2650 kg/m^3
Mould temperature	35 - 45 ℃	Liquidus temperature	658.2 ℃
Casting speed	2 mm/s	Solidus temperature	632.1 ℃
Ingot diameter	120 mm	Latent heat	358.5 J/g
Water flux	1.8 m^3/h		

3.2 Comparison between calculated and measured results

The results obtained from the experiment are shown in Fig. 2 and the comparison with the results obtained by simulating calculation is shown in Fig. 3. It can be noted that the calculated results coincide with the measured very well.

The setting rate of the ingot can be also determined by the simulation results of the temperature field. Fig. 4 shows the setting rate curve during the electromagnetic casting of Al alloy with size of 125 mm in diameter. It can be seen that a peak value of setting rate appears at the beginning of pouring because of the sudden cooling of the molten metal, and then the setting rate keeps a relative steady value which is about 2 mm/s when the casting process attained to steady state.

The setting rate calculated agrees with the casting speed adopted in the experiment. It also gives out the proof for the accuracy of the calculated results.

4 SIMULATION OF TECHNICAL PARAMETERS

Key technical parameters, which influence the setting rate during the electromagnetic casting process of Al alloy, include the cooling water flow rate, position of the water jet hole, pouring temperature, etc.

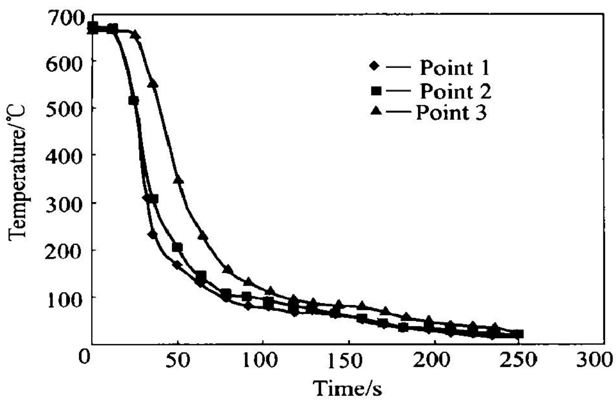

Fig. 2 Temperature vs time of measured points

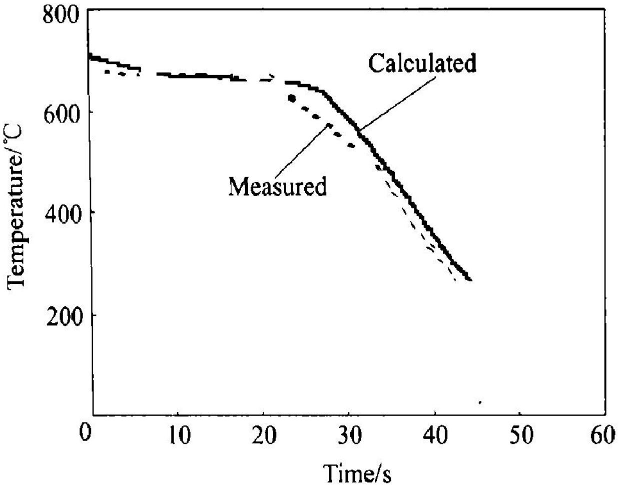

Fig. 3 Comparison between calculated and measured results of Point 1

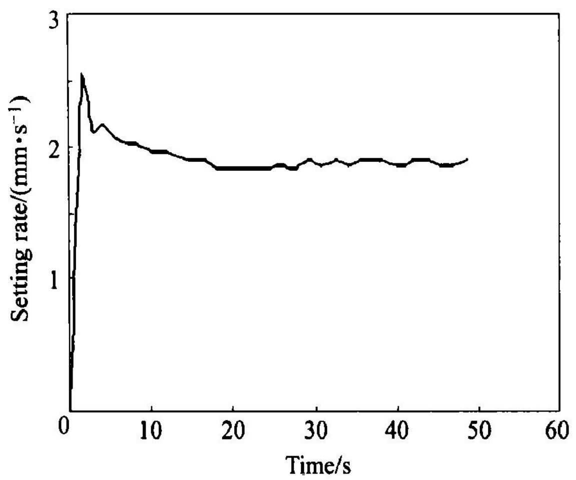

Fig. 4 Variety of setting rate with time

4.1 Effect of cooling water flow rate

Fig. 5 shows the relationship between the setting rate and the cooling water flow rate. It can be seen that the setting rate increases with the increasing of water flow rate. The setting rate increases by approximately 0.5 mm/s when the water flow rate has a 0.6 m^3/h augment. It is because that the heat transfer coefficient becomes larger with the increase of the cooling water flow rate, a bigger casting speed is needed to match with it so as to maintain the liquid-solid interface outside ingot at a same level designed in anticipation.

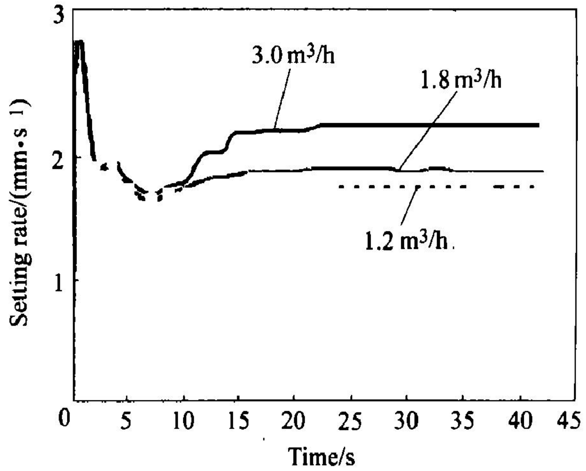

Fig. 5 Setting rate at different cooling water rate

4.2 Effect of position of water jet holes

The influence of water jet hole position on setting rate is demonstrated in Fig. 6. It can be seen that, the longer the distance from the position of the water jet holes to the bottom of the mould is, the greater the setting rate and the shorter the time for reaching steady state will be. This is due to the fact that, when increasing the water jet hole position, the temperature gradient at the liquid-solid interface increases and the solidifying process become more rapidly. From the simulation results, it can be noted that the setting rate increases by 0.14 mm/s and 0.3 mm/s when the distance is reduced from 20 mm to 15 mm and from 15 mm to 10 mm respectively. It is obvious that the position of the water jet hole has greater influence on the setting rate than that of cooling water flow rate.

4.3 Effect of pouring temperature on setting rate

Fig. 7 shows the influence of pouring tempera-

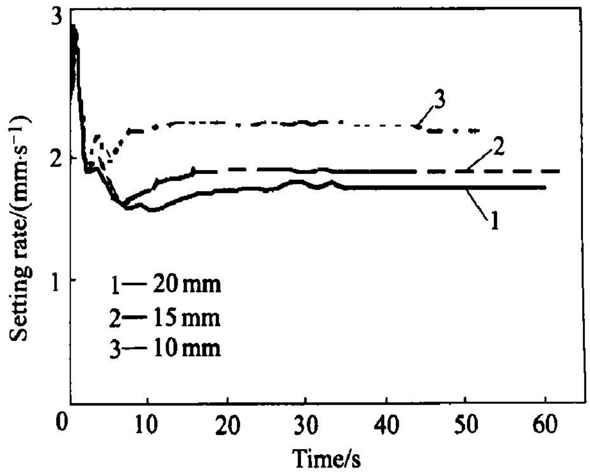

Fig. 6 Effect of water jet holes position on setting rate

ture on the setting rate under the condition of keeping the other parameters invariable. The setting rate increases when pouring temperature is lowered, because the lower temperature shortens the solidification time.

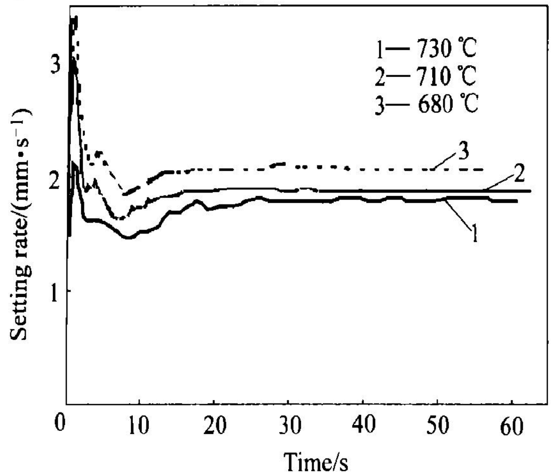

Fig. 7 Influence of pouring temperature on setting rate

The results indicates that matching setting rates are 2.07, 1.91 and 1.78 mm/s when pouring temperatures are 680, 710 and 730 ℃, respectively. However, considering the delivery of liquid metal, the pouring temperature should be kept at 710 - 730 ℃.

5 INFLUENCE OF INDUCTION HEAT ON SETTING RATE

It is well known that the inducting heat generated during the electromagnetic casting process will heat both of the mould and ingot, which will result in the decrease in the setting rate. Fig. 8 shows the influence of induction heat on the setting rate. It can be observed that the setting rate is not affected obviously. The main reason is that the effect of the mould shield decreases the magnetic induction density in it, therefor decreases the effect of the induction heat .

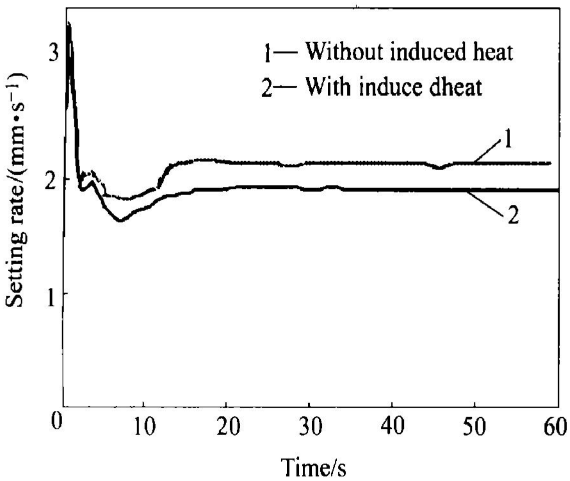

Fig. 8 Influence of induced heat on setting rate

6 CONCLUSIONS

1) The calculated results agree well with the measured, the program can be used to optimize the technical parameters of electromagnetic continuous casting of Al alloy.

2) The position of the water jet holes have the biggest effect on the setting rate. The most valuable way to control casting speed is to change the distance of the water jet hole to the bottom of mould bottom. The setting rate increases respectively by 0.14 mm/s and 0.3 mm/s when the distance changes from 20 mm to 15 mm and from 15 mm to 10 mm.

3) The cooling water flow rate is another important technical parameter affecting the setting speed. The setting rate increases by approximately 0.5 mm/s when the water flow rate has a 0.6 m^3/h augment.

4) The induction heat has no obvious effect on the setting rate during the electromagnetic continuous casting of Al alloy.

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