Simulation on Dendritic growth of Aluminum Alloy under Magnetic Assisted Solidification

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Abstract: Applying electromagnetic fields during casting or welding processes has been a hot research topic in recent years. In the absence of direct contact with the material, an external magnetic field can affect the flow of the melt, solute distribution, heat transformation, and dendritic growth morphology during the solidification process, which has a decisive impact on the mechanical properties of the product. It is crucial to understand the potential alloy solidification mechanism in order to improve the casting quality.This paper investigates the influence of magnetic damping effect and Seebeck effect on dendritic growth process under magnetic assisted solidification.

Keywords:aluminum alloy; dendritic growth; magnetic field; numerical simulation

1 Introduction

The inhibitory effect of magnetic field on the flow of conductive liquid is called magnetic damping effect, and the melt during solidification is considered as conductive liquid. When the melt is subjected to convection, applying a magnetic field perpendicular to the direction of melt movement will generate an induced current, and the resulting induced current and magnetic field will generate a Lorentz force that is completely opposite to the direction of melt flow. However, it has also been found that applying a stable magnetic field during the solidification process drives the flow of the molten pool through the thermoelectric magnetic force generated by the Seebeck effect. This thermoelectric magnetic force is generated in the paste-like region between dendrites, thereby altering the transfer process of heat and solute along the solid-liquid interface and ultimately affecting the formation of solidification microstructure.

2 Numericalmodel

The mathematical model for simulating aluminum alloy dendrite growth using the phase field method is detailed in Ref. [1], and the magnetic damping effect is described by the following equation [2]:

$$\frac{\partial\rho}{\partial t}+\nabla\cdot\rho u=F_d+F_b+F_{MF} \tag{1}$$

$$\begin{aligned}&\frac{\partial\rho u}{\partial t}+\nabla\cdot\left(pI+\frac{B^2}{2}I+uu-BB\right)=\\&\upsilon\nabla\cdot\left(\rho\left(\nabla u+\nabla^T u\right)\right)+F_d+F_b+F_{MF}\end{aligned} \tag{2}$$

The magnetohydrodynamic control equation is obtained by introducing the Ohm's law modified by the Seebeck effect [3]:

$$F_{TEMF}=\sigma_e((-S\cdot G)\times B+(u\times B)\times B) \tag{3}$$

$$\frac{\partial\rho}{\partial t}+\nabla\cdot\rho u=F_d+F_b+F_{TEMF} \tag{4}$$

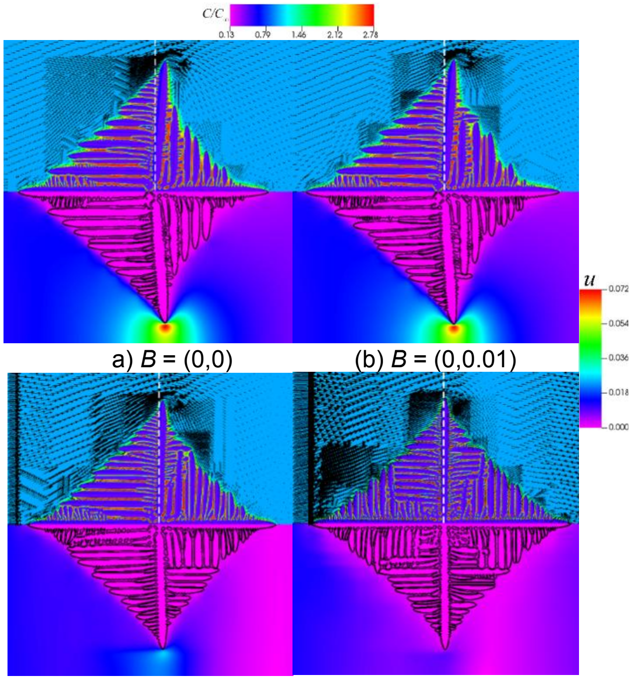
$$\begin{aligned}&\frac{\partial\rho u}{\partial t}+\nabla\cdot\left(pI+\frac{B^2}{2}I+uu-BB\right)=\\&\upsilon\nabla\cdot\left(\rho\left(\nabla u+\nabla^T u\right)\right)+F_d+F_b+F_{TEMF}\end{aligned} \tag{5}$$

Where $S$and $G$are the Seebeck coefficient and temperature gradient, respectively.

3 Result and discussion

Dendrite growth under magnetic damping effect

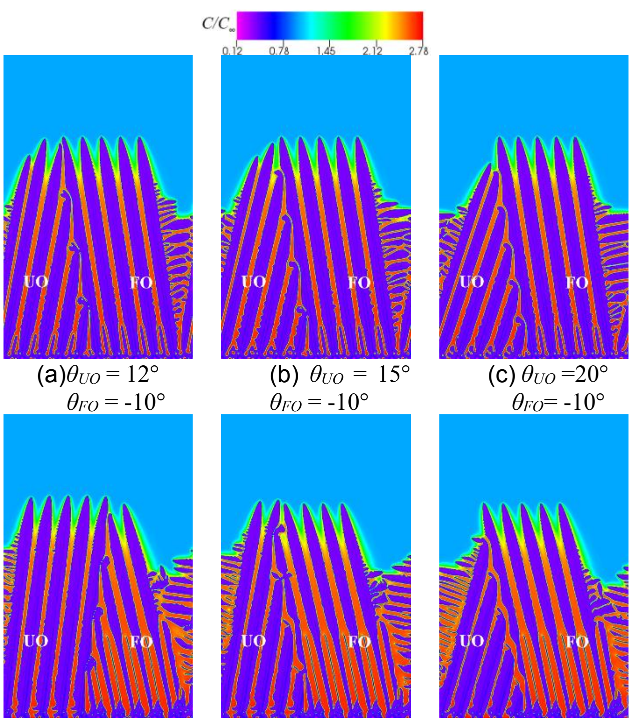
The lateral flow velocity is set to 0.01, and the magnetic field direction is vertically upward. Magnetic field strength $B=(B_x,B_y)$, where B_x and B_y correspond to the transverse and longitudinal magnetic field strengths, respectively. Fig. 1 shows the dendritic growth, solute distribution, and fluid velocity under four different conditions of forced convection, with longitudinal magnetic field strengths of 0, 0.01, 0.05, and 0.1, respectively. In the absence of a magnetic field, the growth rate of upstream dendrite tips is greater than that of downstream dendrite tips, as shown in Figure 1(a). When a longitudinal magnetic field is added, an induced current perpendicular to the paper surface is generated in the fluid with transverse flow velocity. Subsequently, an orthogonal magnetic field acts on this current and applies a Lorentz force opposite to the flow to suppress the flow. As the magnetic field intensity increases, the flow velocity within the computational domain decreases, the difference in growth rate between upstream and downstream dendrite tips decreases, and the phenomenon of dendrite tilting caused by convection gradually disappears, as shown in Figures 1(b-d).



a) B = (0,0) (b) B = (0,0.01)

(c) B = (0,0.05) (d) B = (0,0.1)

Figure 1 Dendrite growth under different longitudinal magnetic field intensities



(a)θ_{UO} = 12° θ_{FO} = -10° (b) θ_{UO} = 15° θ_{FO} = -10° (c) θ_{UO} =20° θ_{FO}= -10°

(d)θ_{UO} = 12° θ_{FO} = -10° (e)θ_{UO} = 15° θ_{FO} = -10° (f) θ_{UO} =20° θ_{FO}= -10°

Figure 2 Simulation of columnar dendritic growth: (a-c) B=0; (d-f) B=0.6

Dendritic growth under the Seebeck effect

Figure2 shows the simulated competitive growth of converging columnar dendrites under pure diffusion and thermoelectric convection with different growth orientation angles. Ten seeds with equal distance distribution are arranged at the bottom of the computational domain, and the first half of the seeds have different growth orientations compared to the second half. In Figures 2(a-c), under pure diffusion conditions, UO columnar dendrites are always eliminated by FO columnar dendrites. When a magnetic field is applied, the position between UO and FO columnar dendrites changes, and UO columnar dendrites instead eliminate FO columnar dendrites, as shown in Figure 2(d). In Figure 2(e), when the angle between the growth direction of UO columnar dendrites and the temperature gradient direction increases to 15°, three main branches of UO columnar dendrites are relatively backward and are eliminated by FO columnar dendrites, but FO columnar dendrites can no longer continue to eliminate UO columnar dendrites. In Figure 2(f), When θ_{UO} increases to 20°, even with the addition of a magnetic field, UO columnar dendrites are completely eliminated.

4 Conclusion

Under the action of lateral forced convection, the longitudinal magnetic field can generate a Lorentz force opposite to forced convection, thereby suppressing flow within the computational domain. During the columnar dendritic growth, the competitive behavior between dendrites is influenced by both the intrinsic orientation angle and magnetic field strength. The magnetic field affects the competitive`growth process by changing the growth orientation angle of dendrites.

5 Acknowledgments

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References

[1] Qiu Y, Wu M, Qin X, et al. Phase-field lattice-Boltzmann study on fully coupled thermal-solute-convection dendrite growth of Al-Cu alloy[J]. China Foundry, 2024, 21(2): 125-136.

[2] Dellar P J. A note on magnetic monopoles and the one-dimensional MHD Riemann problem[J]. Journal of Computational Physics, 2001, 172(1): 392-398.

[3] Cao L, Liu D, Jiang P, et al. Multi-physics simulation of dendritic growth in magnetic field assisted solidification[J]. International Journal of Heat and Mass Transfer, 2019, 144: 118673.