Influence of an Axial Magnetic Field on Microstructures and Alignment in Directionally Solidified Ni-based Superalloy

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The effect of an axial magnetic field on the dendrite morphology in directionally solidified Ni-based superalloy was investigated experimentally. Results show that an application of the magnetic field modified the morphology of the dendrite remarkably. Under a relatively weak magnetic field (B < 0.5 T), the primary dendrite spacing decreases with the increase of magnetic field intensity. However, under a relatively high magnetic field (B ≥ 2 T), the primary dendrite spacing increases with the increase of magnetic field intensity. Moreover, it was found that the strong magnetic field is capable of inducing the fracture of the dendrite and the columnar to equiaxed transition (CET). With the increase of the magnetic field and the decrease of the growth speed, the fracture of the dendrite and the CET under the magnetic field is enhanced. The above results may be attributed to the TE magnetic convection in the liquid and the TE magnetic force acting on the dendrite.

KEY WORDS: axial magnetic field; dendrite morphology; Ni-based superalloy.

1. Introduction

Directional solidification had been widely used to produce turbine blades of Ni-based superalloys. Dendrites are typical structures observed during the directional solidification of alloys. The dendrite spacing, especially the primary dendrite spacing, is an important factor to determine the mechanical properties of directionally solidified superalloys.1) Many processes were developed to decrease the primary dendrite spacing of solidified alloys.2–4) These methods are mainly based on improving the thermal gradient and cooling rate of the solidification process and it is difficult to further improve their performances due to the restrictions of practical process conditions. Moreover, the columnar-to-equiaxed transition (CET) in the grain structure of metal alloy casting has fascinated researchers in the solidification area.5–8) Recently, the magnetic field has widely been applied during the solidification process and the results showed the magnetic fields affected the solidification microstructure of alloys remarkably. Indeed, it has been found that a static magnetic field can influence the microstructure, critical transformation speeds from cellular to dendrite crystal, and CET, and so on.9–11)

This work aims to investigate the effect of an axial magnetic field on the dendrite morphology in directionally solidified Ni-based superalloy. Results show that an application of the magnetic field modified the morphology of the dendrite remarkably. Indeed, under a relatively weak magnetic field (B < 0.5 T), the primary dendrite spacing decreases with the increase of magnetic field intensity. However, under a relatively high magnetic field (B ≥ 2 T), the primary dendrite spacing increases with the increase of magnetic field intensity. Moreover, it was found that the strong magnetic field is capable of inducing the fracture of the dendrite and the CET. With the increase of the magnetic field and the decrease of the growth speed, the fracture of the dendrite and the CET under the magnetic field is enhanced. The above results may be attributed to the TE magnetic convection in the liquid and the TE magnetic force acting on the dendrite during directional solidification under the magnetic field.

2. Description of the Experimental Device

The chemical compositions of the used superalloy DZ417G are 0.18 wt.% C, 8.96 wt.% Cr, 3.08 wt.% Mo, 9.72 wt.% Co, 0.86 wt.% V, 0.015 wt.% B, 5.41 wt.% Al, 4.50 wt.% Ti, 0.23 wt.% Fe, 0.002 wt.% P, 0.002 wt.% S, 0.04 wt.% Si, 0.05 wt.% Mn, and Ni as balance. The raw ingot with a diameter of 100 mm was prepared in an induction furnace. The samples for directional solidification with 4 mm in diameter and 180 mm in length were electro-discharge machined from the raw ingots and enveloped in high purity corundum tubes with the inner diameter of 4 mm and length of 200 mm. The schematic view of the directional solidification apparatus under an axial high magnetic field was shown in Fig. 1. It consists of a static superconducting magnet, a Bridgman-Stockbarg type furnace, and a growth velocity and temperature controller. The superconducting
magnet can produce an axial static magnetic field with the adjustable intensity up to 14 T. In this magnet, there is a uniform magnetic field in an 8 cm zone at the center of the magnet. The furnace, which consists of nonmagnetic material, has a negligible effect on the field uniformity. The temperature in the furnace can reach 1 600°C and was controlled to a precision of ±1 K. A water-cooled cylinder containing liquid Ga-In-Sn metal (LMC) was used to cool down the sample. The temperature gradient in the sample was controlled by adjusting the temperature of the furnace hot zone, which was insulated from the LMC by a refractory disc. To perform directional solidification, the apparatus was designed in such way that the sample moved downward while the furnace remained fixed. During the experiment, the sample in the corundum crucibles was placed at the center of the magnet, and the liquid/solid interface of the sample was placed in the uniform magnetic field. Then, the samples were melted and directionally solidified in the Bridgman apparatus by pulling the crucible assembly at various speeds into the LMC cylinder. The growth speed and magnetic field for the above experiments are listed in Table 1. Microstructures were examined in the etched condition by optical microscopy. The morphology and orientation characteristics of the dendrite were investigated using electron back-scattered diffraction (EBSD) in a high-resolution scanning electron microscope (FEG SEM, JEOL 6500F) equipped with a Channel 5 EBSD system (HKL Technology-Oxford Instrument). The sample surface was prepared by electropolishing in a solution of ethyl alcohol (800 ml) and perchloric acid (200 ml) with voltage 20 V over an 80 s time period. The accelerating voltage of scanning electron microscope is 20 KV to get a good Kikuchi pattern and one pattern generated during one-step scanning (5 μm) corresponded to an indexed pixel. Each point in the EBSD maps is colored according to an automatically color unit triangle of the standard inverse pole figure. It should be mentioned that different types of grain structures correspond to different critical elongation. In the Hunt model,\textsuperscript{5} grains are equiaxed with elongation lower than 2. In the present work, the grain with elongation smaller than 2 were assigned as equiaxed grain and measured by using the freely available ImageJ.

3. Results

Figure 2 shows the longitudinal structures near the liquid/solid interface in directionally solidified Ni-based superalloy at the lower growth speed with various magnetic fields. One can notice that the morphology of the dendrite in the case of no magnetic field was typical dendritic. However, when a relatively high magnetic field (B ≥ 2 T) is applied, the dendrite was destroyed significantly. With the decrease in the growth speed, the effect of the magnetic field became stronger and at last the columnar to equiaxed transition (CET) occurred.

Further, the microstructures directionally solidified at a certain growth speed under various magnetic fields were observed in details. Figure 3 shows the microstructures near the liquid/solid interface directionally solidified at 20 μm/s under various magnetic fields. The regular columnar dendrite structures were obtained without and with a lower magnetic field. However, when the magnetic field increases to 2 T–6 T, a few dendrites were fractured and the array of the dendrite became irregular. Meanwhile, the freckle segregation formed on the edge to the center of the sample.

The EBSD technology was used to visualize the morphology and crystallogeny orientation of the dendrite. Figure 4 shows the inverse pole figure (IPF) maps and the corre-
sponding pole figures for the structure as shown in Fig. 2. The correspondence between color and crystal orientation was shown in the stereographic triangle inserted at left lower corner. One can notice that when the strong magnetic field of 4 T was applied at the growth speed of 20 μm/s, the regular dendrite was destroyed at the edge of the sample. With the increase of the magnetic field and the decrease of the growth speed, the number of equiaxed grains at the edge of the sample increased and gradually extended from the edge to the center of the sample. When the stronger magnetic field was applied at the growth speed of 5 μm/s, the equiaxed grains appeared full of the sample. Moreover, it can be learned that in the case of no magnetic field, the <001>-crystal direction of the dendrite was aligned along the solidification direction. However, when the magnetic field was applied, the <001>-crystal direction deflected from the solidification direction. It’s worth noting that the different colors in pole figures stand for the degree of clustering. The regions of high intensity (near the red end of the color scale) are associated with clustering of points in the discrete crystal direction in IPF maps.

Figure 5(a) shows the fraction of the equiaxed grains as a function of the growth speed or the magnetic field. One can learn that the fraction of the equiaxed grains decreased with increasing growth speed and increased with increasing magnetic field. Figure 5(b) shows the primary dendrite spacing as a function of the magnetic field during directional solidification at the growth speed of 10 μm/s. The primary dendrite spacing decreases with the magnetic field under a relatively weak magnetic field (B<0.5 T), and then
increases with the magnetic field when the magnetic field exceeds a certain value.

4. Discussions

Normally, two kinds of forces could produce during directional solidification under the magnetic field. One is the magnetization force arising from the magnetocrystalline anisotropy of the dendrite. The other is the thermoelectric (TE) magnetic force which is caused by the interaction between the TE current and the magnetic field.

To study the magnetocrystalline anisotropy of the dendrite in the Ni-based superalloy and the effect of the magnetization force on the dendrite array, the Ni-based alloy was solidified isothermally under the strong magnetic field. Figures 6(a) and 6(b) show respectively the EBSD map and corresponding pole figures for the structure in solidified Ni-based alloy at a cooling rate of 18 K/min under the 10 T magnetic field. As shown in the stereographic triangle inserted at left lower corner in Fig. 6(a), one can see that the crystal directions were not obviously aligned under the magnetic field. This implies that the magnetocrystalline anisotropy of the dendrite in the Ni-based superalloy is weak and the magnetization force is negligible even under the strong magnetic field.

Therefore, the TE magnetic effects should be responsible for the above results. It is well known that in any material a temperature gradient $\nabla T$ produces a Seebeck electromotive force $ST$, where $S$ is the TE power of the material. If the gradients of $S$ and $T$ are not parallel, then a TE current is generated in the system, as shown in Fig. 7(a). When an external magnetic field $B$ is applied, since the TE current $J_{TE}$ cannot be everywhere parallel to $B$, thus, the Lorentz forces $J_{TE} \times B$ (i.e., the TE magnetic force) will produce. The TE magnetic force in the liquid will induce the TE magnetic convection, as shown in Fig. 7(b). The amplitude of the TE magnetic convection under various scales as a function of the magnetic field was investigated during directional solidification of Al–Cu hypereutectic alloys and the results revealed that the TE magnetic convection at the scales of sample ($\lambda = 1,500 \mu m$) and dendrite ($\lambda = 500 \mu m$) reaches a maximal value under 0.17 T and 0.43 T magnetic field, respectively, and then decreases as the magnetic field continues to increase. The effect of the convection on the dendrite/cell spacing has ever been studied. Lehmann et al. proposed the dendrite/cell spacing to flow velocity $U$ which is parallel to the columnar as follows:

$$\lambda = \lambda_0 \sqrt{1 + (U / R)} \quad (1)$$

where $\lambda_0$ is the primary spacing without convection, $U$ the
velocity and R the growth speed. According to Eq. (1), it can be deduced that the TE magnetic convection will reduce the dendrite/cell spacing. At the same time, the TE magnetic force will act on the dendrites (see Fig. 7(c)) and cause the deformation and fracture of the dendrite. The TE magnetic force acting on the dendrite has been investigated and the following approximation for the TE magnetic force in solid dendrites:

$$F_S = \frac{-\sigma_L \sigma_S f_L}{\sigma_L f_L + \sigma_S f_S} (S_S - S_L) GB$$

where $\sigma_L$, $\sigma_S$ are the electrical conductivity of liquid and solid, respectively; $f_L$, $f_S$ are the liquid and solid fractions, respectively; $S_L$, $S_S$ are the thermoelectric power of the liquid and solid, respectively; $G$ the temperature gradient. Form Eq. (2), it can be deduced that the TE magnetic force acting on the dendrite increases linearly with the increases of the magnetic field intensity. The magnitude of the TE magnetic force under the 10 T magnetic field is of order of $10^5$ N/m$^3$, as shown in Fig. 7(b). This force acting on the dendrite will fracture the primary dendrite arm and increase the primary dendrite spacing when the magnetic force is large. 

Fig. 4. EBSD maps and pole figures for the longitudinal structures near the liquid/solid interface directionally solidified without and with the magnetic field. (Online version in color.)

Fig. 5. (a) Fraction of equiaxed grains as a function of the growth speed or the magnetic field during directional solidification; (b) primary dendrite spacing as a function of the magnetic field during directional solidification. (Online version in color.)

Fig. 6. EBSD maps and corresponding pole figures for the structures in solidified isothermally Ni-based alloys at a cooling rate of 18 K/min under a 10 T magnetic field. (Online version in color.)
field reaches a certain value, as shown in Fig. 7(d). Thus, on one hand, the TE magnetic convection in the liquid decreases the primary dendrite spacing. One the other hand, the TE magnetic force acting on the dendrite increases the primary dendrite spacing. The influence of the TE magnetic convection at the sample and dendrite scales on the dendrite morphology under a strong magnetic field becomes weak; however, the TE magnetic force acting on the dendrite becomes strong. Therefore, the primary dendrite spacing decreases under a weak magnetic field and then increases as the magnetic field continues to increase during directional solidification (see Fig. 3(b)).

Since the TE magnetic force increases as the magnetic field increases, the fracture of the dendrite is enhanced with increasing of the magnetic field. Moreover, it is not difficult to understand that the effect of the TE magnetic force acting on the dendrite/cell occurs mainly in the mushy zone. Therefore, the staying time of cell and dendrite in the mushy zone also play crucial roles. Since the staying time in the mushy zone increases with decreasing the growth speed, the effects of a strong magnetic field will be enhanced and the fraction of equiaxed grains decreases with increasing the growth speed.

5. Conclusions

The influence of an axial magnetic field on the solidification structure in directionally solidified Ni-based superalloys was studied, and the results obtained are summarized as follows:

(1) A relatively weak magnetic field (B < 0.5 T) decreases the primary dendrite spacing and a relatively strong magnetic field (B ≥ 2 T) increases the primary dendrite spacing during directional solidification.

(2) A relatively strong magnetic field is capable of inducing the fracture of the dendrite and the CET. With the increase of the magnetic field and the decrease of the growth speed, the fracture of the dendrite and the CET is enhanced.

(3) The above results may be attributed to the TE magnetic convection in the liquid and the TE magnetic force acting on the dendrite during directional solidification under the magnetic field.

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