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Effects of electric current pulse on stability of solid/liquid interface of Al–4.5 wt.% Cu alloy during directional solidification

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Abstract

This paper investigates the effects of the electric current pulse (ECP) on the interface stability of Al–4.5% Cu alloy during the directional solidification. Experimental results show both the cellular spacing and the mushy zone depth decrease with increasing current density, moreover, the solid–liquid interface morphology transforms from dendritic to cellular or even planar interface. The secondary dendrites are suppressed due to the homogeneous distribution of the solute and the increase of temperature gradient originated from ECP. The decrease of the cellular spacing results from branching of the cellular tip caused by Joule heat of the current exerting on cellular tip.
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1. Introduction

Because the directional solidification can control the growth direction of crystals and eliminate transverse grain boundary effectively, it is an important process to manufacture high quality components, such as semiconductor [1], magnetic functional material [2], in situ composite material [3] and so on. Recently, many new directional solidification techniques were developed based on the traditional process, including supercooling directional solidification [4], electromagnetic confinement shaping directional solidification [5] and directional solidification with an external field [6,7]. These new techniques made great contributions to obtain ultra-fine columnar crystal and to investigate solidification mechanism. Theoretical and experimental studies show that the electric current including DC, AC and ECP, has obvious influences on solidification process [8–11]. Lucien et al. [12] reported that during the directional solidification of Sn–0.9 wt.% Cu alloy, the current pulse resulted in the disruption of the aligned rod morphology, giving rise to the segment of the rod (Cu6Sn5) phase embedded in Sn matrix. Many investigations [12–14] revealed the morphological instability under the ECP. However, there is a serious gap in understanding of the interfacial morphology by the directional solidification with ECP treatment. Hereby, in this paper, we report the effect of ECP treatment on the interfacial morphology of Al–4.5 wt.% Cu alloy during the directional solidification.

2. Experimental procedure

The Al–Cu alloys were prepared by pure Al (99.7%) and Cu (99.99%) in a resistance furnace. The homogeneous liquid was sucked up into Ø 4 mm glass tubes with a length 200 mm. The experimental apparatus were presented in Fig. 1. The alumina crucible, where the rod with a size of Ø 4 mm × 320 mm was placed, was fixed in a Bridgman–Stockbarger furnace. The upper electrode was consumable, and the coolant was Ga–In–Sn alloy. For these experiments, the pulling rate was 3, 8, 14 and 96 μm/s, respectively. The sample was melted in an electric resistance furnace with a temperature of 1500 K. The directional solidification process was initiated after the melt had kept at 1500 K for 20 min. The measured temperature gradient was 123 K/cm. The sample was quenched into water after a ECP treatment of 20 min.

As shown in Fig. 2, during the course of discharge, the current reaches its maximum in a short time, and then attenuates to zero rapidly. This course was carried out periodically. In

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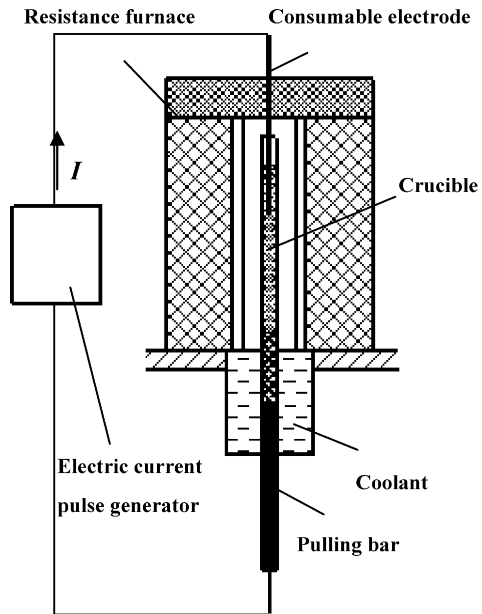

Fig. 1. Sketch of the experimental setup.

the experiment, the frequency of the applied current pulse was 200 Hz. As the schematic map shown in Fig. 1, the positive polarity is in the melt, and the negative polarity of electrode is connected to the solid samples.

The samples were cut along longitude at the midline, and polished and etched for metallographic examination. The etching reagent was the 10% HNO_3 aqueous solution.

The temperature was measured by a Ø 0.25 mm chromel–alumel thermocouple, which was covered by the alumina coating on its tip. The thermocouple mounting on a constant position of the sample moved synchronously with the sample. The temperature of the melt was recorded by a computer. The temperature gradient of the liquid in front of the solid–liquid interface was calculated in virtue of the cooling curve measured by the thermocouple. The cellular spacing was measured according to the method proposed in Ref. [15].

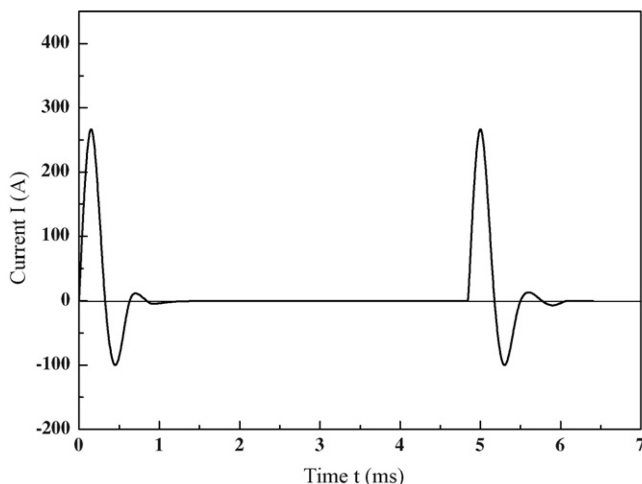

Fig. 2. Pulse current waveforms applied in the experiment.

3. Results

3.1. Solid–liquid interface morphology

Fig. 3 shows the effect of ECP on the interface morphology at different growth rates. As shown in Fig. 3(a), without ECP treatment, the interface is regular cellular morphology at the pulling rate of 3 μm/s. When a pulse current with density of 1.59×10^3 A/cm^2 is applied, dramatic transformations of the interface, such as the bifurcation of bulk cellular crystal, the remarkable decrease of cellular spacing, diminishing of mushy zone depth, and the stabilization of interface, are found. When the current density is 2.79×10^3 A/cm^2, the solid–liquid interface transforms from cellular to planar interface.

Fig. 3(b) presents the interface morphology with a pulling rate of 8 μm/s. The interface morphology without ECP treatment is cellular crystal growth. When ECP is applied, the cellular spacing decreases and the cellular tip is bifurcated.

Without ECP treatment, the microstructure is cellular–dendritic crystal with 14 μm/s pulling rate, as shown in Fig. 3(c). With the increase of ECP current density, the cellular spacing decreases, and microstructure changes from cellular–dendritic to cellular crystal. When the current density is 5.57×10^3 A/cm^2, the microstructure becomes regular cellular.

According to Fig. 3(d), when the pulling rate is 96 μm/s, the microstructure without ECP treatment is the typical dendritic crystal with developed secondary dendritic crystal. With the increase of the current density, the developed secondary dendritic crystal gradually disappears. The dendritic crystal changes into cellular crystal when the current density is 5.57×10^3 A/cm^2.

The experiment results show that the pulse current can improve the stability of the solid–liquid interface morphology at different growth rates. The transition condition from planar to dendritic growth is summarized in Fig. 4. As it is shown, ECP makes the transition growth rate increase. Particularly, the transition growth rate from cellular to dendritic crystal interface increases remarkably.

3.2. Cellular spacing

According to our experimental results, the ECP has great influences on the cellular spacing. The spacing decreases gradually with the increase of the pulse current density. The cellular spacing decreases through the bifurcation of the cellular tip at different growth rates. Fig. 5 shows the dependence of the primary dendritic arm spacing on the current density with the pulling rates 8 and 14 μm/s.

3.3. Mushy zone depth

As shown in Fig. 3, the mushy zone depth decreases gradually with the increase of the current density. Fig. 6 shows the dependence of the mushy zone depth on the current density with the pulling rate of 14 μm/s. This short mushy zone is an important feature of the interface transformation from cellular to planar and from dendritic to cellular.

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