Phase Field Simulation for Grain Refinement in Dendrite Growth of A356 Aluminum Alloy

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Abstract: Although A356 aluminum alloy possesses poor ductility and strength, the refinement of the initial α-Al phase has shown promise in improving these properties. The impact of grain refinement mechanisms on the organization and morphology of A356 aluminum alloys has not been thoroughly investigated. In this paper, we constructed a Phase-field lattice-Boltzmann model to explore the influence of the refinement mechanism on the growth of α-Al dendrites during the non-isothermal solidification process of A356 aluminum alloy. The results demonstrate that the approach of alloying by adding elements, introducing forced convection, and increasing the degree of subcooling has proven to be effective in refining the dendrites of A356 aluminum alloy. The presence of Fe element further promotes the thinning of α-Al dendrites, and this effect is also found after melting ultrasonic treatment at a lower initial casting temperature. These findings are expected to provide theoretical support for effectively improving the hardness, ductility, and overall performance of Al-based alloys.

Keywords: Dendrites,Grain refinement, Phase-field method, Aluminum alloys

1 Introduction

A356 aluminum alloy is frequently used in automobile engine components and wheel rims. Its excellent castability, high strength-to-weight ratio, and exceptional corrosion resistance are what make it attractive[1], but its ductility and strength are somewhat limited. The refining of the α-Al phase in the alloy can significantly improve the strength and ductility of the alloy.The methods can be broadly categorized as physical refinement, thermodynamic refinement, and chemical refinement [2,3].Nevertheless, there is a lack of comprehensive research on the microstructure refinement mechanism and the growth of polycrystalline structures in Al-based multicomponent alloys.

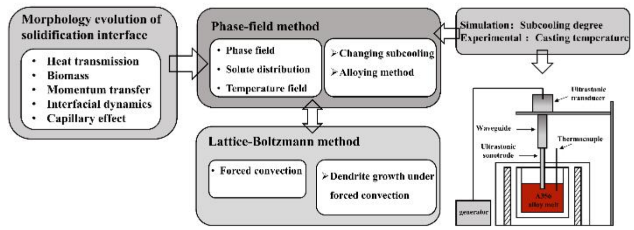

Figure 1. Schematic correlation between phase-fieldsimulation and melt ultrasonic treatment.

For the first time, we utilize the phase-field lattice-Boltzmannmodel to explore the grain refinement mechanisms on thedendritic morphology in A356 aluminum alloyin this paper. The simulation results were also correlated with the experimental results after ultrasonic melt treatment, the schematic is shown in Figure 1. The results may provide research insights for improving the ductility and hardness of other Al-based alloys.

2 Phase-field Method

In this study, the solidification phase-field model in the EasyPhase software package of Prof. Yuhong Zhao's group was used to describe the α-Al dendrite growth of A356 aluminum alloy under non-isothermal solidification conditions. The phase field order parameter is denoted by ϕ, with solid phase $\phi = +1$ and liquid phase $\phi = -1$ .To simulate the movement of the liquid phase and its convection effect on the concentration evolution equation, we employed a lattice-Boltzmann method.

In our calculations, we discretize the phase and solute field equations using the finite volume method, the temperature field equations using the alternating direction implicit (ADI) algorithm, and the flow field using the lattice Boltzmann method.

3 Result and discussion

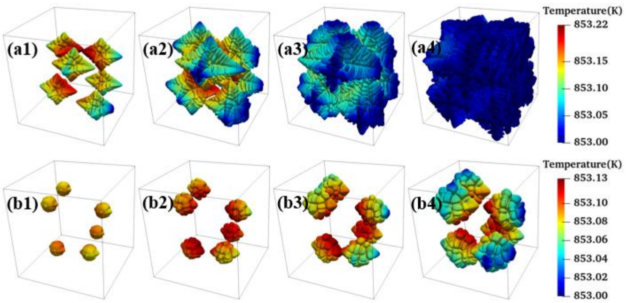

Figure 2. Three-dimensional temperature distribution of A356 aluminum alloy without (a1-a4) and with (b1-b4) Mg solute element. (a1-c1) $t = 3000\Delta t$, (a2-c2) $t = 5000\Delta t$, (a3-c3) $t = 7000\Delta t$, (a4-c4) $t = 10000\Delta t$

Temperature distribution of A356 aluminum alloy before (a1-a4) and after (b1-b4) the addition of Mg solute elements is shown in Figure2. During the initial stages of solidification, the latent heat of solidification diffuses from the center towards the surrounding areas. At $t = 5000\Delta t$, following the introduction of Mg element, the temperature of the dendrite tip near the boundary is higher than before. Consequently, the collision time of heatbetween individual dendrites is delayed, thereby influencing the growth rate of the dendrites. Moreover, the diffusion rate of latent heat during solidification is decreased. This extended diffusion time allows for enhanced grain refinement and serves to impede the growth of the dendrites.

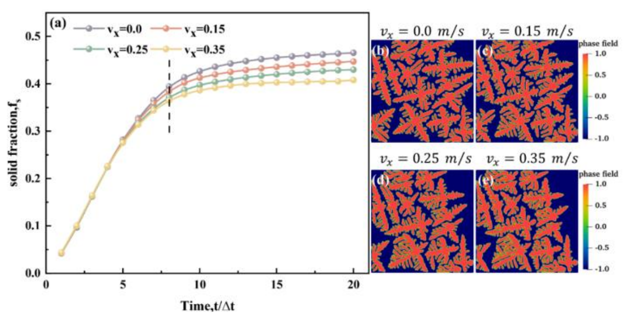

Figure 3. (a) Solid phase fraction curves of A356 aluminum alloy at different flow rates and dendritic morphology corresponding to the black dashed line, the flow rates are (b) $v_x = 0.0$ m/s , (c) $v_x = 0.15$ m/s, (d) $v_x = 0.25$ m/s, (e) $v_x = 0.35$ m/s, respectively.

The solid phase fraction of A356 aluminum alloy with time at different flow rates as well as the corresponding dendrite morphology at $t = 7000\Delta t$ (black dashed line) as shown in Figure 3. As the flow rate increases from 0.0 m/s to 0.35 m/s, the rate of solidification in the dendrites decelerates,resulting in a reduced in the solid phase fraction. This phenomenon can be attributed to the increased transport of heat and solute from the countercurrent side to the tip of the dendrite arm on the downstream side at higher flow rates. As a result, the growth rate of the dendrite arm on the countercurrent side accelerates, causing the dendrite tip to become more susceptible to interactions with boundaries or neighboring dendrites. Additionally, minor protrusions emerged on the countercurrent side of the horizontal dendrite arms, but they did not fully develop into well-formed secondary dendrite. Consequently, these factors contributed to a decrease in the solid phase fraction.

4 Conclusion

(1) The addition of the Mg element, implementation of forced convection, and increase in subcooling in A356 aluminum alloy can effectively achieve grain refinement and improve its ductility and hardness. The increase of Mg content can provide more effective nucleation sites for α-Al nucleation and promote grain refinement. The introduction of forced convection increases the thermal and compositional subcooling in the downstream zone, which hinders dendrite growth on the downstream side. Increasing the degree of subcooling accelerates the secondary dendrite differentiation and the primary dendrite arms are finer, forming finer dendrites.

(2) The application of melt ultrasonication during casting lowers the initial casting temperature, consequently augmenting the degree of subcooling. This increase in subcooling leads to the refinement of α-Al dendrites. Both simulations and experiments have corroboratedthis trend of morphological changes.

(3) Elemental Fe has been observed to reduce the driving force during the solidification and further increases the refinement of α-Al dendrites.

5 Acknowledgments

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