The transition mode of dilute binary alloys during directional solidification near to the absolute stability limit

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Abstract

The morphological evolution near the absolute stability limit during directional solidification has been studied systematically on dilute Al–Mn alloys. It is found that the interfacial morphology of Al–0.52wt%Mn and Al–1.2wt%Mn alloys changes from coarse cellular structure to fine cells, and then again to be coarsened with the increase of velocity to near the absolute stability limit. This indicates that there exists a minimum cell spacing corresponding to the maximum effective constitutional supercooling. As the growth rate approximates to or exceeds the critical velocity of absolute stability by calculation according to M–S theory, the interfacial morphology of Al–0.52wt%Mn alloy may still retain a cellular structure. For Al–1.2wt%Mn alloy, when the growth velocity is near the absolute stability limit, the fine cells may change to a band or grain-like structure which in some cases takes an oscillating manner, which possibly implies the existence of a non-linear effect during high growth rate. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Near absolute stability limit; Band structure; Oscillatory structure

1. Introduction

The phenomena of directional solidification growth at low and intermediate growth rates are well understood [1–4]. On the other hand, there is a lack of precise and extensive experimental research results in the region of growth rate close to the absolute stability limit, because it is very difficult to achieve steady-state unidirectional heat flow at high growth rate.

It is indicated that the near rapid directional solidification rate is around $10^{-4} - 10^{-1}$ m/s a $G_1 = 100$ K/cm. In the region between near-equilibrium slow growth rate and rapid solidification rate beyond the equilibrium condition, there may occur by a series of transition effects of interface stability and morphologies [5,6]. With the increase of growth velocity, the interface morphology evolves from initial planar front to cells and dendrites at the stage of near-equilibrium, and with further increase of growth rate they transform reversely from dendrites to cellular structure and then to absolute stability of planar front at non-equilibrium.

In the present work, the morphological evolution during directional solidification near the absolute stability limit on dilute binary alloys in Bridgman-type growth has been systematically studied.

2. Experimental results

Using self-made Bridgman type apparatus, a thermal gradient can be obtained as high as 300 K/cm. Proper alloys were selected for the experiments, if their absolute stability limits ($V_{ab}$) by calculation according to M–S theory were lower than or near to $10^3$ μm/s, which was to be considered as the maximum with the present experimental apparatus. Therefore, Al–0.52wt%Mn and Al–1.2wt%Mn alloys were used that had a calculated $V_{ab}$ equal to 5300 and 12,220 μm/s, respectively. The range of pulling rate was from 50 to 10,000 μm/s in the experiments.

The main experimental results are given as follows:

1. In directionally solidified microstructures of both Al–0.52wt%Mn and Al–1.2wt%Mn alloys, with the increase of growth velocity to the near absolute stability limit by calculation according to M–S theory the cellular spacing changes from coarse cells to fine cells and then again to a coarse cellular structure. The typical morphological evolution of Al–0.52wt%Mn is shown Fig. 1. The main features are: (1) at various velocities the microstructures are all columnar cellular structure; (2) when the growth rate is lower than 600 μm/s, the interfacial morphology appears to be coarse cellular structure; (3) as the growth rate increases from 600 to 3000 μm/s the cells become finer, and the cellular spacing is decreased with the
increase of growth velocity; (4) when the growth rate is over 3000 μm/s a coarsening tendency of fine cells is found. The change of the average spacing of the cells from coarse to fine and to coarse again shows that there should exist a minimum of cell spacing. The minimum spacing is approximate to 10 μm, which is relevant to a transition rate $V_t$ is about 3000 μm/s.

2. For Al–1.2wt%Mn alloy when the growth rate approaches 5000 μm/s, perturbation could cause the cellular structure abruptly to transform to bands composed of fine cells and coarse cells (shown in Fig. 2(a) and (b), or to a periodic structure composed of fine cells, and grain-like and fine cells (shown in Fig. 3(a) and (b)).

For Al–0.52wt%Mn alloy, an oscillating structure is not observed.

3. Discussion and conclusions

The occurrence of the finest cellular structure for both Al–0.52wt%Mn and Al–1.2wt%Mn alloys corresponds quite well with the predictions by Hunt–Lu’s numerical model [7] (shown in Fig. 4) and KGT’s model [8] (shown in Fig. 5). The phenomena of cell spacing from coarse to fine and then to coarse with the increase of the growth rate are relevant to the change of effective constitutional supercooling [9] from small to large and then to small (shown in Fig. 5). Fig. 5 indicates that the maximum effective constitutional supercooling corresponds to the minimum cells spacing or cellular tip radius. It should be noted that the corresponding velocity of the transition of cell spacing from coarse to fine and then to coarse is just located at half of the critical velocity $V_{ct}$ of absolute stability calculated by

![Fig. 1. Typical morphological evolution of Al–0.52wt%Mn: (a) $V = 50 $ μm/s; (b) $V = 600 $ μm/s; (c) $V = 1000 $ μm/s; (d) $V = 3000 $ μm/s; (e) $V = 5000 $ μm/s; (f) $V = 8000 $ μm/s.](image1)

![Fig. 2. Bands with different scales of cell arrays in Al–1.2wt%Mn.](image2)
M–S theory. Figs. 4 and 5 show that changes in microstructure in the prediction of Hunt–Lu’s model KGT’s model are in reasonable agreement with the experimental data except for the growth rates around the absolute stability limit calculated by M–S theory. As the growth rate is near to the critical absolute stability velocity, it must be considered that deep cells may keep their cellular structure.

In Fig. 2(a) and (b) the band structure Al–1.2wt%Mn obtained with Bridgman type apparatus is explicitly different from the banded morphologies of other alloys with electron beam or laser treatment [5,10].

Coriell and Sekerka [11] showed that the main reason for forming high rate bands is ‘solute trapping’ of non-equilibrium effects at the interface. Karma and Sarkissian [12] noted that band spacing is

\[ A = K(l_T/l_c), \]

where \( l_T \) is the thermal length, \( l_c \) the solute diffusion length and \( K \) is a constant of order unity. For typical alloys the band spacing is under 1μm.

In the present experiments, the high rate band spacing in Bridgman-type growth is as large as about 100 μm. The feature of that band structure cannot be explained by the theory of linear perturbation at an initial planar interface. This indicates that large band spacing at high rate is not only related to solute trapping of non-equilibrium effects, but also it is related to non-linear effects, i.e. to strong fluctuations at an initial non-planar interface.

In Al–1.2wt%Mn alloys during directional solidification near to the absolute stability limit, the typical high velocity bands and grain-like structure are observed which that possibly implies the existence of a non-linear effect during high growth rate.

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