Journal of Crystal Growth 439 (2016) 66–73

Contents lists available at ScienceDirect

Journal of Crystal Growth

journal homepage: www.elsevier.com/locate/jcrysgro

Effect of interdendritic thermoelectric magnetic convection on evolution of tertiary dendrite during directional solidification

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ARTICLE INFO

Article history:
Received 21 March 2015
Received in revised form
2 November 2015
Accepted 23 December 2015
Communicated by M. Plapp
Available online 13 January 2016

Keywords:
A1. High static magnetic field
A1. Magnetohydrodynamics
A2. Aluminum alloy
A2. Directional solidification
B1. Dendritic morphology

ABSTRACT

The Al-4.5 wt%Cu alloy has been directionally solidified under a high static magnetic field up to 6 T. A novel α-Al dendrite morphology was presented when the < 001 > primary trunk aligned to the magnetic field and temperature gradient. It is observed that tertiary dendrites grew asymmetrically on secondary arms in the plane perpendicular to the primary trunk, and a pinwheel-like pattern formed. A numerical simulation was performed using finite-element code COMSOL software to investigate the thermoelectric magnetic convection (TEMC) induced by the external magnetic field. The results show that the velocity of the TEMC increases with the increasing of the magnetic field and reaches a maximum value near 6 T. Meanwhile, the magnitude of the TEMC on two sides of the secondary arm becomes unequal. Comparison of the experimental and numerical results reveals that the development of the pinwheel-like appearance is in accordance with the flow pattern of the TEMC. It is implies that the modification of the tertiary dendrite could be attributed to the TEMC generated on dendrite scale. This work also provides direct experimental evidence that a high magnetic field (> 1 T) induces fluid flow in mushy zone.

1. Introduction

The columnar dendrite network formed during directional solidification usually consists of primary trunks and well-developed secondary arms and tertiary branches [1]. The morphology of the tertiary dendritic branches has notable effect on the geometry feature of the interdendritic region which dominates the occurrence of casting defects [2]. As a result, it is essential to understand and manipulate the evolution behavior of the tertiary dendrite branches in order to further improve casting qualities. Grugel [3] studied the relationship between solidification parameters and the tertiary arm spacing; Garcia and Spinelli et al. [4–7] characterized the microstructure of tertiary dendrite during transient solidification; Franke et al. [8] modeled the tertiary dendritic instability in the late stage solidification of Ni-based superalloys. However, there is still a lack of approaches to control the growth of the tertiary dendrite branches, especially in the direction perpendicular to the primary dendrite trunk.

It has been accepted that fluid flow plays a critical role in mass and heat transfer during solidification and thus altering the evolution of microstructure. Various types of magnetic fields have been introduced as an effective way to govern the convections in crystal growth processes [9]. Conventionally, a static magnetic field is being exploited to damp the convections in bulk liquid in semiconductor industry. However, the application of the static magnetic field during directional solidification of metallic alloys will gives rise to melt motion, which is called thermoelectric magnetic convection (TEMC) [10]. The flow pattern of TEMC greatly relies on the fashion of the advancing solid–liquid front (i.e., planar or cellular or dendritic interface). The effect of TEMC on planar interface shape [11], cellular arrangement [12], and freckle formation [13–15] have been observed. If the alloy solidifies in a dendritic way, the TEMC is on the scale of several hundreds of micrometers and flows around each individual columnar dendrite [16]. Since the higher-order dendrites develop in the mushy zone, the interdendritic TEMC could lead to morphological change of the tertiary dendrite branches.

The aim of this work is to investigate the effect of TEMC on the evolution of tertiary dendrite branches. The Al-4.5 wt%Cu alloy samples grown from < 100 > oriented seed crystals were directionally solidified under a static magnetic field. Microstructure was examined to characterize the morphological modification. On the other hand, a numerical simulation was performed to reveal the

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http://dx.doi.org/10.1016/j.jcrysgro.2015.12.029
0022-0248/

flow features of the interdendritic TEMC. The relationship between the TEMC and the solidified microstructure was discussed.

2. Experimental

2.1. Experimental procedure

The nominal Al-4.5 wt%Cu alloy was prepared from 99.999 wt% purity Aluminum and 99.99 wt% purity Copper. Appropriate amounts of the pure metals were melted in a resistant furnace under the protection of high purity argon. The melted alloy was casted into a graphite mold to form an ingot with the diameter of 100 mm and the height of 150 mm. The composition of the as-cast ingot was determined by chemical analysis. Then, specimens with a diameter of 3 mm were cut along the ingot using electro-discharge machining. After polishing and cleaning, the specimens were inserted into alumina tubes for directional solidification.

The experimental apparatus is schematically shown in Fig. 1. The Bridgman-type directional solidification assembles are placed into a superconducting magnet. The hot region of the furnace is heated by a cylindrical silicon carbide tube in which a DC current flows. The liquid Ga–In–Sn alloy is used as cooling media and contained in a water-cooling chamber. The temperature gradient in the specimen is controlled by adjusting the temperature of the furnace (Fig. 2). Directional solidification was carried out by pulling the specimen downward. All specimens were directionally solidified without magnetic field at first. The axial orientation near the end of solidified specimen (Fig. 3) was examined. If the dendrite array was the <001> crystallographic direction, the specimen was selected as a seed. Then, the seed was placed into the alumina tube and directional solidified under magnetic field. The

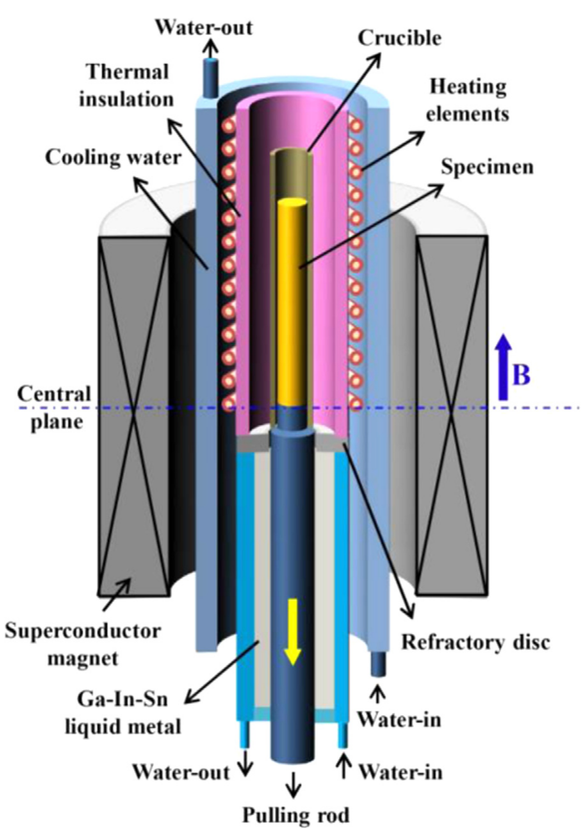

Fig. 1. Schematic illustration of the Bridgman-type directional solidification apparatus in a superconducting magnetic field.

pulling speed was kept at 50 μm s^{-1} and the temperature gradient was set to 27 K cm^{-1}. After required length solidified, quenching was carried out by quickly withdrawing the specimen into the liquid Ga–In–Sn alloy (Fig. 4).

The transverse and longitudinal sections of the solidified specimens were mechanically ground and electro-polished. The transverse sections were cut at 10 mm in the mushy zone from the quenched mush/liquid front. The morphology of the dendrites was examined by back-scattering SEM images (BSE) and optical microscope (OM). Electron back-scattering diffraction (EBSD) measurements were also carried out using an Apollo 300 SEM microscope equipped with an Oxford Nordlys detector. The recording and indexing of the pseudo-Kikuchi lines was performed by the software Channel5 from HKL Technology.

2.2. Numerical simulation

The numerical calculation of TEMC is carried out by using the commercial finite element software COMSOL Multiphysics. The mode is a three-dimensional cylinder with the height of 250 μm and diameter of 100 μm. The solid domain is a simplified dendrite and the rest is liquid. The geometrical feature of the dendrite is analogous to the tip region of the columnar dendrite observed in experiment, where the dendrite branch is developing. The shape of the primary trunk is a paraboloid of revolution and the side arms are represented as cylinders (see Fig. 6). Hot and cold temperatures are imposed on the top and bottom planes of the cylinder to generate the temperature gradient. The absolute Seebeck coefficients and electric conductivities in the solid and liquid domains are set to be different. Since the alloy charge in the alumina crucible is contact with the pedestal of the stainless steel pulling rod (see Fig. 1), the bottom surface of the cylinder is set to be zero electric potential. Adiabatic boundary conditions were given on the sidewall of the cylinder. No-slip boundary condition is applied on all surfaces of the domains and the melt is initially stationary.

The electric current is described by Ohm's Law. The contribution of liquid motion and Seebeck effect is included and expresses as:

$$\vec{J} = \sigma \vec{E} + \vec{u} \times \vec{B} - S \bullet \nabla T \tag{1}$$

where $\vec{J}$ is the electric current density in liquid phase, $\vec{B}$ is the magnetic field flux intensity, σ is the electric conductivity, S is the absolute thermoelectric coefficient of the conducting medium, ∇T is the temperature gradient and $\vec{u}$ is the velocity of the fluid flow. The electrical field E is negligible in calculation because the highly conducting solid and liquid phases in mushy zone act as an electrical short circuit in directional solidification. The Lorentz force in liquid is generated by the interaction of the current and magnetic field:

$$\vec{F} = \vec{J} \times \vec{B} \tag{2}$$

The Navier–Stokes equation for laminar flow in this case can be written as:

$$\frac{\partial(\rho \vec{u})}{\partial t} + \rho\left(\vec{u} \bullet \nabla \vec{u}\right) = -\nabla p + \mu \nabla^2 \vec{u} + \vec{F} \tag{3}$$

where μ is the dynamic viscosity of the liquid. Substituting the body force term $\vec{F}$ in Eq. (3) by the Lorentz force, we get:

$$\frac{\partial(\rho \vec{u})}{\partial t} + \rho\left(\vec{u} \bullet \nabla \vec{u}\right) = -\nabla p + \mu \nabla^2 \vec{u} + \sigma \vec{E} \times B - \sigma S \bullet \nabla T \times \vec{B} + \sigma(\vec{u} \times \vec{B}) \times \vec{B} \tag{4}$$