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Numerical Simulation of Magnetic Field for Electromagnetic Casting of Hollow Billets

Distribution of magnetic field during electromagnetic continuous casting of hollow billets of aluminum alloys is studied by the method of numerical simulation. Two-dimensional axis-symmetric finite element model including water-cooled core, outer mould, ingot, inner and outer induction coil has been established. Distribution of magnetic flux density is obtained by solving magnetic vector potential formulations.) In electromagnetic casting, inner and outer induction coil interact, magnitude and admeasurements of current affect directly distribution of magnetic flux density.) Magnetic flux density near interior surface of pipe wall is increased notably by increasing appropriately frequency.) Phase difference affects the magnitude and direction of the gradient of magnetic flux density.

Keywords: Aluminum alloys, electromagnetic field, hollow ingot, low-frequency casting, numerical simulation

Introduction

Aluminum alloy tubes of high performance have been used in many fields such as electric power, refrigeration. Its manufacture process comprises casting, rolling & extruding of aluminum alloys. But this process is complex, the utilization ratio of metal is low, and the quality of product cannot satisfy all kinds of requirement. In order to reduce the cost and to improve the product quality, technology of near-net-shape casting was presented and many kinds of casting methods have been developed. Each method has its merit and shortcoming (Harada et al., 2000).

Recently, the electromagnetic casting technique of aluminum alloys attracts attention of researchers because it can improve surface quality and as-cast structure of ingots. I) A metal melt forms a meniscus under the action of Lorentz force, which reduces the contact length between metal melt and crystallizer and weakens primary cooling intensity, thus improving the quality of ingot surface (Vivès, 1989). II) The forced convection driven by Lorentz force can promote heterogeneous nucleation, and reduce the solute concentration gradient and temperature gradient in melt, simultaneously, it can make the molten pool shallower and the mushy zone wider, leading to improve microstructure of ingots (Vivès, 1989; Zhang, 2002). III) Electromagnetic field acts on the metal melt, which can strengthen the diffusion of solute element, can increase solute element content in crystalline grain and make them homogeneous (Dong, 2004). During electromagnetic casting of hollow billets, the electromagnetic fields of two coils in water-cooled core and the outer mould affect the metal melt together, which make the electromagnetic field distribution state complicated. Therefore, distribution of magnetic flux density must be accurately grasped in order to study the solidifying mechanism in electromagnetic fields, to obtain the optimum technology parameters, and to improve the product quality. It is difficult to understand continuous distribution state and dynamic change process of electromagnetic fields in metal melt because physical

measurement in casting process need the specialized facility and is hard to realize. With the development of calculating technology, especially, finite element theory and the method, application research of FEM at the analysis domain of electromagnetic field make great progress (Morisue, 1982; Leonard et al, 1988 and Rodger et al, 1983). It indicates in practice that the result of very high credence can be obtained by magnetic vector potential method when one calculates the alternating electromagnetic field of complicated boundary conditions. Therefore, the method has increasingly become effective means of theoretical study and settlement of actual engineering problem (Vivès, 1985).

In this paper, two-dimensional axis-symmetric finite element model for electromagnetic casting process of aluminum alloys hollow billets of $\phi 290 \times 35 \text{ mm}$ is established. The effect of alternating current of different intensity, frequency and phase difference in inner and outer coil on distribution of magnetic flux density has been analyzed and discussed. It provides a theoretical basis for selecting the reasonable technological parameters.

Nomenclature

A = Magnetic vector potential
 B = Magnetic flux density, T
 E = Electrical field intensity, V/m
 H = Magnetic field intensity, A/m
 J_s = Known source currents in induction coil, A/m²
 J_e = Induced current, A/m²
 n = Unit normal vector
 t = Time, s
 V = Electric scalar potential
 $\nu (= 1/\mu)$ = Magnetic reluctivity, A²/N
 μ = Magnetic permeability, N/A²
 σ = Electrical conductivity, (1/ Ωm)

Formulations of Electromagnetic Field Analysis

Mold Establishment

The electromagnetic field that generated by the alternating current in the induction coil is the induction field near field source in electromagnetic casting, which satisfies the condition of quasi-steady state. A typical eddy current problem is depicted in Fig.1. Where Ω_1 is eddy current region full of the conducting media, and it contains the metal melt, ingots, water-cooled core and outer mould etc. Induced current J_e can be generated by induced electromotive force in Ω_1 . Where Ω_2 is a surrounding region free of eddy current, and it contains known source currents, air dielectric, inner and outer induction coil. The union of Ω_1 and of Ω_2 , i.e., the entire problem region will be denoted by Ω . Electromagnetic field is depicted by the magnetic vector potential A as well as the electric scalar potential V , the field vectors are obtain from the potentials as (Biro,1988 Oszkár,1989):

$$\mathbf{B} = \nabla \times \mathbf{A} \quad (1)$$

$$\mathbf{E} = -\frac{\partial \mathbf{A}}{\partial t} - \nabla V \quad (2)$$

in Ω_1 :

$$\nabla \times \nu \nabla \times \mathbf{A} - \nabla \nu \nabla \cdot \mathbf{A} + \sigma \frac{\partial \mathbf{A}}{\partial t} + \sigma \nabla V = 0 \quad (3)$$

$$\nabla \cdot \left(-\sigma \frac{\partial \mathbf{A}}{\partial t} - \sigma \nabla V \right) = 0 \quad (4)$$

in Ω_2 :

$$\nabla \times \nu \nabla \times \mathbf{A} - \nabla \nu \nabla \cdot \mathbf{A} = \mathbf{J}_s \quad (5)$$

Figure 1. Regions and boundary conditions in typical eddy current problem.

Boundary Conditions

The boundary of Ω_2 and hence of Ω is divided into two parts in accordance with the two types of boundary conditions of practical importance: on Γ_B , the normal component of flux density is prescribed, whereas on Γ_H the tangential component of magnetic

field intensity is given (Biro,1988).

on boundary Γ_B :

$$\mathbf{n} \times \mathbf{A} = 0 \quad (6)$$

$$\nu \nabla \cdot \mathbf{A} = 0 \quad (7)$$

on boundary Γ_H :

$$\nu \nabla \times \mathbf{A} \times \mathbf{n} = 0 \quad (8)$$

$$\mathbf{n} \cdot \mathbf{A} = 0 \quad (9)$$

The boundary conditions on Γ_{12} between Ω_1 and Ω_2 are as follows:

$$\mathbf{A}_1 = \mathbf{A}_2 \quad (10)$$

$$\nu_1 \nabla \times \mathbf{A}_1 \times \mathbf{n}_1 + \nu_2 \nabla \times \mathbf{A}_2 \times \mathbf{n}_2 = 0 \quad (11)$$

$$\nu_1 \nabla \cdot \mathbf{A}_1 - \nu_2 \nabla \cdot \mathbf{A}_2 = 0 \quad (12)$$

$$\mathbf{n} \cdot \left(-\sigma \frac{\partial \mathbf{A}}{\partial t} - \sigma \nabla V \right) = 0 \quad (13)$$

where $\mathbf{n}$ is outer normal on the corresponding surface, and the subscripts 1 and 2 refer to quantities in the regions Ω_1 and Ω_2 , respectively. ν_1, ν_2 is magnetic reluctivity of Ω_1 and Ω_2 respectively. Equations and boundary conditions satisfy Coulomb's gauge. In numerical calculation, electrical conductivity of metal melt, ingots and crystallizer are $4.13 \times 10^6 \text{ 1}/\Omega\text{m}$, $3.33 \times 10^7 \text{ 1}/\Omega\text{m}$, and $1.03 \times 10^7 \text{ 1}/\Omega\text{m}$ respectively, relative permeability of aluminum alloy, crystallizer and atmosphere are 1.

Results and Discussions

The Effect of Current Intensity on Magnetic Field

Figure 2. Distribution of magnetic flux density in electromagnetic casting process (400A/200A,50Hz).

During electromagnetic casting of hollow billets, distribution of electromagnetic field is affected by the factors including induction coil, crystallizer and so on, but intensity, frequency, and phase of current are more important technological parameters to adjust and control casting process. Fig.2 shows distribution of electromagnetic field with current value of 400/200A, a frequency value of 50Hz and phase difference of 0° (the inner coil is in water-cooled core, the outer coil is in outer mould).

Fig.3 shows the change of magnetic flux density along straight line L which is clear in Fig.2 with the inner coil current value of 400A and the outer current ranges from 80A to 400A. The phase difference and the frequency value were 0° , and 50Hz, respectively. It indicates that distribution of magnetic flux density become more homogeneous when electric current in outer induction coil is an approximate half of inner coil current.

Fig.4 shows the distribution of magnetic flux density when the inner/outer coil current increases from 200/100A to 600/300A. The stronger the current, the more notable the attenuation of magnetic flux density. The magnetic flux density of each point in ingot increases linearly along with current intensity while enhanced amplitude is very small at center of pipe wall. Therefore, current and other parameters should be jointly adjusted if it is needed to increase the magnetic flux density at center of pipe wall.

Figure 3. The relation between magnetic flux density and outer coil current with same inner coil current.

Figure 4. The relation between magnetic flux density and intensity of current.

The Effect of Frequency on Magnetic Flux Density

The frequency is one of important parameters in the electromagnetic casting. During casting, the penetrability of

magnetic field depends chiefly on the current frequency besides electrical conductivity of ingots. Generally, the lower the frequency, the stronger penetrability of magnetic field and the magnetic flux density at the center of ingot. However, the inner and outer coil simultaneously takes effect in process of casting pipe and the state has changed. Fig.5 shows the change of magnetic flux density along straight line L under condition that the inner / outer coil current were 400/200A, phase difference was conducted at 0° , and the frequency of current increased from 5Hz to 100Hz. With increasing frequency, magnetic flux density near interior surface of pipe wall and gradient of magnetic flux density in pipe wall remarkably increase. But the minimum of magnetic flux density increased, and then reduced.

Figure 5. The relation between magnetic flux density and frequency.

Figure 6. The relation between magnetic flux density and phase difference.

The Effect of Phase Difference on Magnetic Flux Density

In electromagnetic casting of general round ingot or square ingot, because of using only single coil, the phase question doesn't involve. But phase difference is very important parameter in electromagnetic casting of hollow billets. It affects not only magnitude but also direction of the gradient of magnetic flux density in ingot. The Lorentz force field depends directly on the gradient of magnetic flux density, which affects temperature field, velocity field and the contact pressure on the crystallizer by metal melt. Fig.6 shows distribution of magnetic flux density when the phase difference between inner and outer coil current were 0° , 90° , 180° and 270° , respectively. Direction of the gradient of magnetic flux density is contrary completely when phase difference is 90° and 270° .

Conclusions

The following conclusions can be reached in this paper: I) The stronger current, the more notable attenuation of magnetic flux density. The magnetic flux density of each point in ingot increases linearly along with increase of current intensity while enhanced amplitude is very small at center of pipe wall. II) With increasing frequency, magnetic flux density and its gradient near interior surface of pipe wall is remarkably increased, but the minimum of magnetic flux density increased, and then reduced. III) Phase is an important parameter in electromagnetic casting of hollow billets. It affects magnitude and the direction of gradient of magnetic flux density.

Acknowledgement

The authors would like to thank the referees for their helpful comments.

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