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Numerical and experimental studies of surface-pulsed magneto-oscillation on solidification

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ABSTRACT

Experimental and numerical methods were used to study the distribution of magnetic field, flow field, temperature, and solidification structure in pure Al under surface-pulsed magneto-oscillation (SPMO). The numerical modeling showed that electromagnetic force changed with time and location in molten Al. In the melt, electromagnetic force resulted in cyclic tensile and compressive loads and in intensive forced-convection. Application of SPMO refined the solidified structure and reoriented the growth direction of columnar grains. Surface oscillations induced by electromagnetic force resulted in grain refinement while the corresponding forced convection contributed to change of growth direction of columnar grains.

1. Introduction

The electric current pulse (ECP) and pulsed magnetic field (PMF) have been attracting more and more attention because they are techniques that are convenient to use and relatively safe for the environment. Liao et al. (2007) studied the effect of ECP on the solidified structure of Al. One disadvantage of the ECP technology is that the electric pulse must be directly passed through the metal melt. Special attention must be focused on production safety and the melt is easy to be contaminated. Gao et al. (2007) found that PMF induced by the electric current in the coil has to reach extremely high value in order to obtain satisfactory effect. As a result, undesirable splashing can occur at the top surface of the melt. In order to make improvement, Gong et al. (2008) developed a new technology named surface pulsed magneto-oscillation (SPMO), in which a cookie-like induction coil was employed. Yin et al. (2012) found that remarkable structural refinement was achievable with SPMO on Al melt. Refinement occurs with SPMO because the application of electromagnetic force causes crystal rain to form the top surface or mold wall. SPMO technology has many advantages. It is easy to use, and the coil touches neither the melt nor the mold. As a result, SPMO may have high potential for industry application. However, neither Gong et al. (2008) nor Yin et al. (2012) were able to clarify the variation of electromagnetic force and the flow field distribution during the whole period of application because of its transient, variable, and complex process. Fortunately, numerical simulation, which has never done on SPMO before, can provide effective analysis for experimentation and production. Many works on simulation of electromagnetic fields applied in material solidification process have been carried out. Kermanpur et al. (2011) developed a couple-field electromagnetic-thermal simulation model to design suitable induction coils for the electromagnetic levitation melting of metals. Barman et al. (2009) performed numerical and experimental studies on transport phenomena during solidification of an aluminum alloy in the presence of linear electromagnetic stirring. The results showed that the numerical predictions of temperature variations were in good agreement with experiments, and flow field evolution correlated well with resulting microstructure. Kolesnichenko et al. (1994) simulated electromagnetic force and flow distribution under PMF, and the variation in the pulse applying period was investigated. Le et al. (2007) simulated the flow pattern and temperature field of direct chill (DC) casting of magnesium alloys. They found that the lower temperature gradient and the shoaled liq-

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Nomenclature

B	Magnetic flux density vector [$Wb\,m^{-2}$]
C_p	Specific heat [$J\,kg^{-1}\,K^{-1}$]
D	Electric flux density vector [$C\,s^{-2}$]
E	Electric field intensity vector [$V\,m^{-1}$]
F	Electromagnetic force [N]
H	Magnetic field intensity vector [$A\,m^{-1}$]
J	Total current density vector [$A\,m^{-2}$]
I	Pressure [Pa]
Q_v	Volumetric heat source [$J\,m^{-3}\,s^{-1}$]
T	Temperature [°C]
T	Time [s]
U_i	Orthogonal velocity [$m\,s^{-1}$]
X_i	Global Cartesian coordinates
ϵ	Permittivity [$F\,m^{-1}$]
λ	Second coefficient of viscosity [$kg\,m^{-1}\,s^{-1}$]
μ_0	Magnetic permeability [$H\,m^{-1}$]
ρ_0	Electric charge density [$C\,m^{-3}$]
σ	Conductivity [$\Omega^{-1}\,m^{-1}$]
I	Electric current
$\zeta\ \omega$	constant

uid sump resulted from forced convection after applying Electronic Magnetic (EM) field. Ha et al. (2003) conducted a numerical study of the magnetic field effect on turbulent flow field, heat transfer, and solidification and confirmed the capability to help stable shell growth of steel slabs of electromagnetic brake. B. Li et al. (2011) and Y.J. Li et al. (2011) simulated electromagnetic force and flow distribution in nickel-based super alloy melt with low voltage pulsed magnetic field (LVPMF) using commercial ANSYS finite element software. Ma et al. (2009) investigated the distribution of magnetic force, flow field distribution, and Joule heat under pulsed magnetic field (PMF). A numerical simulation was carried out, showing that the magnetic force in axial direction produced the convection of the melt and the magnetic force in radial direction produced the vibration of the melt.

It is apparent that application of an electromagnetic field affects the solidification process in a range of temperature and flow field variation. In this work, electromagnetic field, fluid flow, and temperature distribution in Al melt under SPMO were investigated with respect to the refinement effect of SPMO on the Al solidification structure.

2. Numerical models

2.1. Model and boundary conditions

The SPMO casting setup shown in Fig. 1a consisted of an SPMO coil, a mold and the melt. The Finite Element Method (FEM) model shown in Fig. 1b was built on this setup. PLANE13 (from ANSYS©), which is a computational code for calculation of electromagnetic field, flow field, and temperature field, was used in the calculation. Different grid sizes were chosen for different portion of the model. The finest grid was used in melt. The simulating procedure was divided into three steps: first, the RLC (where R, L and C stand for electrical resistance, induction, and capacity) electric circuit was solved and then substituted into the electromagnetic field model. Second, the fluid flow model was solved with the acquired electromagnetic force in the electromagnetic field model. Finally, the temperature field was solved with the acquired Joule heat predicted by the electromagnetic field model.

The thermal physical parameters of the melt and mold are known to change with temperature. The main parameters of the pulse current used in the simulation include peak value and discharging frequency of electric pulse. Typical value are $100h_I$ A and $2k_t$ Hz, where h_I and k_t are the coefficients of the pulse generator. These values generally remain constant in the circuit.

The electrical resistivity was assumed to be 2.65×10^{-7} (Huang et al., 2008) and $1.72 \times 10^{-8}\ \Omega\,m$ (Paul, 2004) for the aluminum melt and the coil, respectively. The density and viscosity of the fluid were assumed to be $2.385\ g\,cm^{-3}$ and 2.51 mPa s, respectively (H.T. Zhang et al., 2007; Q. Zhang et al., 2007).

2.2. Governing equations

To simplify mathematical model and save calculation time, the calculation was based on following assumptions: (1) the change of density of Al melt is smaller and can be neglected, so Al melt used in simulation was considered as a incompressible conductor; (2) the coil could be considered as current carrier with a smaller diameter, in which current density remained uniform throughout the coil; (3) no deformation occurred in the melt under magnetic force; (4) the system was cylindrical and symmetric and could thus be rendered as a two-dimensional model for simulation. Without above assumptions, more complicate model and more grids should be built and more calculation time would be expended.

The governing Maxwell equations of electromagnetic field can be expressed by:

$$\nabla \times E = -\frac{\partial B}{\partial t} \quad (1)$$

$$\nabla \times B = 0 \quad (2)$$

$$\nabla \times D = \rho_0 \quad (3)$$

$$\nabla \times H = \frac{J + \partial D}{\partial t} \quad (4)$$

where E is magnetic flux density vector, B is magnetic flux density vector, D is electric flux density vector, ρ_0 is electric charge density, H is magnetic field intensity vector and J is total current density vector.

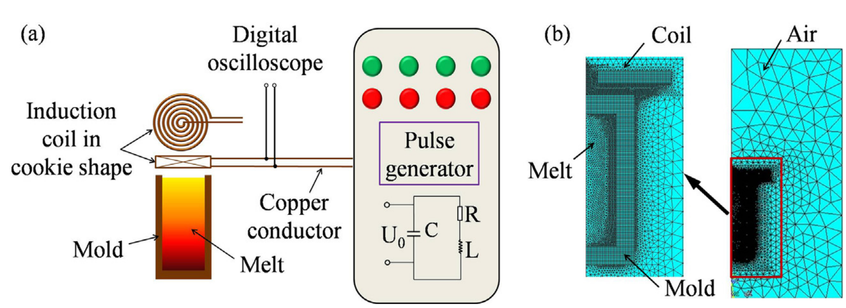

Fig. 1. Schematic of SPMO casting setup (a) and FEM model used in the simulation (b).