Joule heating in electromagnetic casting

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Abstract

According to the experimental analysis of temperature distribution in an Al ingot of electromagnetic casting, the induction thermal profile in the horizontal and vertical directions is studied. The influence of inductor currents on the thermal distribution of the ingot is also analyzed. The relation between the average temperature in the ingot cross-section and the metal height is studied. Finally, the gross Joule heating is calculated from the experimental and regression curve. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Electromagnetic casting; Joule heating; Skin depth

1. Introduction

Electromagnetic casting (EMC) is a special semi-continuous process. Fig. 1 depicts the EMC installation, which consists of an inductor, screen, cooling water box, bottom block and trough, etc. With the casting system, several kinds of ingots are cast in the Dalian University of Technology. Fig. 2 shows rectangular EMC ingots \((520 \times 130 \times 100 \text{ mm}^3)\) made of aluminum and its alloys. The absence of contact with the mold eliminates mechanical defects on the surface of the ingot, so the EMC ingots have a very smooth and uniform surface irrespective of the dimensions and the alloys. Fig. 3 is a surface comparison of an EMC and a direct chill casting (DC) ingot.

During the EMC process, the Joule heating produced by the induced currents will heat the metal and obviously influence the temperature field of EMC. Processing the Joule heating with a logical and simple method is a precondition for the numerical simulation of EMC. Prasso described a three-dimensional mathematical model for the temperature field of EMC [1], but this model is a quasi-steady one, which is independent of time and is not appropriate in describing the initial stage of solidification.

Jin et al. carried out a three-dimensional unsteady numerical calculations of solidification in the EMC process [2]. This model considered the characteristics of semi-continuous casting and the unsteady heat transfer in the EMC process. Especially, Joule heating is incorporated into the calculation meshes with a temperature method. Computed results showed good agreement with experimental results.

Because of the difference of EMC system and technical parameters, the processing methods for Joule heating in the above-mentioned models have no universality. Considering Joule heating as the heat source term is the common way in numerical calculation, but up to now, there has not been an accurate method to incorporate the Joule heating into the meshes that can really represent the rule of heat distribution. To solve this problem for the temperature field calculation of EMC, this paper describes an experimental investigation and the gross calculation of Joule heating.

2. Experimental procedure

The experimental system consists of an ingot, screen, inductor, thermocouples, data logger, etc. The size of the ingot is \(520 \times 130 \times 40 \text{ mm}^3\), and the size of the inductor is \(590 \times 168 \times 40 \text{ mm}^3\). The thermocouples are inserted in holes of the ingot placed inside the inductor. Medium-frequency power is adjusted to the common level of the EMC process. A molytek data logger is used to record the temperature.

The position of the ingot and the measurement points in the same section are changed with every run. The inductor currents are also varied to examine the Joule heating throughout the ingot.

3. Results and discussion

3.1. Distribution of Joule heating

Experimental results for these runs appear in Figs. 4–7.
As shown in Fig. 4, the temperature changes with the different vertical position of the ingot. Following each run, the position of $Z = 0$ is the bottom of the inductor. At the position of $Z = 25$ mm, the change in temperature is remarkable. The reason is that this position coincides with the strongest magnetic field position, which obeys electromagnetic theory.

The effect of changing the inductor currents is shown in Fig. 5. When the inductor current changes from 5600 to 4000 A, the highest temperature at the measure points changes from 317 to 130°C after the power is turned on for 10 min. The heating velocities are 27, 20 and 10°C min$^{-1}$. This means that the influence of the inductor current on the Joule heating is very significant. A comparison between the corner point, the border point and the center point is shown in Fig. 6. The temperature change at the corner part is the highest. The temperature at point 1 (at the border of the ingot) is higher than that at point 3 (at the center). Because the induced current comes from the alternating magnetic field, the Joule heating changes with the magnetic distribution. There is stronger magnetic flux density at the corner of the ingot because of the overlap of
the magnetic field. The skin effect leads to higher Joule heating at point 1. On the other hand, the temperature of point 3 is not changed as soon as the power is turned on, just as for points 1 and 2, but change occurs about 1 min later. From electromagnetic theory, the skin depth of the induced currents can be calculated by means of Eq. (1):

\[
\delta = \sqrt{\frac{2\mu \sigma \omega}{f}}.
\]

(1)

where \(\mu\) is the magnetic permeability \((4\pi \times 10^{-7} \text{ H m}^{-1})\), \(\sigma\), the electric conductivity \((3.8 \times 10^6 \text{ \Omega m}^{-1})\), and \(\omega = 2\pi f\); where \(f\) is frequency applied in this experiment \((2500 \text{ Hz})\). Thereby, the skin depth is about 5.2 mm. Point 3 is about 50 mm from the border, which is why this paper assumes it is not heated directly: the increase in temperature is due to the transfer heat from the border part.

Fig. 7(a) and (b) shows the \(y\)-direction distribution of Joule heating, depending on the different times and heights. An inductor current of 4800 A is supplied. The distance between the measurement points is 2.5 mm. The temperature in the near-surface region is higher, which reduces with the increasing of \(y\) in a definite range. This is more obviously when the power is turned on for more minutes. The change of temperature in the center part is gradual. From Simpson’s works [3], the relationship between the induced currents and the skin depth is derived from the following equation:

\[
I = e^{-y/\delta} I_0,
\]

(2)

where \(I\) is the induced current inside the ingot, \(y\), the distance from the surface to the center of the ingot, \(\delta\), the skin depth, and \(I_0\), the maximum induced current on the surface of the ingot. The induced currents concentrate in the near-surface region of the ingot. The current density reduces rapidly with the increase in the distance from the ingot surface. From Fig. 7, the temperature change mainly occurs in the range of 6 mm. As stated above, the skin depth calculated is 5.2 mm. There is good agreement between measurements and calculations. Consequently, it is accurate to consider Joule heating only in the depth of current penetration.

Fig. 8 shows the regression curve of the temperature change at \(Z = 25\) mm along the \(y\)-direction. The regression equation is as follows:

\[
T = 0.07y^2 - 1.42y + 151.7.
\]

(3)

Similarly, from the experimental data, different \(T-y\) curves relying on different heights and times could be regressed. Accordingly, the numerical simulation of EMC can be carried out well.

3.2. Calculation of Joule heating

In order to calculate the amount of Joule heating, the experimental data and the regression average of temperature change with different heights are all shown in Fig. 9. The \(Z-\Delta T\) curve approaches a quadratic distribution. The regression equation for the height range from 0 to 40 mm is:

\[
\Delta T = -0.1z^2 + 4.02z + 129.83.
\]

(4)

Integrating this curve, the change of average temperature all over the ingot can be computed as follows:

\[
\Delta T = \frac{\int_{0}^{40} (-0.1z^2 + 4.02z + 129.83)dz}{40} = 157^\circ \text{C},
\]

(5)

from which the quantity of Joule heating can be obtained.

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**Fig. 7.** Distribution of temperature along the \(y\)-direction at different heights: (a) \(t = 120\) s; (b) \(t = 420\) s.

**Fig. 8.** Regression curve in the \(y\)-direction at \(t = 420\) s, \(z = 25\) mm.
4. Conclusions

The experimental data reveal a strong dependence of Joule heating on inductor current. Consistent with the magnetic field distribution, the maximum Joule heating is achieved in the position, where the magnetic flux density is the greatest.

Joule heating is more significant in the near-surface region of the ingot than in the center region. The change of temperature in this range could be described as a multinomial. The depth to which the induced currents penetrate into the ingot is about 5.2 mm.

The change in average temperature along the liquid column direction can be approximatively described as a quadratic equation, from which the power of inductive heating is calculated to be about 2.16 kW, about 8% of the effective power.

Acknowledgements

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