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Twinned dendrite growth during Bridgman solidification

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ABSTRACT

Twinned dendrites were successfully produced with high reproducibility in Al–4.5 wt.% Cu alloys at various growth speeds (V) of 100, 200, 500, 1000, 1500 and 2000 μm s^{-1} during Bridgman solidification. Under a relatively high thermal gradient (G, around 200 K cm^{-1}), the growth speed condition necessary for the twinned dendrite growth has been broadened. Experimental results indicate that the increase in growth speed has substantially changed the twinned morphologies. Importantly, the isolated twinned dendrite growth was observed at the growth speeds less than 1 mm s^{-1} (100, 200, and 500 μm s^{-1}). At higher growth speeds, the finer twinned dendrites developed the usual appearance of an ordered sequence of alternating twinned and untwinned lamellae. The G/V value is considered as the critical factor for the isolated or usual twinned dendrite growth. A detailed analysis of the melt flow confirms that the slight convection during Bridgman solidification is large enough for the twinned dendrite growth. Furthermore, a visualized way to evaluate the velocity of the in-plane twinned extension was provided and the extension velocity was typically one third of the growth speed (500 μm s^{-1}). Based on frequent "penetration" growth phenomena among secondary arms, a possible lateral propagation mechanism of the twinned dendrites has been hypothesized.

1. Introduction

Twinned dendrite growth was observed for the first time in semi-continuous casting of industrial aluminum alloys more than 60 years ago [1–3]. Using electron backscattered diffraction (EBSD) analysis technique, crystallographic characteristics of the twinned dendrites have been largely confirmed [4–8]: unlike usual ⟨100⟩ axes of cubic metals, the twinned dendrite trunks always grow along ⟨110⟩ directions and are split in their centers by a straight coherent (111) twin plane. Secondary dendrite arms grow primarily along ⟨110⟩, and also sometimes ⟨100⟩ directions, and their impingement of the two neighboring dendrites creates wavy incoherent twin boundaries. Thus, the so-called feathery grains, each consisting of a sequence of twinned columnar dendrites, exhibit the alternant twinned and untwinned lamellae morphology.

It is known that the twinned dendrites have growth advantage over regular columnar dendrites under the same solidification conditions [7]. The morphology of the twinned dendrite tip and then the tip undercooling are supposed to be associated with this favorable growth kinetics [9–11]. Considering the energy of the twin plane, a paraboloid needle shape typically observed for regular dendrites, may not be applicable to the twinned dendrites. Three conjectures have been put forward: a grooved tip [12], an edgy tip [13], and a doublon tip [14]. Among them, the doublon-type dendrite tip with a thin liquid channel in the trunk center proposed by Henry et al. [14] has been strongly supported by several recent phase-field simulations and scanning transmission electron microscopy (STEM) analysis, using a focused ion beam (FIB) technique [10,11]. However, the detailed mechanism of the preponderant twinned growth is not entirely clear. While the easy extension of twinned dendrites along their twin planes can be attributed to regular dendrite branching [15,16], there is still some uncertainty about their lateral propagation mechanism, perpendicular to the twin planes.

Numerous studies [4–7,10,14–16] focus on the analyses and characterization of the twinned dendrite growth appearing in a direct-chill (DC) casting or similar solidification processes. The twinned dendrite growth during these processes is believed to occur when the following solidification conditions are met: (i) a relatively high thermal gradient (typically 100 K cm^{-1}); (ii) a large growth speed (typically 1 mm s^{-1}); (iii) the presence of convection in the melt [7,17]. However, it should be noted that during the above-mentioned casting processes, the growth speed and the thermal gradient are coupled and both of them decrease as the distance from the chill plate increases [18]. On the other hand, the Bridgman directional solidification technique can provide a steady-state solidification condition. The thermal gradient

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at the interface G and the growth speed of the solid V can be separately controlled so that the effect of each experimental variable on the microstructural evolution can be precisely characterized [18–20]. Under well-controlled conditions, it is also practical to quench the dendrite growth morphology during steady-state growth. This technique, a very efficient method to study fundamental relations between the microstructures and the processing variables, was previously considered inefficient to produce twinned dendrites for the slight melt convection in small crucibles [16,18]. Nevertheless, in this work, twinned dendrites were successfully produced with high reproducibility in Al–4.5 wt.% Cu alloys using an improved Bridgman vertical vacuum furnace described in the next section. This paper provides the experimental results and detailed investigations on the growth behavior of the twinned dendrites during the Bridgman solidification.

2. Experimental procedure

Cast ingots of Al–4.5 wt.% Cu alloy were prepared with high purity Al (99.99 wt.%) and Cu (99.99 wt.%) in a vacuum induction furnace under argon atmosphere. Heated to about 900 °C in a high-purity graphite crucible, the alloy melt was cast into a copper mold. Samples with diameter of 6.9 mm and length of 110 mm were machined from the as-cast ingots. Inserted into a high-purity alumina crucible (inner diameter 7 mm and length 115 mm), the samples were directionally solidified in an improved Bridgman vertical vacuum furnace as shown in Fig. 1. The water cooled cylinder containing liquid Ga-25 wt.% In-13 wt.% Sn metal was used for high heat extraction rates. By adjusting the hot zone temperature and the thickness of thermal insulation baffle, the thermal gradient G in the mushy zone was improved within a relatively high scope (see Table 1) in comparison with the previous reports [5–7,15,21]. After being heated up to 800 °C at a controlled rate and thermally held for 20 min, the samples were pulled downwards into liquid metal bath at various speeds (10, 20, 50, 100, 200, 500, 1000, 1500 and 2000 $\mu m\ s^{-1}$). When the solidification distance reached about 70 mm, quenching experiments were performed to obtain the morphology of the solid/liquid (S/L) interface. Each experiment was repeated three times to improve its reliability. The frequency of the twinned dendrite growth and the corresponding solidification parameters are shown in Table 1.

Table 1
Frequency of twinned growth at various growth speeds and corresponding solidification parameters.

Frequency of twinned growth	V ($\mu m\ s^{-1}$)	G ($K\ cm^{-1}$)	$G{\cdot}V$ ($K\ s^{-1}$)	G/V
0/3	10	227	0.227	2.27×10^5
0/3	20	225	0.225	2.25×10^5
0/3	50	213	1.065	4.26×10^4
3/3	100	199	1.99	1.99×10^4
2/3	200	197	3.94	9.85×10^3
3/3	500	191	9.55	3.82×10^3
3/3	1000	179	17.9	1.97×10^3
2/3	1500	172	25.8	1.15×10^3
3/3	2000	163	32.6	8.15×10^2

The directionally solidified samples were sectioned longitudinally and transversely to the thermal gradient. After mechanical polishing, both sections were etched with a diluted Keller solution (1 ml HF, 3 ml HNO_3, and 46 ml H_2O) to reveal the microstructure. An Olympus TG-3 optical microscope was employed for metallographic examination. For EBSD analysis, the samples containing twinned dendrites were polished again to mirror quality and then electrochemically etched to remove the deformed surface layers. EBSD measurements were performed using a Tescan Mira 3 FEG SEM enhanced with an Oxford HKL Nordly Max EBSD system. The HKL Channel 5 software was used for EBSD data acquisition and post processing.

3. Results

3.1. Metallographic microstructures and detailed EBSD analyses

Fig. 2 shows the longitudinal microstructures in directionally solidified Al–4.5 wt.% Cu alloy at the growth speeds of 50, 100, 200, 500, 1000, 1500 and 2000 $\mu m\ s^{-1}$. It exhibits regions where regular columnar and twinned dendrites are fully developed (typically between 40 and 70 mm from the bottom of the samples). For clarity, the regions of regular columnar and twinned dendrite

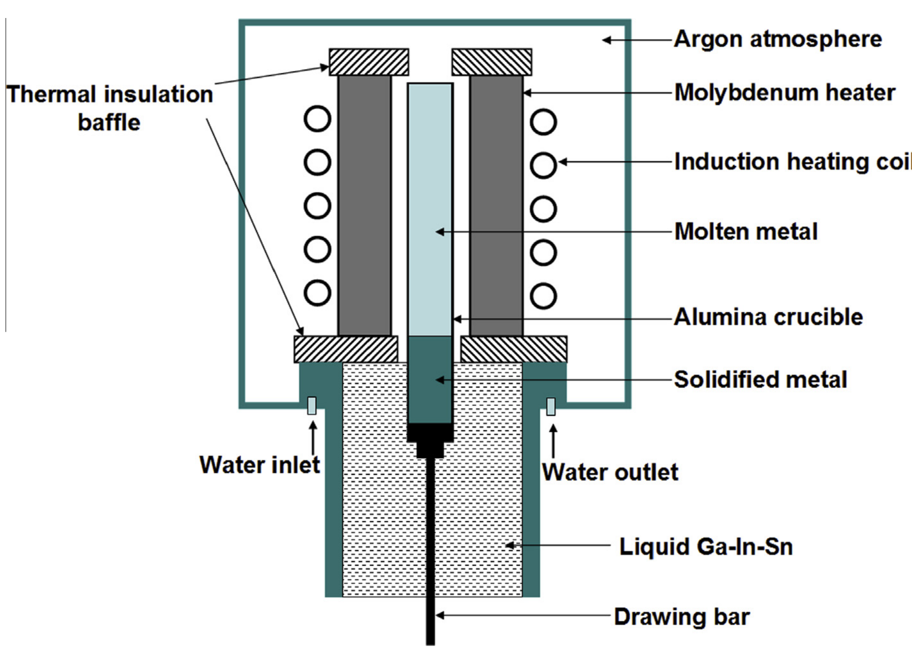

Fig. 1. Schematic of the Bridgman solidification furnace used in the present work.