The frequency effect on electromagnetic confinement and shaping of liquid metal

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Abstract

Electromagnetic confinement and shaping is a kind of newly developing solidification technology. With the electromagnetic field imposed, the metal is melted to some superheating degree by Joule heating and is confined and shaped to the desired form by the electromagnetic force at the same time. The frequency effect of the electromagnetic field on the electromagnetic confinement and shaping is investigated. The relationship between the Joule heat, the electromagnetic force and the frequency is revealed from the viewpoint of the magnetohydrodynamics theory. The results show that, given the condition of the same magnetic field strength, the time-averaged volume electromagnetic force at the melt surface is approximately proportional to the field frequency, whilst at the same time the volume Joule heating rate is approximately proportional to the square of the field frequency. However, as the frequency increases, the shaping stability and the surface quality decrease due to the violent surface electromagnetic stir. The frequency effect is also correlative to the sample’s size and electric conductivity. The bigger is the sample, the lower ought to be the frequency and vice versa. The bigger is the electric conductivity, the lower can be the frequency and vice versa. Thus there is an optimum frequency range for each different sample, which is tens to hundreds of kilohertz for the small-size or medium-size steel sample. The experimental research is carried out with aluminium, copper and stainless steel samples, and the results show good agreement with the theoretical predictions. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Frequency; Electromagnetic confinement and shaping; Electromagnetic force; Joule heat

1. Introduction

Although much work has been done to develop a new generation of directionally solidified superalloy, monocrystal superalloy, eutectic in situ composite and intermetallic compound based composite [1], the thermal gradient of the solidification apparatus widely used is less than 100 K cm⁻¹. To ensure the directional growth, the cooling rate must be very slow (0.1–2 K s⁻¹), which leads to a coarse microstructure, severe segregation and other defects, and restricts the further property increase of these materials.

Years of research has led to the belief that the mechanical properties of directionally solidified alloys can be significantly improved by increasing the cooling rate and refining the dendrite structure. In the past decade, a series of directional solidification apparatuses with various temperature gradients (50–1000 K cm⁻¹) have been established in the authors’ laboratory [2,3], which make it possible to carry out research on near rapid directional solidification. It has been shown that with sub-high cooling rate (10⁷–10⁹K s⁻¹), the primary dendrite arm spacing is greatly reduced, the sidebranch growth is restrained, the dendrite segregation is reduced, and defects are avoided. Therefore, the mechanical properties are drastically improved. However, up to now, directionally solidified or monocrystal superalloy turbine blades are formed in an investment casting mould. The thick ceramic mould with bad thermal conduction seriously reduces the temperature gradient and the solidification rate of the metal melt. In order to obtain a high temperature gradient and a superfine microstructure, a new solidification technique of electromagnetic confinement and shaping without the mould is proposed [4].

The electromagnetic confinement and shaping technique applies electromagnetic force to confine the metal melt and shape it into the desired form. The electromagnetic field can be considered as an “electromagnetic mould”. In this paper, the frequency effect of the electromagnetic field on the electromagnetic confinement and shaping is investigated. The relationship between the Joule heat, the electromagnetic force and the frequency is revealed from the viewpoint of the magnetohydrodynamics (MHD) theory, which is the theoretical foundation of multi-frequency electromagnetic shaping.

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2. Formulation

In the cylindrical coordinate system \((r, \theta, z)\), it is assumed that the induction coil exerts a high frequency electromagnetic field parallel to the \(z\)-direction on the charge surface, which is:

\[
H(r, \theta, z) = (0, 0, H_z(r, t))
\]

where:

\[
H_z(r, t) = H_z(r) \exp(i\omega t)
\]

From the MHD theory [5–7], it can be seen that:

\[
\frac{\partial \mathbf{H}}{\partial t} = \eta \nabla^2 \mathbf{H} + \nabla \times (\mathbf{V} \times \mathbf{H})
\]

in which \(\eta = 1/(\sigma \mu)\) is the magnetic diffusion coefficient and \(\mathbf{V}\) is the fluid velocity of the liquid metal. Generally speaking, the magnetic Renaldo number of common metal is very small, so that the second term on the right hand side of Eq. (3), which is the convection term, can be ignored compared with the first term, which is the diffusion term. Thus:

\[
\frac{\partial \mathbf{H}}{\partial t} = \eta \nabla^2 \mathbf{H}
\]

Considering the boundary condition, i.e. the magnetic intensity on the charge surface is \(H_0\), so that the magnetic intensity and the induced current density in the charge can be expressed as [8]:

\[
H_z(r, t) = H_0 J_0^{-1}(kR) J_0(kr) \exp(i\omega t)
\]

\[
J_0(r, t) = kH_0 J_0^{-1}(kR) J_1(kr) \exp(i\omega t)
\]

Where, \(J_0(kr)\) and \(J_1(kr)\) are, respectively, the zero order and the first order Bessel functions, \(k = (-\omega \sigma \omega)^{1/2}; \omega = 2\pi f\) where \(f\) is the frequency of the electromagnetic field; \(\mu\) is the magnetic permeability of the charge; \(\sigma\) is the electrical conductivity; and \(R\) is the charge radius. Because the electromagnetic force is:

\[
\mathbf{F} = \mathbf{J} \times \mu \mathbf{H}
\]

and the Joule heating is:

\[
Q = \mathbf{J}^2 \sigma^{-1/2}
\]

It is not difficult to obtain the time-averaged volume electromagnetic force \(F_v(r)\) and the volume Joule heating rate \(Q(r)\), which are respectively:

\[
F_v(r) = -2^{-3/2} A^{-1} \beta \mu H_0^2 \Psi(\beta r)
\]

\[
Q(r) = 2^{-1} A^{-1} \beta^2 \sigma H_0^2 \Pi(\beta r)
\]

According to the relationship between the Bessel function and the Kelvin function, the electromagnetic force function \(\Psi(\beta r)\) and the Joule heating function \(\Pi(\beta r)\) can be expressed as:

\[
\Psi(\beta r) = \text{ber}_0(\beta r)(\text{ber}_1(\beta r) + \text{bei}_1(\beta r))
\]

\[
\Pi(\beta r) = \text{ber}_1^2(\beta r) + \text{bei}_1^2(\beta r)
\]

where \(\text{ber}_n\) and \(\text{bei}_n\) are \(n\) order Kelvin functions.

The parameters \(A\) and \(\beta\), which are related to the frequency \(f\), are:

\[
A = \text{ber}_0^2(\beta R) + \text{bei}_0^2(\beta R)
\]

\[
\beta = (2\pi \mu \sigma f)^{1/2}
\]

With a series expansion applied, it can be shown that \(\Psi(\beta r)\) is always positive. Therefore the negative sign of \(Q(\beta r)\) indicates that the molten metal is subjected to radial electromagnetic pressure. This is the basic principle of the electromagnetic confinement and shaping of the liquid metal.

3. Numerical calculation and analysis

As the skin depth is \(\delta = (\pi \mu \sigma f)^{-1/2}\), the variable \(\beta\) can be written as:

\[
\beta = 2^{1/2} \delta^{-1}
\]

For the steel charge, the typical sample radius chosen is \(R = 10\), \(15\), \(20\), \(30\) mm, the conductivity \(\sigma = 6.6 \times 10^7 \Omega^{-1} \text{ m}^{-1}\), the electromagnetic field frequency \(f = 50\), \(100\), \(200\), \(400\) kHz. The Kelvin function is expanded in series and \(H_0\) is considered as constant. With the numerical calculation, the electromagnetic force \(F_m\) and the Joule heating rate \(Q_m\) on the charge surface are obtained as Tables 1 and 2. Approximately:

\[
F_m \propto f, \quad Q_m \propto f^2
\]

### Table 1

| \(f_1 = 50\) kHz | \(f_2 = 100\) kHz | \(f_3 = 200\) kHz | \(f_4 = 400\) kHz |
|------------------|------------------|------------------|------------------|
| \(R = 1.0 \times 10^{-2}\) m | \(1.49 \times 10^{-1} H_0^2\) | \(2.98 \times 10^{-1} H_0^2\) | \(6.06 \times 10^{-1} H_0^2\) | \(1.20 H_0^2\) |
| \(R = 1.5 \times 10^{-2}\) m | \(1.53 \times 10^{-1} H_0^2\) | \(3.04 \times 10^{-1} H_0^2\) | \(6.14 \times 10^{-1} H_0^2\) | \(1.21 H_0^2\) |
| \(R = 2.0 \times 10^{-2}\) m | \(1.55 \times 10^{-1} H_0^2\) | \(3.06 \times 10^{-1} H_0^2\) | \(6.17 \times 10^{-1} H_0^2\) | \(1.22 H_0^2\) |
| \(R = 3.0 \times 10^{-2}\) m | \(1.56 \times 10^{-1} H_0^2\) | \(3.09 \times 10^{-1} H_0^2\) | \(6.21 \times 10^{-1} H_0^2\) | \(1.22 H_0^2\) |
Table 2
Relationship between the charge radius, the field frequency and $Q_m$

| $R_1$ ($10^{-2}$ m) | $f_1 = 50$ kHz | $f_2 = 100$ kHz | $f_3 = 200$ kHz | $f_4 = 400$ kHz |
|---------------------|----------------|-----------------|-----------------|-----------------|
| 1.0                  | $4.29 \times 10^4 H_{\phi}^2$ | $1.71 \times 10^5 H_{\phi}^2$ | $7.06 \times 10^5 H_{\phi}^2$ | $2.77 \times 10^6 H_{\phi}^2$ |
| 1.5                  | $4.49 \times 10^4 H_{\phi}^2$ | $1.77 \times 10^5 H_{\phi}^2$ | $7.28 \times 10^5 H_{\phi}^2$ | $2.81 \times 10^6 H_{\phi}^2$ |
| 2.0                  | $4.60 \times 10^4 H_{\phi}^2$ | $1.80 \times 10^5 H_{\phi}^2$ | $7.31 \times 10^5 H_{\phi}^2$ | $2.84 \times 10^6 H_{\phi}^2$ |
| 3.0                  | $4.70 \times 10^4 H_{\phi}^2$ | $1.83 \times 10^5 H_{\phi}^2$ | $7.40 \times 10^5 H_{\phi}^2$ | $2.86 \times 10^6 H_{\phi}^2$ |

Table 3
Relationship between charge radius, and $f_{\text{min}}$

| $R$ (mm) | $f_{\text{min}}$ (kHz) |
|---------|-----------------------|
| 22      | 20                    |
| 14      | 50                    |
| 10      | 100                   |
| 7       | 200                   |
| 5       | 400                   |

It can also be seen that $F_m$ and $Q_m$ increase with the enlargement of the charge radius, but the increment decreases with increase in the frequency. With the frequency continuously increasing, the influence of the radius can be ignored. It should be noted that the electromagnetic force and the Joule heating are all proportional to the square of the surface magnetic intensity $H_{\phi}$ that is determined by the coil current. As it is very difficult to increase the coil current in the high-frequency electromagnetic field, it is much more effective to enhance the magnetic intensity by enlarging the coil current under a slightly lower frequency condition in order to increase the electromagnetic force and the Joule heating substantially. This means that relatively low frequency is beneficial with a large steel sample.

Related research [9] gives the following criterion electromagnetic force for confining liquid metal with different size:

$$ a = 2^{1/2} \delta^{-1} R = \beta R \geq 7 \quad (17) $$

This indicates the lower limit of the required frequency $f_{\text{min}}$ for different charge radii. Thus, if only the electromagnetic pressure is considered, the frequency choice range is very wide. Approximately:

$$ f_{\text{min}} \propto R^{-2}, \quad f_{\text{min}} \propto \sigma^{-1} \quad (18) $$

Therefore, the bigger the sample, the lower ought to be the required frequency; the bigger is the electric conductivity, the lower can be the required frequency and vice versa. There is an optimum frequency range for each different sample, which is tens to hundreds kilohertz for the small-size or medium-size steel sample. When the radius of the steel sample is $R = 10$ mm, the confinement frequency should be no less than 100 kHz (Table 3).

The analysis above shows that, with the frequency increased, the heating rate can be obviously increased while the electromagnetic pressure may be raised to some extent. However, the electromagnetic stirring on the charge surface is aggravated at the same time, which may have pernicious effects on the processing stability and the surface quality. Thus it can be concluded that the tentative plan of high-frequency melting and lower-frequency confining is feasible, which is called dual-frequency electromagnetic confinement and shaping. The frequency for melting need not be very high when the frequency for confinement and shaping is not strictly demanded. It must be noted that the analyses above are all conditional on the same magnetic intensity. It is the magnetic intensity or rather the coil current that has great influence on the melting and confining of the metal. Therefore, it is very important to raise the coil current in order to enhance the electromagnetic field.

4. Experimental research

On the basis of the aforementioned theoretical analysis, the upper melting coil connected to the 350 kHz high-frequency induction heating power, and the confinement coil below is connected to the 50 kHz supersonic-frequency induction heating power. The solid sample withdrawn by the pulling mechanism is first zone-melted, confined to the desired shape and then solidified. Fig. 1 shows a sketch of the prototype system.

**Fig. 1. Sketch of the prototype system.**
5. Concluding remarks

1. On the condition of the same magnetic intensity, the time-averaged volume electromagnetic force is approximately proportional to the electromagnetic field frequency, and the volume Joule heating rate is approximately proportional to the square of the field frequency. However, as the frequency increases, the shaping stability and the surface quality decrease due to the violent surface electromagnetic stir.

2. The frequency effect is correlative to the sample’s size and electric conductivity. The bigger is the sample, the lower ought to be the frequency and vice versa. The bigger is the electric conductivity, the lower can be the frequency and vice versa. There is an optimum frequency range for each different sample, which is tens to hundreds kilohertz for the small-size or medium-size steel sample.

3. The tentative plan of high-frequency melting and lower-frequency confining is feasible, which is called dual-frequency electromagnetic confinement and shaping. The optimum frequency for melting lies in the high frequency range (hundreds of kilohertz). It is the magnetic intensity or rather the coil current that has great influence on the melting on the metal and confining of the metal. Therefore, it is very important to raise the coil current in order to enhance the electromagnetic field. Experimental research carried out with aluminium, copper and stainless steel sample, shows good agreement with the theoretical prediction.

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