MODEL FOR COARSENING OF SDAS AND ITS VERIFICATION IN MULTICOMPONENT SC SUPERALLOYS①

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ABSTRACT

Based on a general relationship of secondary dendrite arm spacing (SDAS) λ_2 to solidification time t: $\lambda_2^3 = k_0 t$, a dependence of λ_2 on thermal gradient and solidification rate has been presented by assumption of paraboloidal dendrite tip. With the model, secondary dendrite arm spacings predicted for multicomponent superalloy DD8 and PWA-1480 were in conformity with experimental data.

Key words: secondary dendrite arm spacing directional solidification SC superalloy

1 INTRODUCTION

The formation of sidebranchs is a result of an intrinsic morphological instability of a needle dendrite[1]. Dendrite arm coarsening would occur during solidification due to its thermodynamic unstability[2,3]. The coarsening of the sidebranch process depends on the solidification conditions and the composition of an alloy. In general, a reduction in surface energy provides the thermodynamic driving force for the isothermal stage of the coarsening process. The secondary arm coarsening during the solidification process is similar with the isothermal coarsening process[4]. Several models have been proposed to account for the coarsening of dendritic sidebranchs[2-4]. Most of the authors of these papers suggested the arms with large curvature would disappear by remelting and the arms with smaller curvature would grow. Both Kirkwood[5] and Mortensen[3] derived a same relationahip, $\lambda_2^3 = k_0 t$, where t is local solidification time, k_0 is a systematic constant. And the difference between the two models is only in the calculation of k_0. The explicit relationship between λ_2 and solidification conditions (such as thermal gradient G and solidified velocity V) was still unknown in these models. In fact, the local solidification time is a function of both intrinsic factors of an alloy and the solidification conditions. A relationship of V and λ_2 has been established based on the general coarsening model, $\lambda_2^3 = k_0 t$, and dendritic models of Ivantsov[6] and Kurz[7]. The purpose of this paper is to discuss the effect of G and V on λ_2 and to examine the feasibility of the relationship in a single crystal multicomponent superalloy.

2 THEORETICAL MODEL

From Kirkwood[5] model:

$$\lambda_2^3 = k_0 t \tag{1}$$

During directional solidification local solidification time is[8]:

$$t = \triangle T' / (GV) \tag{2}$$

where $\triangle T'$ is the difference between the tip temperature and nonequilibrium solidus. For the nonequilibrium solidification the constitution of the remainder of interdendrite liquid would finally reach eutectic one. Thus $\triangle T'$ is obtained by:

$$\triangle T' = T^* - T_e$$

T^* is the dendritic tip temperature, T_e is eutectic temperature. Using the tip undercooling $\triangle T^*$, the $\triangle T'$ can be written as:

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$$\triangle T' = T_L - T_e - \triangle T^* \qquad (3)$$

Model for Coarsening of SDAS and its verification T_L is liquidus temperature. The tip undercooling can be related to the solute buildup at the dendrite by the slope of the liquidus, m :

$$\triangle T^* = - m(C_l^* - C_\infty) \qquad (4)$$

where C_l^* is the concentration of the liquid ahead of a dendrite tip, C_∞ is the inital concentration of the alloy. By solution to the diffusion model presented by Ivantsov[6]: $\Omega = P \cdot \exp(P)E_1(P)$, where P is Peclet number, E_1 is the exponential integral function, Ω is supersaturation in the interfaee.

An approximation to the Ivantsov solution is taken as:

$$\Omega = 2P/(2P + 1) \qquad (5)$$

Substiuting $\Omega = (C_l^* - C_\infty)/C_l^*(1 - k)$ into eq. (5), combining (5) and (4) with $\triangle T_0 = mC_\infty(k - 1)/k$, the final result is

$$\triangle T^* = 2kP\triangle T_0 \qquad (6)$$

where k is the equilibrium solute parition coefficient. The dendritic tip radius, ρ, has obtained by Kurz-Fisher model[7], which is:

$$\rho = 2\pi\left(\frac{D\Gamma}{k\triangle T_0 V}\right)^{1/2} \qquad (7)$$

where D is the solute diffusion coefficient in the liquid, Γ is the Gibbs-Thomson coefficient. With the combination of eqs. (1) ~ (3), eq. (6), eq. (7), and $P = V\rho/(2D)$, the final result is:

$$\lambda_2^3 = \frac{u}{GV} - \frac{q}{G\sqrt{V}} \qquad (8)$$

where $u = k_0(T_L - T_e)$, $q = 2\pi k_0 \times \sqrt{k\triangle T_0 \Gamma / D}$, both are systematic constants which depend on the physical properties of the alloy.

From eq. (8) the relationship of λ_2 and V is not a single linear for their logarithmic value. There is an obvious difference between eq. (8) and the models[7,8]. Since the values of k_0, D and Γ are difficult to determine for an alloy system, especially for a multicomponent one, eq. (8) could not be used to calculate the secondary arm spacings. But it is meaningful to use eq. (8) for the analysis of the effect of solidification rates on secondary arm spacings. At a constant thermal gradient eq. (8) can be written as:

$$\lambda_2^3 = a/V - b/\sqrt{V} \qquad (9)$$

where $a = u/G$, $b = q/G$. The plot of λ_2^3 vs. V is shown in Fig. 1. The intersecting point of the curve with V axis is the upper limit of V. Since $\lambda_2 > 0$, thus:

$$V_{max} = \frac{a^2}{b^2} = \frac{(T_L - T_e)^2 D}{4\pi^2 k\triangle T_0 \Gamma} \qquad (10)$$

On the other hand, the dendritic tip undercooling must be smaller than $(T_L - T_e)$:

$$\triangle T^* < T_L - T_e \qquad (11)$$

Substituting eq. (11) into eq. (6), one can obtain:

$$V < \frac{(T_L - T_e)^2 D}{4\pi^2 k \triangle T_0 \Gamma} \qquad (12)$$

Eq. (12) and eq. (10) stand for the same meaning.

The transition velocity from cells to dendrites is[7]:

$$V_{tr} = \frac{GD}{\triangle T_0 k} \qquad (13)$$

In the regime of $V_{tr} < V < V_{max}$, the effect of V on λ_2 accords with eq. (9).

From eq. (8) the relationship of λ_2 and G, that is $\lambda_2^3 \propto G^{-1}$, can be obtained.

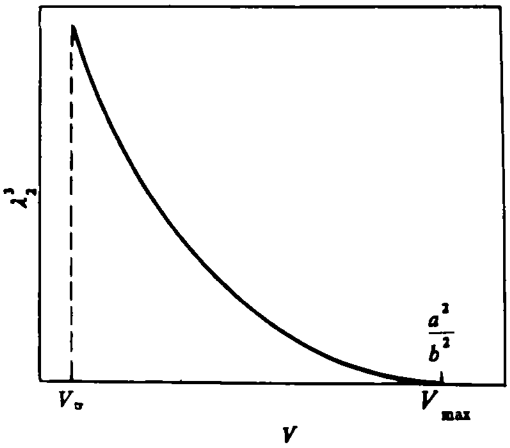

Fig. 1 Relations of λ_2^3 and V

3 RESULTS AND DISCUSSION

With seeding technique a multicomponent Ni-based single crystsal superalloy DD8 with a composition of Ni-16 Cr-8.5 Co-6.0 W-3.9 Al-3.8 Ti-1.0 Ta, C < 0.01 (in weight percent) was directionally solidified in a LMC unidirectional solidification furnace. The solidus and liquidus temperature of DD8 are 1 295 and 1 310 ℃ respectively and the equilibrium freezing range is $\triangle T_0 = 15$ ℃. The solidification conditions and secondary arm spacings are listed in Table 1. Fig. 2 shows the secondary dendrite morphologies of the superalloy DD8 under two different cooling rates.

At a constant thermal gradient, $G = 12 \sim 15$ K/mm, a relationship of the λ_2 and the V is obtained for PWA-1480 by using polynomial least-squared fit to the data listed in Table 1.

$$\lambda_2^3 = (6.9/V - 0.12/V^{-1/2}) \times 10^6 \qquad (14)$$

where λ_2 is in μm, V in μm/s.

Table 1 Secondary arm spacing measurements in DD8 and PWA-1480 at various G and V

superalloys	G /K·mm⁻¹	V / μm·s⁻¹	λ_2 / μm
DD8	25	50	40
DD8	15	50	50
DD8	6.7	83	58
DD8	6.7	17	84
DD8	6.7	125	39
DD8	6.7	167	38
PWA-1480	12	10	87
PWA-1480	12	67	46
PWA-1480	14	233	29
PWA-1480	15	233	27
PWA-1480	15	133	33

Data on PWA-1480 are from ref. [9]

Fig. 2 Secondary dendritic morphologies with different cooling rates ($\times 50$)
(a) $GV = 1.25$ K/s (b) $GV = 0.56$ K/s

Eq. (14), as shown by solid curve in Fig. 3, agrees with experimental data for PWA-1480. The deviation between the curve and some experimental data for DD8 may be due to the changes of the thermal gradients. From eq. (14) λ_2 are in different sensitivity for low and high solidification velocities V being 10 and 20 μm/s correspond to λ_2 of 87 and 68 μm respectively. The difference between the two values of the λ_2 is 19 μm. When V is 100 or 200 μm/s, λ_2 is 38 and 30 μm respectively. At low velocity λ_2 changes obviously when V has a small change. However at high velocity there is only a slight influnce of V on λ_2.

There are not enough data to make regression analysis for the effect of G on λ_2. Comparing the model $\lambda_2^3 \propto G^{-1}$ (the solid line in Fig. 4) and

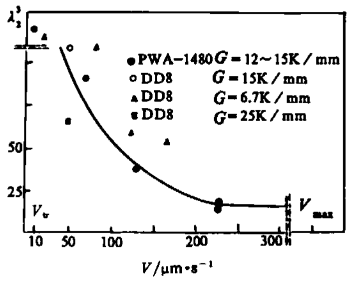

Fig. 3 Influence of solidified velocity on secondary arm spacing

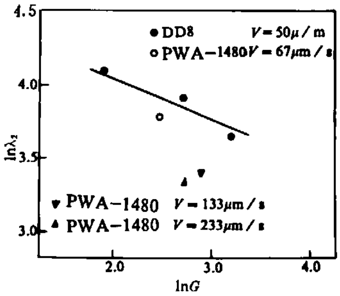

Fig. 4 Influence of temperature gradient on secondary arm spacing

experimental data, the experiment agrees with the model for DD8, but a large deviation exists for PWA-1480. This is due to the high solidification velocities. However, with increase of thermal gradient the secondary arm spacings decrease, which is the same as that in a binary alloy.

4 CONCLUSION

For dendritic directional solidification the effect of thermal gradient and solidification velocity on the secondary arm spacing can be written as $\lambda_2^3 = [[\mu/(GV)] - [q/(GV^{-\frac{1}{2}})]]$, where μ and q are systematic constants. At $G = 12 \sim 15$ K/mm, the relationship of λ_2 and V is $\lambda_2^3 = (6.9/V - 0.12/V^{1/2}) \times 10^6$ for PWA-1480, where λ_2 is in μm, V in μm/s. At low velocity (near transition of cells to dendrites V_{tr}) λ_2 is very sensitive to the change of V. But at high velocity V has a slight effect on λ_2. The effect of G on λ_2 in the multicomponent is the same as that in binary alloys.

REFERENCES

1 Huang, S C *et al*. Acta Metall, 1981, 29: 701, 717.

2 Kattamis, T Z *et al*. Trans Metall Soc of AIME, 1967, 239: 1504.

3 Mortensen, T. Metall Trans A, 1991, 22A: 569.

4 Bower, T F *et al*. Trans Metall Soc of AIME, 1966, 236: 624.

5 Kirkwood, D H. Materials Science and Engineering, 1985, 73: 1.

6 Ivantsov, E P. Dokl. Akad. Nauk SSSR, 1947, 58: 567.

7 Kurz, W; Fisher, D. J Acta Metall, 1981, 29: 11.

8 Kurz, W; Fisher, D J. Fundamentals of solidification. Aedermannsdorf: Trans Tech Publications Ltd, 1986.

9 Vijayakumar, M *et al*. Materials Science and Engineering, 1991, A132: 195.