

Cellular/Dendritic Transition in Directional Solidification of Tb_{0.27}Dy_{0.73}Fe_{1.95} Alloy

Chengchang Ji¹, Shigen Zhu¹, Jianguo Li², Yaohe Zhou²

¹ College of Material Science and Engineering, Donghua University, Shanghai 200051, China

Email: jicc@dhu.edu.cn

² School of Materials Science and Engineering, Shanghai Jiao Tong University, Shanghai, 200030, China

Abstract: A theoretical formation of cellular/dendritic transition of alloy was derived as follows:

$$\frac{G_L}{V} = \frac{\Delta T_0 k_0}{2D}$$

. When the interface morphology of Tb_{0.27}Dy_{0.73}Fe_{1.95} alloy begins to change from cell to dendrite, the theoretical value of G_L/V is $17.4 \times 10^2 \text{ K}\cdot\text{s}/\text{mm}^2$. The experimental results of cellular/dendritic transition, however, indicate that the value of G_L/V is in $9.60 \sim 10.45 \times 10^2 \text{ K}\cdot\text{s}/\text{mm}^2$, which is smaller than the theoretical value. The experimental results also indicate that when the interface morphology is cellular or non-side branch dendritic, the preferred orientation of Terfenol-D crystal is $\langle 110 \rangle$, when the morphology is advanced dendritic, the preferred orientation of Terfenol-D crystal is $\langle 112 \rangle$. Relationship among the solidification conditions, the interface morphologies and the preferred orientations of Terfenol-D crystal was also established. The relationship provides the theoretical and technical fundamental for preparing a certain orientation Terfenol-D crystal.

Key Words: cellular/dendritic transition, interface morphology, orientation, solidification condition, Tb_{0.27}Dy_{0.73}Fe_{1.95} alloy

1. INTRODUCTION

Rare earth giant magnetostrictive material TbDyFe alloy, called Terfenol-D, is considered to be a potential smart material [1]. It has been developed rapidly since 1970's because of its widely uses and giant magnetostrictive property [2]. Terfenol-D, however, is a strong anisotropic material. Crystals of Terfenol-D with $\langle 110 \rangle$, $\langle 112 \rangle$, $\langle 113 \rangle$ preferred orientation or $\langle 110 \rangle + \langle 112 \rangle$ mixed orientation can be obtained under the different solidification conditions.

Pervious work [3-4] indicated that the crystal interface morphology is very important to the preferred orientation of Terfenol-D. For this reason, theoretical analysis and experiments have been made to understand the characteristics of the cellular/dendritic transition under the different directional solidification conditions.

2. EXPERIMENTAL

Tb_{0.27}Dy_{0.73}Fe_{1.95} master rods with the dimension of $\phi 7\text{mm} \times 120\text{mm}$ were melted and cast in a super high temperature gradient equipment developed by the authors [5], and then the master rods were directionally solidified

in the same equipment.

The master alloy rod is contained in a high purity and thin wall quartz crucible which is fixed in the middle of a pancake induction coil. High purity argon gas was filled into the chamber. An approximately 5mm long molten zone is formed by heating with the pancake coil driven by a 175KHz current. After the zone is molten fully, the quartz crucible is lowered with different velocity and the temperature gradient. The interface morphology is obtained by quenching rapidly into the liquid metal of Ga-In-Sn alloy. Specimens were cut from the solidified rod for metallographic examination and crystal orientation detection using an electron beam scatter diffraction patterns method.

3. THEORETICAL ANALYSIS OF THE CELLULAR/DENDRITIC TRANSITION

For the theoretical model of cellular/dendritic transition, many studies have been carried out. We derive the relationship of cellular/dendritic transition based on the kinetic theory of interface stability. Burden-Hunt [6-7] and Trivedi [8] theories about cellular/dendritic crystal

growth.

Burden and Hunt derived the dimensionless parameters expression (equ.1) under the condition of ignoring the interdendritic interacting and the non-uniform of temperature gradient.

$$\frac{\Delta T}{\Delta T_0} = \left[\frac{\phi k_0}{1 - \phi(1 - k_0)} \right] \left[1 + \frac{1}{2} AN_g(P_c) + \frac{2B}{P_c^2} f(P_c) \right] \quad (1)$$

$$\Delta T_0 = \frac{mC_0(1 - k_0)}{k_0}$$

$$\phi = P_c \exp(P_c) \text{Ei}(P_c)$$

$$N_g(P_c) = \frac{1 - \phi}{\phi - P_c + P_c \phi} - \frac{1}{\phi}$$

$$f(P_c) = 0.96 + P_c - \frac{P_c}{\phi}$$

$$A = \frac{2G_L D}{\Delta T_0 V k_0}$$

$$B = \frac{V \Gamma}{2Dk_0 \Delta T_0}$$

$$\Gamma = \frac{\sigma}{\Delta S_f}$$

$$\text{and } \frac{\Delta T}{\Delta T_0} = \frac{k_0(C_t - C_0)}{C_0(1 - k_0)} \quad (2)$$

Where ΔT is the actual temperature interval of alloy, ΔT_0 the freezing range of alloy, V the crystal growth velocity, G_L the temperature gradient in liquid, k_0 the equilibrium solute distribution coefficient, D the diffusion coefficient, P_c is the Peclet number, C_t the composition of dendritic tip, m the slope of the liquids, Γ the Gibbs-Thomson coefficient, σ the solid/liquid interface energy, ΔS_f the mole fusion entropy, R the radius of dendritic tip, A and B is the dimension parameter, respectively.

After using the stability principle of dendritic tip, Trivedi considered that the dendritic tip is in equilibrium between

the instability effect of constitutional undercooling and the stability effect of interface tension. So the relationship can be derived as follows:

$$\frac{C_t}{C_0} = \frac{1}{2} A + \frac{BL}{P_c^2} \quad (3)$$

$$\text{Where } L = \frac{1}{2}(1+1)(1+2)$$

Substituting eq.(2) and eq.(3) into eq.(1), we obtain

$$\frac{1}{2} A + \frac{BL}{P_c^2} - 1 = \frac{\phi(1 - k_0)}{1 - \phi(1 - k_0)} \left[1 + \frac{1}{2} AN_g(P_c) + \frac{2B}{P_c^2} f(P_c) \right] \quad (4)$$

Under the condition of cellular/dendritic transition, the value of P_c is very small, therefore, the value of ϕ is very small too, the value of the right hand side of eq.(4) is far smaller than 1, eq(4) becomes

$$\frac{G_L D}{\Delta T_0 V k_0} + \frac{V \Gamma L}{2Dk_0 \Delta T_0 P_c^2} = 1 \quad (5)$$

After derivation of eq.(5) and let $\frac{dP_c}{dV} = 0$, we can

obtain

$$\frac{G_L}{V} = \frac{\Delta T_0 k_0}{2D} \quad (6)$$

Substituting relative parameters ($\Delta T_0 = 348 \text{ }^\circ\text{C}$,

$k_0 = 0.08$, $D = 8 \times 10^{-9} \text{ m}^2/\text{s}$) of Tb_{0.27}Dy_{0.73}Fe_{1.95} alloy

[9-10] into eq.(6), we can obtain

$$\frac{G_L}{V} = 17.4 \times 10^2 (\text{K}\cdot\text{s}/\text{mm}^2)$$

The result indicates that when the value of G_L/V equals $17.4 \times 10^2 \text{ K}\cdot\text{s}/\text{mm}^2$ the cellular/dendritic transition will take place, that is to say, when the value of G_L/V is smaller than $17.4 \times 10^2 \text{ K}\cdot\text{s}/\text{mm}^2$, the interface morphology of Tb_{0.27}Dy_{0.73}Fe_{1.95} alloy will begin to change from cell to dendrite.

4. EXPERIMENTAL RESULTS AND DISCUSSIONS

In our experiments, the metallographes and the orientations of the solidified alloys have been carried out. It is found that Terfenol-D crystal can grow with cellular or dendritic during its solidification and there is a mixed zone in which cellular and dendritic morphologies exist together between the cellular growth zone and the dendritic growth zone. A series of experimental results of orientations and interface morphologies indicate that Terfenol-D crystal with $\langle 110 \rangle$ preferred orientation can be obtained when the solid/liquid interface is cellular, and with $\langle 110 \rangle$ or $\langle 112 \rangle$ orientations can be obtained when the solid/liquid interface is dendritic. When the solid/liquid interface grows with cellular and dendritic together, the crystal orientation is random including $\langle 110 \rangle$, $\langle 112 \rangle$ and $\langle 113 \rangle$ orientations. Table I shows the partial experimental results of the solid/liquid interface morphologies and the Terfenol-D preferred orientations under the different solidification conditions (G_L/V).

It is clear that the experimental value of G_L/V is in $9.60 \sim 10.45 \times 10^2 \text{K}\cdot\text{s}/\text{mm}^2$ when the interface morphology begins to transit from cellular to dendritic. The experimental data of G_L/V is obviously lower than the theoretical value. The error arises primarily from follow aspects. (1) Local thermodynamic equilibrium of the solid/liquid interface is considered in the course of theoretic derivation. During the actual solidification, however, the interface is in non-equilibrium, the critical

cellular/dendritic transition velocity V_{tr} is always greater than the theoretical cellular/dendritic transition velocity, that is to say, the non-equilibrium effect increases the stability of the cellular interface. (2) During the actual directional solidification, the actual temperature interval ΔT between the solidus and the liquidus is always smaller than the freezing range ΔT_0 of alloy.

From table I, we also can find that two orientations exist when the solid/liquid interface is dendritic, that is to say, in the dendritic growth zone, Terfenol-D crystal with $\langle 110 \rangle$ and $\langle 112 \rangle$ orientations can be obtained. From the metallographes, we can find that the interface morphology is non-side branch dendritic, the orientation of Terfenol-D is $\langle 110 \rangle$, and when the interface morphology is advanced dendritic, the orientation becomes $\langle 112 \rangle$. It is the reason that the lamellar space of Terfenol-D crystal is too small to provide enough time and space to develop the dendritic crystal under the condition of higher temperature gradient and higher crystal growth velocity [11]. The interface morphology of non-side branch can be considered as a cellular morphology, and the Terfenol-D crystal with $\langle 110 \rangle$ can occur. Therefore, it can be considered that when the interface morphology is advanced dendritic, the preferred orientation of Terfenol-D is $\langle 112 \rangle$, and when the interface morphology is non-side branch dendritic, the orientation of Terfenol-D crystal is $\langle 110 \rangle$.

Table I Relationship among the solid-liquid interface patterns, the preferred orientations and the different solidification conditions during directional solidification of $\text{Tb}_{0.27}\text{Dy}_{0.73}\text{Fe}_{1.95}$ alloy

No.	G_L K/cm	V $\mu\text{m}/\text{s}$	$\frac{G_L}{V} \times 10^{-2}$ ($\text{K}\cdot\text{s}/\text{mm}^2$)	Morphology	Orientation
1	500	22.7	22.03	C	$\langle 110 \rangle$
2	700	50.5	13.86	C	$\langle 110 \rangle$
3	900	50.0	18.00	C	$\langle 110 \rangle$
4	500	48.5	10.31	C+D	$\langle 113 \rangle + \langle 110 \rangle + \langle 112 \rangle$
5	700	67.0	10.45	C+D	$\langle 110 \rangle + \langle 113 \rangle$
6	900	93.3	9.65	C+D	$\langle 110 \rangle + \langle 113 \rangle$
7	500	200	2.50	D	$\langle 112 \rangle$
8	700	150.0	4.67	D	$\langle 112 \rangle$
9	800	146.0	5.48	D	$\langle 110 \rangle$
10	900	123.0	7.32	D	$\langle 110 \rangle$
11	900	333.3	2.70	D	$\langle 110 \rangle$

C-cellular, D-dendritic

Connecting a series of experimental results, relationship among the solidification conditions, the crystal orientations and the interface morphologies is obtained, as shown Fig.1.

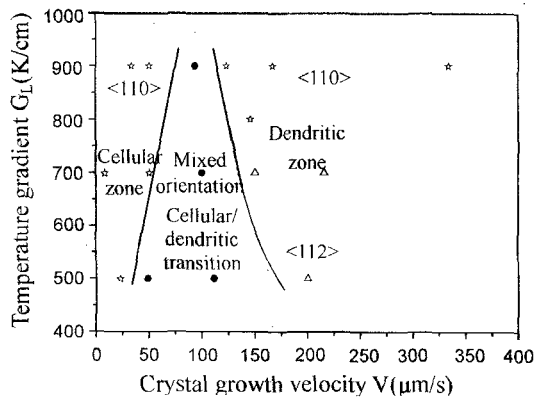


Fig.1 Relationship among the solidification conditions, the crystal orientations and the interface morphologies

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5. CONCLUSIONS

5.1 A theoretical equation of cellular/dendritic transition of Tb_{0.27}Dy_{0.73}Fe_{1.95} alloy was derived as follows:

$$\frac{G_L}{V} = \frac{\Delta T_0 k_p}{2D}$$

5.2 The theoretical solidification conditions (G_L/V) of cellular/dendritic transition of Tb_{0.27}Dy_{0.73}Fe_{1.95} alloy is $17.4 \times 10^2 \text{K} \cdot \text{s}/\text{mm}^2$. The experimental value of G_L/V is in $9.60 \sim 10.45 \times 10^2 \text{K} \cdot \text{s}/\text{mm}^2$, which is smaller than the theoretical value.

5.3 When the interface morphologies are the cellular and non-side branch dendritic, the preferred orientation of Terfenol-D is <110>; when the morphology is advanced dendritic, the preferred orientation is <112>.

5.4 Theoretical and practical basis are provided for preparing a certain oriented Terfenol-D crystal.

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