Study on the interaction between the shape and the temperature field of the melt in the electromagnetic shaping process

Jun Shen\textsuperscript{a,b,*}, Jianping Hou\textsuperscript{a}, Hengzhi Fu\textsuperscript{a}, Junyi Su\textsuperscript{b}

\textsuperscript{a}State Key Laboratory of Solidification Processing, Northwestern Polytechnic University, P.O. Box 543, Xi’an 710072, People’s Republic of China
\textsuperscript{b}Xi’an Jiaotong University, Xi’an 710049, People’s Republic of China

Received 14 June 1999

Abstract

Based on analyses for the electromagnetic pressure on the melt and the heat induced in the melt, the ratio of heat to pressure $Q_0/P_0$ is defined, to give the relationship between $Q_0/P_0$ and the thickness $a$, the electromagnetic parameter ($\mu \gamma$) of the melt and the electric current frequency $f$ under the electromagnetic confinement and shaping process. If $Q_0/P_0$ is large, any adjustment to the melt shape will easily cause a variation of the temperature in the melt. In this situation, there appears to be a more sensitive interaction between the shape and the temperature field and a more narrow adjustment range for the process. Experiments on thin plate samples with a cross-section of 6 mm x 18 mm are done with two kinds of induction coils. The results show that when a coil with a trumpet inside wall is used and the positions of the melt top and the S/L interface are properly selected, the melt periphery is nearly vertical and the temperature gradient ahead of the S/L interface is high. Under these conditions, a more stable and wider coupling between the shape and the temperature field is continuously maintained and samples with a smooth surface and unidirectional crystals are successfully obtained. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Electromagnetic shaping process; S/L interface; Interaction

1. Introduction

The electromagnetic cast technique was used for obtaining aluminum ingots with large cross-section in the 1980s, low electric current frequency usually being selected in this process [1–3]. In the authors’ laboratory, research carried out recently has focused on the electromagnetic shaping of a blade-like and thin plate casting. It is known that in order to hold a given shape of the magnetic field should be adjusted instantly at all time. For an ingot with a large cross-section, the variation of magnetic flux density has only a little effect on temperature field [4,5], but for those with a thin cross-section, the variation of magnetic flux density will cause an obvious change of temperature in the melt, that leads to a move of the position of the S/L interface. The displacement of the interface changes the relationship between the static pressure of the melt and the electromagnetic pressure and makes the melt shape vary unexpectedly. Similar unexpected variation of melt shape also happens when the temperature is adjusted by changing the magnetic field. This is because of a significant effect of the magnetic field on both the electromagnetic pressure and the temperature. Thus it is considered impossible to adjust the melt shape or temperature field without influence on one another. By comparison, the process of electromagnetic confinement and shaping for thin plate has two new characteristics: (1) the magnetic flux density plays the same important roles in heating and shaping; (2) the melting and shaping can be completed simultaneously by a single induction coil. In this study, the ratio of heat to pressure is defined and discussed, and the interaction between the shape and the temperature field of the melt is also investigated experimentally.

2. Theoretical analyses

In earlier research work [6], the authors advanced the equations relating to the induced current density in the melt and the electromagnetic pressure on the melt in the electromagnetic confinement and shaping of plate. Eqs. (1) and (2) in the following are for induced current density $J_i$ in the plate melt and for the electromagnetic

* Corresponding author.

1468-6996/01/$- see front matter © 2001 Elsevier Science Ltd. All rights reserved.
PII: S1468-6996(01)00052-3
Fig. 1. Scheme of the distributions of magnetic flux density $B$, and current density $J_y$

pressure $P_m$ on the plate melt, respectively:

$$J_y = B \sqrt{\frac{2\pi f \gamma \sinh 2Kx - \cos 2Kx}{\mu \cosh Ka + \cos Ka}},$$  

$$P_m = B^2 \frac{1}{2\mu \cosh Ka + \cos Ka} \int_0^{Ka} \sqrt{\cosh^2 t - \cos^2 t} \, dt,$$

where $K = \sqrt{\pi f \mu \gamma}$. As shown in Fig. 1, $B$ is the magnetic flux density on the periphery of the melt, $a$ the thickness of the melt, $f$ the current frequency, and $\mu$ and $\gamma$ are the magnetic conductivity and electric conductivity of the melt, respectively. As shown in Fig. 1(b), the power produced by induced current in volume $dV$ with a bottom area $A = 1$ and a thickness $dx$ is

$$dQ = \frac{J_y^2}{\gamma} (1 \, dx).$$

Substituting Eq. (1) into Eq. (3) results in

$$dQ = B^2 \frac{2\pi f}{\mu (\cosh Ka + \cos Ka)} (\cosh 2Kx - \cos 2Kx) \, dx.$$  

The heat energy produced in volume $V$ with a bottom area $A = 1$ and thickness $a$ is

$$Q = 2 \int_0^a dQ.$$  

Substituting Eq. (4) into Eq. (5) the whole power produced in volume $V$ is

$$Q = B^2 \frac{2\pi f \sinh Ka - \sin Ka}{\mu K \cosh Ka + \cos Ka}.$$  

Fig. 2. $Q_d/P_m$ — $f$ curves for plates of aluminum melt ($\mu \gamma = 5.03 \, \text{H} \, \text{m}^{-1}$) and steel melt ($\mu \gamma = 0.84 \, \text{H} \, \text{m}^{-1}$) with a thickness $a = 6 \, \text{mm}$.

The average power produced in unit volume is

$$Q_0 = \frac{Q}{V}.$$  

Substituting $V = 1a$ and Eq. (6) into Eq. (7):

$$Q_0 = \frac{1}{a} \int_0^{Ka} \frac{4\pi f}{\mu^3 \gamma} \sinh Ka - \sin Ka \, B^2.$$  

For comparing the contributions of magnetic flux density in heating and shaping, the $Q_0/P_m$ ratio of the average power absorbed by the melt in unit volume to the electromagnetic pressure on unit area, is defined as the ‘ratio of heat to pressure’. This ratio reflects the heating ability on melts in different confinement and shaping systems when the electromagnetic pressures on the melt is the same. From Eqs. (8) and (2)

$$Q_0 = \frac{\sinh Ka - \sin Ka}{\int_0^{Ka} (\cosh^2 t - \cos^2 t)^{3/2} \, dt} \frac{4\pi f}{\mu \gamma}.$$  

The result of the numerical integration of Eq. (9) is shown in Figs. 2 and 3. It gives the relationship between the ratio of the heat to pressure $Q_0/P_m$ and the thickness $a$ and electromagnetic parameter $\mu \gamma$ of the melt and the current frequency $f$. The curves in Figs. 2 and 3 show that the

Fig. 3. $Q_d/P_m$ — $a$ curves for plates of aluminum melt ($\mu \gamma = 0.53 \, \text{H} \, \text{m}^{-1}$) and steel melt ($\mu \gamma = 0.84 \, \text{H} \, \text{m}^{-1}$) at frequency $f = 300 \, \text{kHz}$.
ratio decreases with decrease of the current frequency and increase of the thickness and the electromagnetic parameter of the melt. When the melt thickness is large or the frequency is low or the electromagnetic parameter is large, the ratio is small and the melt absorbs less heat, when the same electromagnetic pressure acts on it, so that an adjustment of the magnetic field has a negligible effect on the temperature of the melt. This conclusion is in good agreement with the results in the electromagnetic casting of large aluminum ingots. Inversely, if the melt thickness is low or the frequency is high or the electromagnetic parameter is small, the ratio of heat to pressure is large and the melt will absorb a lot of heat, when while the same electromagnetic pressure acts on it. The high-density heat can melt, the solid alloy in the coil and strongly heat the melt. The magnetic field can not only confine and shape the melt, but can also melt and heat the alloy simultaneously. It is obvious that in order to control the electromagnetic confinement and shaping process of thin plate-like parts, a stable and wide coupling between the melt shape and the temperature field is necessary.

3. Experiments and discussion

The following experiments have investigated the factors that have an effect on the coupling between the shape and the temperature field of a thin plate melt.

Al–2.5%Cu plate samples with a cross-section of 6 mm × 18 mm were selected for the experiments. The frequency of the electric current through the coil is 300 kHz. The experimental apparatus is illustrated in Fig. 4. Experiments are done in two kinds of induction coils: (i) with a trumpet inside wall \((H = 24 \text{ mm}, \alpha = 10^\circ)\); and (ii) with a vertical inside wall \((H = 24 \text{ mm}, \alpha = 0^\circ)\), respectively. The position of the solid/liquid interface is controlled by adjusting the volume of flow of the coolant. The melt shapes and positions of the S/L interface and melt top are quenched and fixed by abruptly augmenting the coolant volume of flow, and are then measured. The distributions of the magnetic flux density in space are measured with a detection coil made by the authors. The temperature profiles in the melt along the axis are measured with a thermocouple of 0.3 mm diameter.

Curve No. 1 and curve No. 2 in Fig. 5 are the profiles of the magnetic flux density measured along the periphery of the samples before melting in the coils with a trumpet inside wall and with a vertical inside wall, respectively. The solid...
curves in Figs. 6 and 7 present the electromagnetic pressure profiles along sample periphery, which are calculated from curve No. 2 and curve No. 1 in Fig. 5 with Eq. (2), respectively. The dotted curves in Fig. 6 are the electromagnetic pressure profiles along the sample periphery in the coil with a vertical inside wall when the electric current through the coil is decreased. The straight lines in the two figures are the static pressure distributions of the melts with different top positions. From the curves in Fig. 6, it is known that for a coil with a vertical inside wall, wherever are the position of the S/L interface and the position of the melt top, and whatever is the value of the current density in the coil, the electromagnetic pressure and static pressure always do not coincide well. The unbalance between the static pressure and the electromagnetic pressure will cause deformation of the melt, therefore the melt periphery is not vertical. The quenched sample in Fig. 8(a) shows the melt shape obtained in this kind of induction coil. Usually, the melt with this periphery is not stable and a movement of the S/L interface caused by a fluctuation of temperature results in a non-uniform cross-section or even process failure. However, for an induction coil with a 10° trumpet inside wall, if the positions of the S/L interface and melt top are properly selected (in this experiment, \( h_t = 11 \text{ mm}, \ h_{SL} = 18 \text{ mm} \)) the electromagnetic pressure coincides with the static pressure at every point on the periphery quite well, so that the melt has an ideal vertical periphery. Under these conditions, even if a quite large fluctuation of temperature has caused a movement of the S/L interface over a wide range (as shown in Fig. 7, from position 1 to position 4, the S/L interface moves about 17 mm), the good coincidence between the electromagnetic pressure and the static pressure always exists, thus the periphery of the melt remains vertical. Fig. 8(b) presents photographs of melt shapes fixed by quenching when the S/L interface reached different positions. They explain why the melt shape and the temperature field retain a good and stable coupling over a quite wide range, so that the solidified samples have uniform cross-sections and smooth surfaces. Fig. 9 shows a series of samples obtained under these conditions: they are well shaped and have smooth surfaces, elliptical cross-sections and uni-directional crystals.

The temperature profiles in Fig. 10 (\( T_m \) is the temperature of the liquidus) show that the temperature gradient (\( G_t \)) ahead of the S/L interface increases with the decrease of the position of the S/L interface, and that wherever the position of the S/L interface is, the melt periphery is always vertical, as shown in Fig. 8(b). Thus there is a stable and wide coupling between the melt shape and the temperature gradient. The wide variation range of the temperature gradient makes the solidified structures of different forms and fineness. Especially, if a high temperature gradient ahead of the S/L interface is selected, the solidified structures will have superfine unidirectional crystals that have excellent mechanical properties [7].

4. Conclusions

The theoretical analyses and experimental results show that if a low current frequency or a large electromagnetic parameter or a large thickness is selected, the ratio of heat to pressure becomes small and an adjustment for the melt
shape or for the temperature field has no obvious effect on each other. Thus the control for the confinement and shaping process is relatively easy. However, if the frequency is high or the melt thickness is low or the electromagnetic parameter is small, the ratio of heat to pressure is large. Under these conditions, the melting and shaping of the melt can be completed simultaneously by a single induction coil. This is an advantage in the case of high ratio of heat to pressure. On the other hand, a large ratio favours the design on the induction coil and the selection on the values of the parameters that affect this process to produce a good and wide coincidence between the static pressure and the electromagnetic pressure. The wider is the coincidence range, the more stable and better is the melt shape. In this situation, the coupling range between temperature and melt shape will be quite wide and the temperature gradient ahead of the S/L interface can be adjusted over a quite wide range, which will ensure the successful confining and shaping of thin plate-like parts with a single induction coil.

Acknowledgements

The authors express their thanks for the support of the National Natural Science Foundation (No. 59995440) and of Aeronautic Science Foundation (No. 98H53075) of China.

References

[1] R. Sautelin, W. Haller, Industrial application of electromagnetic casting of aluminum, Light Met. Age 14 (8) (1985) 14.
[2] D.E. Tyler, B.G. Lewis, P.D. Renschen, Electromagnetic casting of copper alloy, J. Met. 37 (9) (1985) 51.
[3] Mitsuaki Furui, Yo Kojima, Fabrication of small aluminum ingot by electromagnetic casting, ISIJ Int. 33 (3) (1993) 400.
[4] B.Q. Li, J.W. Evans, D.P. Cook, An improved mathematical model for electromagnetic casters and testing by a physical model, Metall. Trans. B 22 (2) (1991) 121.
[5] N. El-Kaddah, J.H. Mortimer, New crucibleless melting process promises refractory-free melting for high-quality castings, Light Met. Age 10 (10) (1990) 37.
[6] J. Shen, Analysis for electromagnetic pressure on thin plate melt, Trans. Nonferrous Met. Soc. China 9 (7) (1999) 32.
[7] Z.X. Shi, H.Z. Fu, Effect of solidification interface morphologies on microstructures of a Ni-base superalloy, Chin. J. Met. Technol. 6 (5) (1990) 150.