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Primary cellular/dendritic spacing selection of Al-4.95%Zn alloy under near-rapid directional solidification condition①

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Abstract Al-4.95%Zn alloy is directionally solidified in a modified Bridgman apparatus with higher temperature gradient to investigate response of cellular/dendritic microstructures and primary spacing to the variation of growth velocity under near-rapid directional solidification condition. The results show that, with increasing growth rate, there exists a transition from dendrite to fine cell and a wide distribution range in primary cellular/dendritic spacing at the given temperature gradient. The maximum, $\lambda_{\max}$, minimum, $\lambda_{\min}$, and average primary spacing, $\bar{\lambda}$, as functions of growth velocity, v, can be given by $\lambda_{\max} = 12\,340\, v^{-0.8353}$, $\lambda_{\min} = 2\,953.7\, v^{-0.7717}$, $\bar{\lambda} = 7\,820.3\, v^{-0.8333}$, respectively.

Key words: Al-4.95%Zn alloy; near-rapid directional solidification; cellular/dendritic microstructures; primary spacing

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1 INTRODUCTION

In directional solidification of a single-phase alloy the microstructures formed when growth velocity is increased are planar, cellular, dendritic. With further increasing velocity, the dendritic structure transforms again to cellular, banded and then to a planar structure[1]. Cellular/dendritic spacing, as one of the most important solidification microstructure scales, is of critical significance to the study of solidification theory and control of microstructures. Recently, there have been a lot of theoretical and experimental researches[2,3] on the selection of cellular/dendritic microstructures and primary spacing at low growth velocity under constrained crystal growth condition, in which cooling rate is smaller than 1 K/s. Moreover, with the application of electron beam and laser surface remelting and solidification to the theoretical researches on rapid solidification whose cooling rate is larger than 1 000 K/s in recent years, some advances[4,5] have also been made in experimental investigations on the selection of microstructures and primary cellular/dendritic spacing at high growth velocity. To date, however, within the growth range from dendrite at low growth rate to super fine cell at high growth velocity, namely near-rapid directional solidification condition whose cooling rate is within 1 ~ 1 000 K/s, there have been few experiments on the cellular/dendritic microstructures and primary spacing selection. The main reason is that there is the lack of the directional solidification apparatus with high temperature gradient which maintains unidirectional thermal current and ensures directional growth of the alloy under far away from equilibrium condition and the effective alloy to be solidified. In the light of the analysis of the absolute velocity[6] ($v_{ab} = \Delta T_0 D_L / \Gamma K_0$, where ΔT_0, D_L, Γ and K_0 are the equilibrium freezing range of the alloy, the solute diffusion coefficient in the liquid, the Gibbs-Thomson coefficient and

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the solute distribution coefficient, respectively), the Al-4.95% Zn alloy with the relatively narrow equilibrium freezing range is directionally solidified in a modified Bridgman apparatus to investigate the response of cellular/dendritic microstructures and primary spacing to the variation of growth velocity, which is of theoretic and practical importance to setting up a model of microstructures and characteristic lengths between low and high growth velocity of absolute stability.

2 EXPERIMENTAL METHODS

Al-4.95%Zn alloy was produced by melting together 99.999%Al and 99.99%Zn in a high purity graphite crucible in a vacuum induction furnace and then the molten alloy was poured into a high purity graphite mold. The specimens for directionally solidifying in a Bridgman apparatus with 145 K/cm temperature gradient were made by cold drawing these ingots into thin rods of 5 mm in diameter and 120 mm in length. By taking the transverse section of the directionally solidified specimens, the primary cellular/dendritic spacings and their distribution range were measured by a Cambridge Quantiment 500 Image Processing and Analysis System.

3 RESULTS AND DISCUSSION

3.1 Dendrite-cell transition

Fig.1 shows the variation of typical microstructures of Al-4.95%Zn alloy on the transverse section with increasing growth velocity v within 100 ~ 3000 μm/s at $G = 145$ K/cm. It is found that there exists a microstructure transition process, namely from dendrites to cells within the entire growth velocity range. At low growth velocity, the dendrites are coarse (see

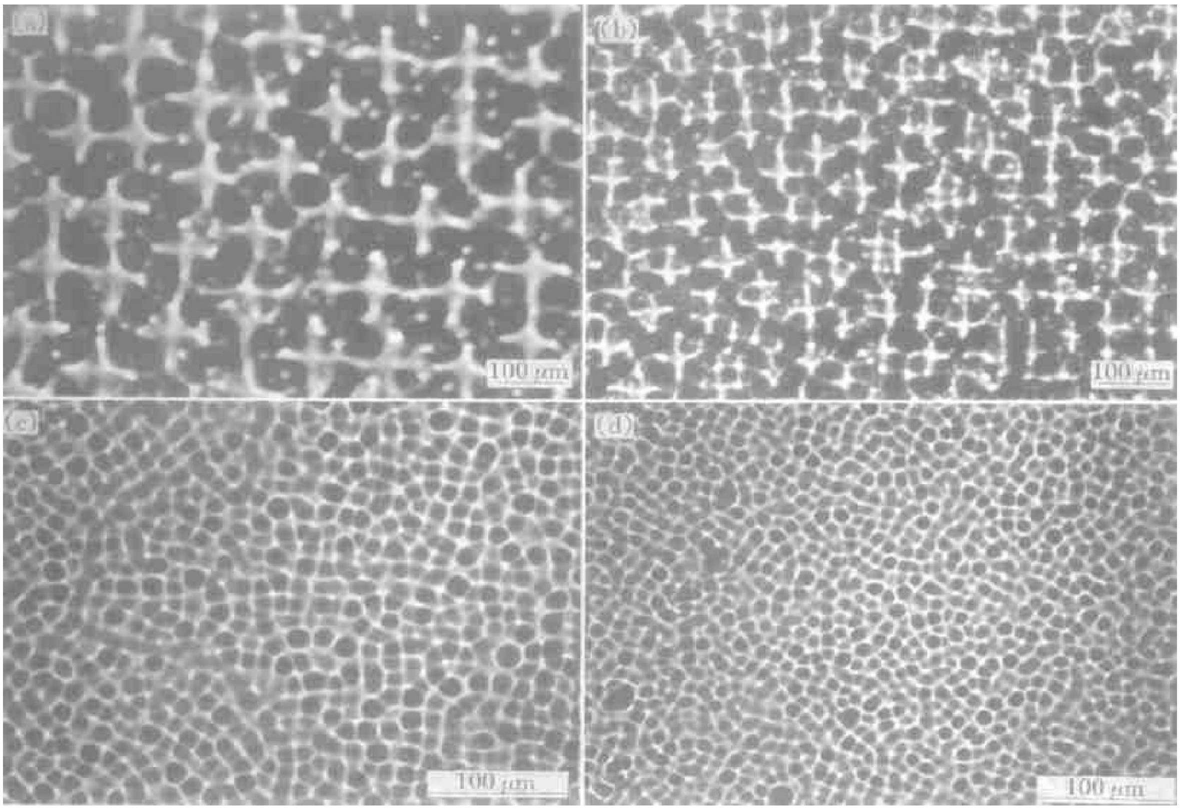

Fig.1 Typical microstructures of Al-4.95%Zn alloy at $G = 145$ K/cm
(a) — $v = 238$ μm/s; (b) — $v = 500$ μm/s; (c) — $v = 1\,500$ μm/s; (d) — $v = 2\,500$ μm/s

Fig.1(a)). With the increase of growth velocity, the dendritic spacing trends to decrease (see Fig.1(b)). At high growth velocity, the fine cells are obtained, as shown in Fig.1(c) and (d). The experimentally determined growth velocity of dendrite-cell transition is within 600 ~ 700 μm/s.

In directional solidification of a given alloy, the solute diffusion, thermal diffusion and capillary effect have a critical influence on the microstructure transition and the characteristic lengths[1]. The influence of these processes occurs over certain characteristic lengths, which are defined as follows.

The solute diffusion length l_D

$$l_D = D_L / v \qquad (1)$$

The thermal diffusion length l_T

$$l_T = \Delta T_0^v / G \qquad (2)$$

and the capillary length d_0

$$d_0 = \Gamma / \Delta T_0^v \qquad (3)$$

where $\Delta T_0^v = m_v C_0 (K_v - 1) / K_v$, in which C_0 is the bulk alloy concentration, m_v and k_v are the effective liquidus slope and effective solute distribution coefficient by taking into considerating the non-equilibrium effect at high velocity, respectively.

Cellular structures become stable at low and at high growth velocity as has been shown by the numerical analysis of Lu and Hunt[7]. The relative magnitudes of the thermal diffusion (stability) and solute diffusion (instability) at low growth velocity, and the relative magnitudes of the capillary effects (stability) and solute diffusion at high growth velocity govern the cellular structure formation. By taking into considerating the competition between the solute diffusion and capillary effects, Trivedi and Kurz have given the condition for dendrite-cell transition at high growth velocity in a simple expression

$$l_D = a d_0 \qquad (4)$$

where a is a constant. Substituting the values of l_D and d_0 from Eqns.(1), (3) to (4), gives

$$v = D_L \Delta T_0^v / a\Gamma \qquad (5)$$

For the significant influence of the non-equilibrium and nonlinear effects on the microstructures at high growth velocities, it is too difficult to precisely determine the value of a by the theoretic analysis. However, the experimentally determined growth velocity of dendrite-cell transition for Al-4.95%Zn alloy is fairly low and non-equilibrium effects of m_v and k_v are not too obvious, so assumes $\Delta T_0^v = \Delta T_0$. The obtained constant a of Eqn.5 is within 553.6 ~ 645.9 by substituting v of Eqn.5 with the growth velocity of 600 ~ 700 μm/s. The thermophysical parameters used for calculation are listed in Table 1.

Table 1 Thermophysical parameters of Al-4.95%Zn alloy[8]

Property	Symbol	Unit	Value
Gibbs-Thomson coefficient	Γ	cm·K	1.20E-5
Slope of liquidus line	m	K/%	1.72
Distribution coefficient	k_0		0.44
Diffusion coefficient (liq.)	D_L	cm^2/s	4.76E-5

3.2 Selection of cellular/dendritic spacing

Table 2 gives the measurement results of cellular/dendritic spacing obtained at G = 145 K/cm, where λ_{max}, λ_{min} and $\bar{\lambda}$ are maximum, minimum and average primary spacing, respectively. It can be seen from Fig.2, which is plotted from the data in Table 1, that there exists a large distribution range in cellular/dendritic spacing with the variation of growth velocity from 100 μm/s to 3 000 μm/s. The ratio of maximum spacing to the minimum value, as a function of growth rate, varies between 2.19 and 3.85. At low

Table 2 Experimental data of primary cellular/dendritic spacing for Al-4.95%Zn alloy at G = 145 K/cm

v/(μm·s^{-1})	λ_{max}/μm	λ_{min}/μm	$\bar{\lambda}$/μm	$\lambda_{max}/\lambda_{min}$
100	218.20	74.50	139.23	2.93
150	195.52	66.01	134.25	2.96
200	171.37	52.68	114.26	3.25
238	143.71	65.53	100.07	2.19
500	83.22	21.57	42.43	3.86
600	66.47	17.99	39.96	3.69
750	38.05	12.85	23.20	2.96
1 000	28.07	12.51	18.44	2.24
1 500	25.78	11.63	17.37	2.22
2 000	22.04	8.57	14.21	2.57
2 500	18.75	7.92	13.07	2.37
3 000	17.51	6.70	11.38	2.61

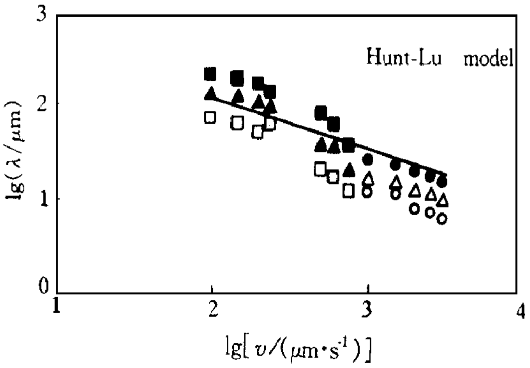

Fig.2 Selection of primary cellular/ dendritic spacing as a function of growth velocity for Al-4.95 %Zn alloy at $G = 145$ K/cm
● — Maximum cellular spacing;
■ — Maximum dendritic spacing;
○ — Minimum cellular spacing;
□ — Minimum dendritic spacing;
△ — Average cellular spacing;
▲ — Average dendritic spacing

growth velocity, the coarse dendrites are obtained. However, with further increasing growth velocity, the fine dendrites and fine cells are observed. The primary cellular/ dendritic spacing decrease with increasing growth velocity. Through regression analysis, the results obtained are as follows

$$\lambda_{\max} = 12\,340\ v^{-0.8353} \tag{6}$$

$$\lambda_{\min} = 2\,953.7\ v^{-0.7717} \tag{7}$$

$$\bar{\lambda} = 7\,820.3\ v^{-0.8333} \tag{8}$$

From Eqn.8, the above experimental results of average cellular/ dendritic spacing for Al-4.95 %Zn alloy at high growth velocity is in poor agreement with the relationship between the dendrite average primary spacing and the growth velocity ($\bar{\lambda} \propto K G^{-\frac{1}{2}} v^{-\frac{1}{4}}$, where K is a constant) predicated by Kurz *et al*[9] and Hunt[11] at low growth velocity.

Recently, Hunt and Lu[11] gave the analytical expressions, which fit the numerical results of the lower limit of stable primary cellular/ dendritic spacing given by their previous numerical model. The variation in primary cellular/ dendritic spacing with growth velocity given by Hunt-Lu model is also shown in Fig.2. The thermophysical parameters used for the calculation are given in Table 1. The experimental results are in good agreement with the Hunt-Lu model.

4 CONCLUSION

There exist a dendrite-cell transition and a large distribution range in primary spacing for Al-4.95 %Zn under near-rapid directional solidification condition. The critical growth velocity of dendrite-cell transition is within 600 ~ 700 μm/s. In the light of the above experimental result on dendrite-cell transition, it is deduced that the constant a of dendrite-cell transition model proposed by Trivedi and Kurz is within 553.9 ~ 645.9. With the increase of growth rate, the maximum, minimum and average primary spacing tend to decrease.

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