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# Migration behavior of solidification nuclei in pure Al melt under effect of electric current pulse

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**Abstract:** A mathematical model considering free nuclei was developed to reveal the migration behavior of the free nuclei. Numerical simulation results show that most of the nuclei on the top surface of the melt move downwards and distribute randomly inside the Al melt, which induces more nucleation sites resulting in grain refinement. At the same time, the effect of nuclei size on the nuclei distribution and refinement employing electric current pulse (ECP) was also investigated. The smaller nuclei migrate a short distance with the Al melt at lower speed. But for the larger nuclei, the migration downwards with higher speed benefits the refinement of interior grains of the melt. The research results help to better understand the refinement process and provide a more reasonable explanation of the grain refinement mechanism using ECP.

**Key words:** electric current pulse; solidification process; grain refinement mechanism; migration behavior; numerical simulation

## 1 Introduction

Electric current pulse (ECP) plays an important role in materials processing, especially in the field of metal solidification [1−4]. It has been testified that the ECP can effectively refine the solidification structure of metal materials [5−10], resulting in high mechanical properties of metallic materials [11,12]. In recent years, more attentions have been paid to revealing the refinement mechanism of the ECP on the solidification structure, and several theories regarding the grain refinement mechanism of the ECP have been proposed. DING et al [13,14] analyzed the effect of the ECP on the electromagnetic field and flow field of Ti−Al melt based on numerical simulation, but the effect of the ECP with respect to resultant microstructure was not clarified. ZHAO et al [15] inferred that the change of solidification structure is resulted from electromagnetic pulse, which could induce the forced convection in the melt and result in the fragmentation of dendrite during the solidification. However, the movement of the fragmentation and its influence on the nucleus rate have not been further investigated. ZHAI et al [16−19] investigated the refinement mechanism of the ECP on the solidification structure of pure Al systematically and proved that the nucleus rate increases with applying the ECP during the initial nucleation stage of the melt and that the ECP makes crystal nuclei on the top surface of the melt fall down and move freely in the molten metal, which promotes the refinement of solidification structure. However, a more detailed explanation about the migration behavior of crystal nuclei under the effect of the ECP lacked explicit research. In our previous study [20], the temperature field and flow field of the melt after applying the ECP were calculated based on the mathematic model, by which the fluctuation of the Al liquid surface could lead to the generation of more nuclei after applying the ECP. But the movement of the free nuclei, the crucial factor for the refinement mechanisms, was not considered in that model. Therefore, a further research is necessary to better understand the mechanism of grain refinement with the ECP.

In the present study, a three-dimensional mathematical model is developed to simulate migration behavior of the free nuclei under the effect of the ECP. The heat effect, electromagnetic effect and mechanical effect caused by the ECP are considered in this model and the nucleus movement is analyzed coupling with fluid flow. The calculated results with this model

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describe the nuclei migration and distribution under the effect of the ECP, and also clarify its relationship with the resultant microstructure.

## 2 Physical and mathematical models

### 2.1 Physical model of solidification process

Figure 1 shows the geometric model of the solidification process. The dimensions of silica sand mould are *d*50 mm×75 mm and *d*40 mm×65 mm for cavity. The paralleled steel electrodes with dimensions of *d*3 mm×8 mm are inserted into the Al melt from the top surface. The electrodes immersed into Al melt are 4 mm in length and 2 mm away from the sidewall. The ECP is applied to the pure Al melt through the parallel electrodes.

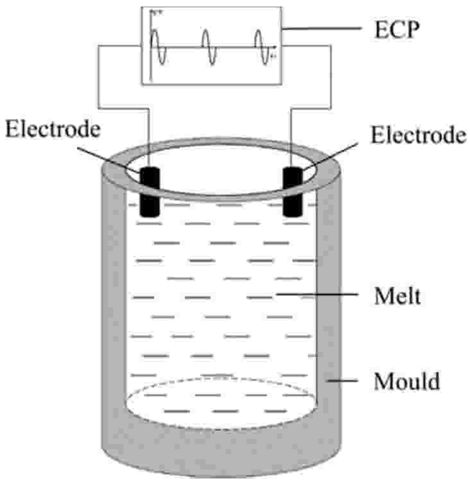


**Fig. 1** Schematic of physical model of pure Al with ECP

### 2.2 Mathematical model

The finite difference method incorporating the volume of fluid (VOF) method is employed to calculate the momentum and energy transport of the melt. Some assumptions for the subsequent calculation and simulation are given as follows: 1) the fluid flow is assumed to be Newtonian, laminar, and incompressible; 2) the melt is assumed to be nonpolar; 3) the nuclei are assumed to be generated on the top surface of the melt.

2.2.1 Governing equations

The differential equations governing the conservation of mass, momentum, and energy based on continuum formulation are used to describe the heat and mass transfer and fluid flow as follows:

Momentum equation:

$$\rho\ (\frac{\partial v}{\partial t}+v\cdot\nabla v)=v\nabla^2 v-\nabla p+R_{\mathrm{SOR}}\cdot v+F_{\mathrm{b}}+\gamma \quad (1)$$

Mass continuity equation:

$$v_F\frac{\partial \rho}{\partial t}+\nabla\cdot(\rho V)=0 \quad (2)$$

Energy equation:

$$\rho(\frac{\partial e}{\partial t}+v\cdot\nabla e)=\nabla\cdot(k\nabla T)+E_{\mathrm{SOR}} \quad (3)$$

where $\rho$ is the fluid density; $v$ is the molten metal velocity; $t$ is the time; $\mu$ is the dynamic viscosity; $p$ is the hydrodynamic pressure; $R_{\mathrm{SOR}}$ is the mass source, including the nuclei mass; $F_{\mathrm{b}}$ is the body force (e.g. gravity, buoyancy and electromagnetic force); $\gamma$ is the surface tension; $v_{\mathrm{F}}$ is the fractional volume open to flow; $E$ is the internal energy per unit mass; $k$ is thermal conductivity; $T$ is the local temperature; and $E_{\mathrm{SOR}}$ is the energy source term generated by pulse current.

2.2.2 Volume-of-fluid (VOF) method

The VOF method is taken to track sharp interface through a fixed grid of control volumes [21]. The configuration of the interface in computational elements is reconstructed according to the value of $F$ in VOF, where $F$ is described as follows:

$$\frac{\partial F}{\partial t}+\frac{1}{v_{\mathrm{F}}}\nabla\cdot(vF)=F_S \quad (4)$$

where $F$ represents the volume fraction occupied by the fluid.

2.2.3 Electromagnetic model

The ECP is applied to the melt through the parallel electrodes, leading to cyclic magnetic field and in reverse inducing cyclic electric current. The distribution of electromagnetic field is governed by Maxwell's equations [22] as follows:

$$\nabla\times\boldsymbol{E}=-\frac{\partial \boldsymbol{B}}{\partial t} \quad (5)$$

$$\nabla\times\boldsymbol{H}=\frac{\partial \boldsymbol{D}}{\partial t}+\boldsymbol{J} \quad (6)$$

$$\nabla\cdot\boldsymbol{D}=\rho_q \quad (7)$$

$$\nabla\cdot\boldsymbol{B}=0 \quad (8)$$

The electromagnetic constitutive equations of simple isotropic material mediums can be expressed as

$$\boldsymbol{D}=\varepsilon\boldsymbol{E} \quad (9)$$

$$\boldsymbol{B}=\mu\boldsymbol{H} \quad (10)$$

$$\boldsymbol{J}=\sigma\boldsymbol{E} \quad (11)$$

where $\boldsymbol{E}$ is the electric field; $\boldsymbol{B}$ the is magnetic flux density; $t$ is the time; $\boldsymbol{H}$ is the intensity of magnetic field; $\boldsymbol{D}$ is the electric displacement; $\boldsymbol{J}$ is the vector of current density; $\rho_{\mathrm{q}}$ is the density of free charge; $\mu$ is the vacuum permittivity; and $\sigma$ is the conductivity.

The Joule heating generated by the current can be expressed as

$$q_{\boldsymbol{E}}=\int\boldsymbol{J}\cdot\boldsymbol{E}\mathrm{d}v \quad (12)$$

The equation of the Lorentz force is described as follows: