Effects of Strong Magnetic Field on Texture and Grain Boundaries During Directional Solidification of Al-4.5Cu Alloy

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Abstract

The formation behavior of textures and grain boundary character distribution in solidification microstructures during directional solidification under a high magnetic field was investigated for paramagnetic Al-4.5Cu alloy (mass fraction, %, hereinafter the same) with Al-5Ti-1B refiner addition. The results indicate that at a temperature gradient of 27 K/cm, grain orientations were random after refinement in the absence of a magnetic field; when a magnetic field was applied, with increasing magnetic field strength, the grain orientation changed and grains became aligned along the easy magnetization axis <310> of α-Al. Concurrent with the development of the <310> texture, the fraction of coincidence site lattice (CSL) grain boundaries increased. The primary mechanism for texture formation is the rotation of magnetocrystalline anisotropic α-Al grains in the melt under the action of magnetic torque. The influence of fluid flow under the magnetic field on texture formation and grain boundaries was also discussed.

Full Text

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Abstract The formation rules of texture and the distribution of grain-boundary characteristics in the solidification structure during directional solidification under a strong magnetic field were investigated for a paramagnetic Al-4.5Cu alloy (mass fraction, %, the same below) refined by addition of Al-5Ti-1B. The results show that when the temperature gradient is 27 K/cm, without application of a magnetic field, the orientations of the refined grains are random; after a magnetic field is applied, as the magnetic-field intensity increases, the grain orientations change, and the grains are arranged with the easy magnetization axis ⟨310⟩ of α-Al parallel to the magnetic field. With the formation of the ⟨310⟩ texture, the proportion of coincidence site lattice (CSL) grain boundaries in the grains increases. Rotation of α-Al grains with magnetic anisotropy in the melt under the action of magnetic torque is the main reason for texture formation. The influence of fluid flow under the magnetic field on texture formation and grain boundaries is also discussed.

Keywords strong magnetic field; Al-4.5Cu alloy; Al-5Ti-1B refiner; directional solidification; orientation; grain-boundary characteristics

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Texture Formation and Grain Boundary Characteristic of Al-4.5Cu Alloys Directionally Solidified under High Magnetic Field

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ABSTRACT Directional solidification of Al-4.5 wt.%Cu alloy refined by adding Al-5Ti-1B has been carried out to investigate the texture formation and grain boundary characteristic of the paramagnetic crystal under a high magnetic field. Optical microscopy (OM) and Electron Back-scattered Diffraction (EBSD) were applied to analyze the microstructures solidified at different temperature gradients (G) and magnetic field intensities (B). The results show that at the temperature gradient of 27K/cm, the orientations of face-centered cubic (fcc) α-Al grains without magnetic field are random. However, as a high magnetic field is imposed, the easy magnetization axes $< 310 >$ of the α-Al grains are aligned parallel to the direction of the magnetic field leading to $< 310 >$ texture. Meanwhile, the ratio of coincidence site lattice (CSL) grain boundaries increases with the increment of magnetic field intensity and reaches its maximum value at 4T, but decreases as the magnetic field enhances further. On the other hand, when the temperature gradient is elevated, columnar dendrite morphology is exhibited without magnetic field; while a 6T high magnetic field is introduced, the columnar dendrites are broken and equiaxed grains of random orientations are obtained. The alignment behavior of the free crystals in melt could be attributed to the magnetic crystalline anisotropy of

α-Al. Moreover, the influence of fluid flow on the texture formation and CSL grain boundary development under magnetic field is discussed. The absence of convection is benefit for grain reorientation and CSL boundary formation. The application of high static magnetic field will inhibit the macro-scale convection. However, the interaction between thermoelectric current and magnetic field will cause micro-scale fluid flow, i.e. thermoelectric magnetic convection (TEMC). The TEMC will give rise to perturbation

near the solid–liquid interface, leading to the appearance of freckles as well as the decreasing of the ratio of CSL boundary. Moreover, it is proposed that the formation of CSL boundary is associated with the rotation of the free grains in melt along specific crystallographic axes by magnetic torque.

KEY WORDS High magnetic field, Al-4.5Cu Alloy, Al-5Ti-1B refinement, Directional solidification, Orientation, Grain boundary characteristic

Texture has a significant influence on the mechanical and physical properties of polycrystalline materials[^1]. Obtaining a specific texture by controlling processing methods has always been a research focus. During the texturing of materials, changes in grain-boundary characteristics are often involved[^2–^5]. Garbacz et al.[^6] considered that texturing strongly affects the distribution of grain-boundary characteristics, and that different types of textures correspond to different fractions of coincidence-site lattice (CSL) boundaries. Studies[^7] have shown that increasing the fraction of CSL boundaries among grain boundaries can improve material properties such as strength, plasticity, and corrosion resistance.

In recent years, with the development of superconducting technology, strong magnetic fields have been widely applied in materials preparation processes[^8–^10]. Solid–solid phase transformations and solid–liquid phase transformations in magnetic fields can induce the formation of texture. Ban Chunyan et al.[^11] found that, when an Al-2.89Fe alloy (mass fraction, %, the same below) was solidified in a 12 T strong magnetic field, the primary Al_3Fe phase arranged along the [121] easy magnetization direction. Zuo Xiaowei et al.[^12] investigated the solidification behavior of Fe-49Sn alloy under a strong magnetic field and found that, with increasing magnetic-field intensity, the degree of alignment of the iron-rich phase along the direction parallel to the magnetic field increased, and the X-ray diffraction intensity of the α-Fe (110) crystal plane increased. Shen Yu et al.[^13] studied the influence of a longitudinal strong magnetic field on the microstructure of directionally solidified Al-40Cu hypereutectic alloy; the results showed that the primary Al_2Cu phase was aligned along the magnetic-field direction. Li et al.[^14,^15] studied the orientation behavior of primary phases during directional solidification of Al-Ni and Bi-Mn systems in a strong magnetic field; the results showed that the primary phases Al_3Ni and BiMn were aligned along the magnetic-field direction. Watanabe et al.[^16] observed that, when Fe-Co alloy was annealed in a magnetic field, the fractions of low-angle grain boundaries and coincidence-site lattice grain boundaries increased with increasing magnetic-field intensity, and found that these low-energy special grain boundaries were positively correlated with the texture strength in the material. Sun Shuangshuang et al.[^17] found that fine-grained structures obtained by electromagnetic vibration of pure aluminum in a strong magnetic field exhibited a certain fraction of coincidence-site lattice grain boundaries. Previous studies have mostly focused on ferromagnetic solid-solution alloys or intermetallic compounds with relatively low crystallographic symmetry such as hexagonal and tetragonal structures; there have been fewer studies on paramagnetic fcc solid-solution alloys.

During directional solidification of metals under a strong magnetic field, in addition to magnetic orientation, thermoelectromagnetic effects also exist[^18]. Thermoelectromagnetic effects can drive flow in the liquid phase and induce stress in the solid phase, making the evolution of the microstructure during solidification more complex. Li et al.[^19] found that, when Al-4.5Cu alloy was directionally solidified under a strong magnetic field, a fine-grained structure could be obtained, and at the same time the fractions of low-angle grain boundaries and $ $3 grain boundaries between grains increased; they considered this to be the effect of thermoelectromagnetic force acting on columnar dendrites. In the present study, an Al-5Ti-1B refiner was added to an Al-4.5Cu alloy to suppress the formation of columnar grains and to introduce grains capable of moving freely in the mushy zone. The formation of texture and the distribution of grain-boundary characteristics in the microstructure of a paramagnetic fcc α-Al solid-solution alloy during directional solidification under a strong magnetic field, without the action of thermoelectromagnetic force, were investigated.

1 Experimental Method

High-purity metal raw materials (99.99% Al and 99.99% Cu) were weighed according to the composition of Al-4.5Cu alloy and placed in a corundum crucible. They were heated in a resistance furnace to 720 °C and held for 20 min after melting. The melt was stirred uniformly with a graphite rod, degassed (by introducing high-purity Ar gas) and deslagged. An Al-5Ti-1B refiner was added at a Ti mass fraction of 0.02% of the total melt mass, followed by standing for 5 min. The melt was suction-cast under negative pressure using a quartz tube with an inner diameter of 3 mm and cooled in air. The obtained sample rods were ground with sandpaper, ultrasonically cleaned in acetone, and sealed in corundum tubes with an inner diameter of 3 mm, outer diameter of 5 mm, and length of 200 mm for directional-solidification experiments.

The experimental apparatus was as described in Ref.[^20]. The longitudinal strong static magnetic field was generated by a 10 T superconducting magnet. The directional-solidification furnace was a Bridgman-type furnace, with a temperature-control accuracy of $\pm$0.1 °C. Different temperature gradients in the samples were obtained by adjusting the furnace temperature. Using the method described in Ref.[^21], the temperature gradients in the samples at different furnace temperatures were measured: when the furnace temperatures were 750, 850, and 950 °C, the temperature gradients were 27, 65, and 101 K/cm, respectively. Before withdrawal began, the samples were held in the furnace chamber for 30 min so that they were partially melted, and then the stepping motor was started to pull them downward. In this experiment, the withdrawal rate was fixed at 10 μm/s. After stable growth over a certain distance (50-60 mm), the samples were quenched at a rate of 15000 μm/s into a water-cooling chamber containing Ga-In-Sn liquid metal. Before the experiment, the position of the solid-liquid interface under different temperature gradients was determined in advance, and the height of the furnace body was adjusted so that the solid-liquid interface remained within the uniform magnetic-field region throughout solidification.

The microstructure at the solid-liquid interface obtained by quenching the samples was cut out for metallographic observation. Longitudinal sections were obtained by cutting parallel to the magnetic-field direction; after grinding and polishing, the microstructure was revealed by corrosion in a 0.5% HF solution (volume fraction), and observed using a Leica DM6000 optical microscope (OM). The steady-growth region of the samples was cut out for orientation and grain-boundary analysis. Transverse sections were obtained by cutting perpendicular to the magnetic-field direction; after electrolytic polishing, electron backscatter diffraction (EBSD) analysis was performed using an Applo300 scanning electron microscope (SEM) equipped with an Oxford Instruments Nordlys chrysanthemum-pattern probe. The obtained data were processed using Channel5 software from HKL.

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2 Experimental Results

Figure 1 shows the microstructures at the solid-liquid interface (indicated by the dashed lines in the figure) of specimens obtained by quenching under different magnetic-field intensities when the temperature gradient was 27 K/cm. Uniformly distributed fine grains can be observed in the liquid phase ahead of the solid-liquid interface, indicating that, after addition of the Al-5Ti-1B refiner, the heterogeneous nucleation substrate particles obtained were uniformly distributed in the liquid phase. After directional solidification began, the liquid phase ahead of the solid-liquid interface became undercooled, and α-Al nucleated and grew on the substrate after acquiring undercooling. As solidification proceeded, grains in the mushy zone continuously settled, producing a

Fig. 1 microstructures

Figure 1: Fig. 1 microstructures

fine-grained structure. Without a magnetic field (Fig. 1a), relatively large undulations existed at the solid-liquid interface, indicating that fluid flow was present in the melt. When a 2 T magnetic field was applied (Fig. 1b), the undulation of the solid–liquid interface decreased, and "freckle" structures appeared in the solid phase; it is generally believed that the formation of "freckles" is related to fluid flow. When the magnetic-field intensity was 4 T (Fig. 1c), the solid–liquid interface tended to be flat, the "freckle" structure disappeared, and the grains were relatively dense. After the magnetic-field intensity was increased to 6 T (Fig. 1d), the solid–liquid interface became inclined, and new "freckle" structures appeared again at the edge of the specimen, indicating that new flow arose in the mushy zone. The above results show that, when the temperature gradient and pulling rate are constant, with increasing magnetic-field intensity (0–4 T), the flow in the melt is first suppressed; when the magnetic field increases to a certain level (6 T), new flow is generated again in the melt.

图 1 温度梯度为 27 K/cm 时，细化后的 Al-4.5Cu 合金在不同磁场强度下固液界面处的纵截面组织

Fig.1 The quenched longitudinal microstructures near the solid/liquid interface of refined Al-4.5Cu alloys directionally solidified without (a) and with magnetic fields of 2T(b), 4T(c) and 6T (d) under temperature gradient G=27K/cm and pulling rate 10um/s (The dashed lines show solid-liquid interfaces)

Figure 2 gives the morphologies of the solidified structures at the solid–liquid interface obtained by quenching under different temperature gradients, with and without a magnetic field. It can be seen that, when the temperature gradients were 65 and 101 K/cm, respectively, under the condition without a magnetic field, the solidified structure exhibited a columnar-crystal morphology (Fig. 2a, c); under a 6 T magnetic field, some columnar crystals were broken up (Fig. 2b, d), and an equiaxed-crystal morphology appeared (Fig. 2d).

EBSD analysis was performed on the transverse-section microstructures of the steady-growth region of the specimens, and grain reconstruction maps were obtained, as shown in Figs. 3 and 4. The colors of the grains correspond to different orientations. According to statistics, when the temperature gradient was 27 K/cm, the average grain diameter without a magnetic field was 143 μm; after applying magnetic fields of 2, 4 and 6 T, the average grain diameters were 211, 165 and 215 μm, respectively. When the temperature gradient was increased to 65 K/cm, the average grain diameter without a magnetic field was 269 μm, and after applying a 6 T magnetic field it was 236 μm. When the temperature gradient was 101 K/cm, the average grain diameter without a magnetic field was 397 μm, and when a 6 T magnetic field was applied it was···

285 μm.

Fig. 2

Figure 2: Fig. 2

Figure 5 shows the inverse pole figures of grains on the transverse section within the steady-growth region at a temperature gradient of 27 K/cm under different magnetic-field intensities. In the inverse pole figures, spots of different colors represent grains with different orientations. It can be seen that, without a magnetic field and with an applied 2 T magnetic field, the grains are distributed randomly (Fig. 5a, b). When the magnetic-field intensity increases to 4 T, the orientation distribution of the grains begins to change (Fig. 5c). Under a 6 T magnetic field, most grains cluster near the <310> orientation (within the dashed semicircle in Fig. 5d).

Fig. 2 The quenched longitudinal microstructures near the solid/liquid interface of refined Al-4.5Cu alloys directionally solidified at $B = 0$ T, $G = 65$ K/cm (a), $B = 6$ T, $G = 65$ K/cm (b), $B = 0$ T, $G = 101$ K/cm (c), and $B = 6$ T, $G = 101$ K/cm (d)

Figure 6 gives the inverse pole figures of the grain orientation distribution within the steady-growth region, with and without a magnetic field, under different temperature gradients. It can be seen that, without an applied magnetic field and at a temperature gradient of 65 K/cm, owing to the formation of some columnar grains, the grain orientations begin to move closer to the <001> pole in the inverse pole figure (Fig. 6a), while the <310> ori-

The number of grains near the $\langle 001 \rangle$ direction decreases (inside the dashed semicircle in Fig. 6b). When the temperature gradient is increased to 101 K/cm, the solidified structure is basically columnar crystals, with their orientations concentrated near the $\langle 001 \rangle$ pole in the inverse pole figure (Fig. 6c), indicating the preferred growth direction of α-Al. After application of a 6 T magnetic field, when the temperature gradients are 65 and 101 K/cm, the magnetic field induces a columnar-to-equiaxed transition in the columnar crystals[^22], producing an equiaxed-grain structure again, but the grain distribution is disordered (Fig. 6b, d).

Using the EBSD grain-boundary character distribution maps (Fig. 7), the fraction of CSL grain boundaries in the steady-state growth portion of the solidified structure was statistically evaluated at a temperature gradient of 27 K/cm under different magnetic-field intensities. The results show that, when the magnetic-field intensity is 0, 2, 4, and 6 T, the fractions of CSL grain boundaries are 12.3%, 12.7%, 15.9%, and 14.8%, respectively. Thus, the fraction of CSL grain boundaries first increases with increasing magnetic-field intensity, reaching a maximum at 4 T; when the magnetic-field intensity is 6 T, the CSL grain-boundary fraction instead decreases. In combination with the grain-orientation distributions (Fig. 5), this indicates that the fraction of CSL grain boundaries in the solidified structure is closely related to texture formation.

Fig. 3 EBSD false-color maps of the transverse microstructures in the steady-state growth portion of refined Al-4.5Cu alloys directionally solidified without (a) and with magnetic fields of 2 T (b), 4 T (c), and 6 T (d) under a temperature gradient of 27 K/cm.

Figure 3: Fig. 3 EBSD false-color maps of the transverse microstructures in the steady-state growth portion of refined Al-4.5Cu alloys directionally solidified without (a) and with magnetic fields of 2 T (b), 4 T (c), and 6 T (d) under a temperature gradient of 27 K/cm.

Fig. 4 EBSD false-color maps of transverse microstructures in the steady-state growth region of refined Al-4.5Cu alloys directionally solidified at different temperature gradients with or without a magnetic field

Figure 4: Fig. 4 EBSD false-color maps of transverse microstructures in the steady-state growth region of refined Al-4.5Cu alloys directionally solidified at different temperature gradients with or without a magnetic field

Fig. 3 Temperature gradient 27 K/cm: EBSD reconstructed maps of transverse-section grains in the steady-state growth portion of refined Al-4.5Cu alloy

Fig. 3 The EBSD false color maps of the transverse microstructures in the steady-state growth portion of refined Al-4.5Cu alloys directionally solidified without (a) and with magnetic fields of 2 T (b), 4 T (c), and 6 T (d) under temperature gradient 27 K/cm.

Figure 4 EBSD reconstructed maps of grains in transverse sections within the steady-state growth region of refined Al-4.5Cu alloys directionally solidified at different temperature gradients, with or without a magnetic field

Fig. 4 The EBSD false-color maps of the transverse microstructures in the steady-state growth portion of refined Al-4.5Cu alloys directionally solidified at: $B = 0$ T, $G = 65$ K/cm (a); $B = 6$ T, $G = 65$ K/cm (b); $B = 0$ T, $G = 101$ K/cm (c); and $B = 6$ T, $G = 101$ K/cm (d).

Fig. 5 The inverse pole figures (IPFs) of transverse microstructures in the steady-state growth portion of refined Al-4.5Cu alloys directionally solidified without (a) and with magnetic fields of 2 T (b), 4 T (c), and 6 T (d) under a temperature gradient of 27 K/cm. The direction of the IPFs refers to the magnetic-field direction, and the colored spots in the region of the dashed semi-circle indicate grains oriented close to the $\langle 310 \rangle$ direction.

Fig. 6 The IPFs of transverse microstructures in the steady-state growth portion of refined Al–4.5Cu alloys directionally solidified at: $B = 0\,\text{T}, G = 65\,\text{K/cm}$

Fig. 5

Figure 5: Fig. 5

Fig. 6

Figure 6: Fig. 6

Fig. 7

Figure 7: Fig. 7

(a), $B = 6$ T, $G = 65$ K/cm (b), $B = 0$ T, $G = 101$ K/cm (c), and $B = 6$ T, $G = 101$ K/cm (d). The direction of the IPFs refers to the magnetic-field direction; the colored spots in the region of the dashed semicircle indicate the grains oriented close to the $\langle 310 \rangle$ direction.

Figure 7 Grain-boundary characteristic maps of transverse-section grains in the steady-state growth region of refined Al-4.5Cu alloy at a temperature gradient of 27 K/cm under different magnetic-field intensities

Fig. 7 The grain boundary characteristic maps of transverse microstructures in the steady-state growth portion of refined Al-4.5Cu alloys directionally solidified without (a) and with magnetic fields of 2 T (b), 4 T (c) and 6 T (d) under temperature gradient 27 K/cm. The colored lines represent the coincidence site lattice (CSL) boundaries

3 Analysis and Discussion

When crystals with magnetic crystalline anisotropy are placed in a static magnetic field, in order to reduce the energy of the system, if they can rotate freely, they tend to make the easy magnetization axis parallel to the magnetic-field direction[^23]. The magnetic torque experienced by a crystal in a uniform magnetic field can be expressed as follows[^24]:

$$T = \frac{\Delta\chi}{2\mu_0} B^2 V \sin 2\theta \tag{1}$$

where $\Delta\chi$ is the difference in magnetic susceptibility between two crystallographic directions of the crystal, μ_0 is the vacuum permeability, B is the magnetic-field intensity, V is the crystal volume, and θ is the included angle between the magnetic field and the crystallographic direction with the maximum magnetic susceptibility.

The refinement mechanism of the Al-5Ti-1B refiner for aluminum alloys is as follows: after the refiner is added to the melt, suspended Al_3Ti or TiB_2 crystal nuclei are generated in the melt[^25]; subsequently, α-Al undergoes heterogeneous nucleation and growth on these substrate phases. Among them, Al_3Ti has a body-centered tetragonal structure, and TiB_2 has a hexagonal structure. In terms of crystal symmetry, both may have more pronounced magnetic anisotropy than fcc α-Al crystals. The substrate phases are suspended in the

Fig. 8

Figure 8: Fig. 8

liquid phase; after a magnetic field is applied, they may rotate, thereby affecting the orientation of the solidified structure. However, Eq. (1) shows that the magnetic torque is proportional to the volume of the crystal. It has been reported in Ref. [26] that the rod-like or plate-like $TiAl_3$ particles observed in the refined grains have an average diameter of 20–40 μm, while the diameter of TiB_2 particles is generally smaller than 2 μm. The diameters of the α-Al grains obtained in the present experiment are all above 150 μm (Fig. 3). The magnetic torque acting on the α-Al phase is far greater than that on the substrate particles. The final orientation of the grains should therefore be determined by the magnetic anisotropy of α-Al.

Zhu Yaoming[^27] measured the magnetic susceptibilities of different crystal planes in single-crystal pure Al. The results showed that the magnetic crystalline anisotropy of single-crystal Al is very significant, with the magnetic susceptibility of the (310) crystal plane reaching the maximum value. According to Eq. (1), when a magnetic field is applied, the $< 310 >$ crystallographic direction of Al grains will rotate to become parallel to the magnetic-field direction; moreover, the higher the magnetic-field intensity, the more pronounced the orienting effect (Fig. 8).

Figure 8 Schematic diagram of the orientation of α-Al grains in a magnetic field

Fig. 8 The schematic of alignment of α-Al crystal under magnetic field: (a) The magnetic torque caused by the magnetic anisotropy of the crystal; (b) The process of rotation and re-orientation when the magnetic field is applied

When the melt temperature is too high, the Al-5Ti-1B refiner undergoes fading. Studies[^25] have shown that when the melt temperature exceeds 800°C, the Al-5Ti-1B refiner loses its refining effect after 10 min of addition. In the present experiment, before withdrawal began, the sample had to be held for a certain period of time (30 min) to establish a stable temperature gradient. When the temperature gradient was relatively high (furnace temperatures of 850 and 950°C), the refiner in the sample partially or completely failed. Therefore, under the condition without a magnetic field, a columnar-grain structure was obtained; the columnar grains could not rotate freely and thus could not rotate the $\langle 310 \rangle$ easy-magnetization direction to become parallel to the magnetic field (Fig. 4a,c). After the magnetic field was applied, the columnar grains were broken up by the thermoelectromagnetic force and an equiaxed structure was obtained. However, because the grain spacing was small and there was no space for free rotation, the resulting refined grain structure had a disordered orientation (Fig. 4b,d), consistent with the report in Ref. [19]. In addition, as the temperature gradient increased, the length of the mushy zone decreased. From the Al–Cu phase diagram, the temperature interval between the solidus and liquidus lines of the Al-4.5Cu alloy is about 74 K. The mushy-zone length ΔL can be estimated by the following equation[^28]:

$$G = \frac{\Delta T}{\Delta L} \tag{2}$$

Here, ΔT is the temperature difference between the solidus and liquidus lines determined for a given composition on the phase diagram. From Eq. (2), when the temperature gradients are 27, 65, and 101 K/cm, the mushy-zone lengths are 27, 11, and 7.3 mm, respectively. Thus, at lower temperature gradients the mushy zone is longer, whereas at higher temperature gradients it becomes narrower. At a constant withdrawal rate, free grains generated in the mushy zone at a low temperature gradient have more time to rotate, which is favorable for orientation. This explains why, at the same magnetic-field intensity (6 T), grain orientation is obvious when the temperature gradient is lower (Fig. 5d), whereas at higher temperature gradients the grain distribution is disordered (Fig. 6b,d).

During solidification, grain-orientation behavior is also affected by melt flow; disturbances caused by flow are unfavorable for grain orientation. When flow exists in the mushy zone, the solid–liquid interface may tilt, producing phenomena such as "banded" structures. In the absence of a magnetic field, because a temperature gradient exists during directional solidification, a density difference is produced in the melt. This density difference can induce convection, causing the solid–liquid interface to tilt (Fig. 1a). The influence of a strong static magnetic field on flow during directional solidification mainly includes two aspects: one is the magnetic damping (MD) effect; the other is the thermoelectric magnetic convection (TEMC) effect. The magnetic damping effect[^29] refers to the Lorentz force induced in a conducting fluid under an applied magnetic field, opposite to the direction of motion. This force suppresses flow, and its damping effect can be characterized by the dimensionless Hartmann number (Ha). The Hartmann number is defined as the ratio of magnetic damping force to the viscous force of the melt[^30]:

$$Ha = \sqrt{\frac{\sigma}{\rho\nu}} BL \tag{3}$$

where σ is the electrical conductivity of the metallic melt, ρ is the melt density, ν is the dynamic viscosity of the melt, and L is the characteristic length. It can be seen that the Ha number increases monotonically with magnetic-field intensity B and is also constrained by the characteristic length L. The suppression of flow at the macroscopic scale (>1 mm) is relatively significant, whereas the suppression of flow at the microscopic scale (<1 mm) is relatively weak. According to Eq. (3), when the sample size is fixed, the magnetic damping effect strengthens as the magnetic-field intensity increases. The macroscopic flow in the melt is suppressed, reducing the "banded" structure and making the solid-liquid interface tend to become flat (Fig. 1c).

The TEMC effect arises because, during directional solidification, a temperature gradient exists at the front of the solid-liquid interface, and the Seebeck coefficients of the solid and liquid phases are different. According to the thermoelectric principle[^22], a thermoelectric current is generated at the front of the solid-liquid interface. After a magnetic field is applied, the thermoelectric current interacts with the magnetic field to produce a Lorentz force; this

The force will drive the flow, thereby generating convection on the macroscopic scale and microscopic scale. The magnitude of the TEMC flow velocity u_{TEMC} is:

$$u_{TEMC} = \sqrt{\frac{\sigma SGBL}{\rho}} \tag{4}$$

where S is the difference in the Seebeck coefficients of the solid and liquid phases. From Eq. (4), it can be seen that the intensity of TEMC increases with increasing magnetic field, and is also affected by the characteristic length L. At a macroscopic scale ($>$ 1 mm), the MD and TEMC effects constrain each other. When the magnetic field strength is relatively weak (2 T), TEMC causes "freckle-like" structures to appear in the solidified microstructure (Fig. 1b), leading to disorder in grain orientation. However, with increasing magnetic field strength (4 T), the magnetic damping effect is enhanced, weakening TEMC; the "freckle-like" structure disappears, which is beneficial to grain orientation (Fig. 1c). Under a 6 T magnetic field, flow on the macroscopic scale is suppressed by magnetic damping, but TEMC at the grain scale (200–500 μm) still exists [31], causing the "freckle-like" structure to reappear (Fig. 1d) and disturbing grain-boundary formation, resulting in a decrease in the fraction of special grain boundaries. At this time, however, the magnetic torque also reaches its maximum, causing a large number of grains to become oriented (Fig. 5d).

The mode of grain-boundary formation in solidified microstructures differs from that in recrystallization annealing. During recrystallization annealing, changes in grain boundaries are achieved mainly through migration in the solid phase [32]. During solidification, two growing grains come into contact with each other, and the remaining liquid film between the grains transforms into solid phase to form the grain boundary. According to the definition of the five degrees of freedom of a grain boundary [33], the nature of the grain boundary can be determined by the orientations of the grains on both sides. As analyzed above, the magnetic field can cause suspended α-Al grains in the mushy zone to rotate and orient, thereby changing the distribution of grain-boundary characteristics in the solidified microstructure. According to Eq. (1), the larger the difference in magnetic susceptibility between two grains, the stronger the magnetic torque acting on the grains. From Ref. [26], it is known that, in α-Al, orientations with larger magnetic susceptibility are generally high-index orientations, whereas the magnetic susceptibility of low-index orientations is relatively small. A CSL grain boundary can be defined as one obtained by rotating one grain by a specific angle about a certain crystallographic direction of another grain. This crystallographic direction is generally a low-index crystal axis [34]. When a sufficiently large magnetic field is applied, and the disturbance from flow in the melt is relatively small, the probability that crystals rotate about a low-index crystallographic direction increases, and the fraction of CSL grain boundaries in the solidified microstructure increases.

4 Conclusion

(1) When Al-4.5Cu alloy refined by addition of Al-5Ti-1B is directionally solidified under a strong magnetic field, owing to the anisotropy of the magnetic susceptibility of α-Al, the refined grains are oriented along the easy magnetization direction $< 310 >$. When the temperature gradient is 27 K/cm, the degree of orientation increases with increasing magnetic field strength.

(2) A high temperature gradient narrows the mushy zone and reduces the space for free rotation of crystals, which is unfavorable for grain orientation. The magnetic damping effect suppresses fluid flow in the melt and is beneficial to grain orientation; thermoelectric magnetic convection increases disturbances in the melt, weakening the orienting effect of the magnetic field.

(3) The fraction of CSL grain boundaries in the solidified microstructure is related to the microstructure type. Applying a magnetic field can increase the fraction of CSL grain boundaries in the refined solidified microstructure. Magnetic-field-induced grain orientation is the reason for the increase in the fraction of CSL grain boundaries. In addition, the fraction of CSL grain boundaries is affected by fluid flow; flow in the melt is unfavorable for the formation of CSL grain boundaries.

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Note: Figure translations are in progress. See original paper for figures.