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Solidification parameters of the solid–liquid interface in crystal growth in response to vibration

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The influence of vibration on the solidification parameters of the solid–liquid interface was investigated by applying a stable longitudinal sinusoidal vibration with different orders of resonant frequencies to the solidification system during crystal growth. Experimental results including the temperature profiles, temperature gradients of the liquid in front of the solid–liquid interface and the growth rates of the solid–liquid interface, are presented and analysed.

1. Introduction

In crystal growth, vibrational interference should be avoided in order to retain high perfection in the growing crystal. Although various types of insulating measures are taken, it is still very difficult to prevent the growth of crystals from being affected by external vibration. Gatos and co-workers [1, 2] observed the influence of an external undesirable vibration on InSb crystal growth. They developed a new technique for determining the instantaneous microscopic growth rates and interface morphology with high precision during InSb single-crystal growth by the Czochralski technique. Quang *et al.* [3] investigated the influence of mechanical vibrations on microscopic growth rates in GaSb crystals pulled from the melt by the Czochralski method. The growth-rate fluctuation and growth layer in crystal growth were analysed in detail by Min Naiben [4]. However, investigation of the changes of solidification parameters and the temperature profiles of the liquid in front of the solid–liquid interface caused by vibration, has not been reported so far. It is obvious that this investigation would be a great help to control crystal growth and be a supplement to the theory of morphological stability.

In the present study, the solidification was carried out by the Bridgman method.

2. Experimental procedure

For experimental purpose, we designed a Bridgman system, which consisted of a precisely controlled Bridgman apparatus, an electromagnetic vibration exciter and an accurate measuring and analysing system, shown in Fig. 1. All the data picked up were treated with microcomputer.

In this study, a stable longitudinal sinusoidal vibration was applied to the rod which was being pulled down; on top of the rod was a crystallizer. The pulldown speed of the rod was kept constant and smooth to avoid any undesired vibration caused by the transmission system. The solidification parameters and the temperature profiles of the liquid in front of the solid–liquid (S–L) interface were controlled to remain

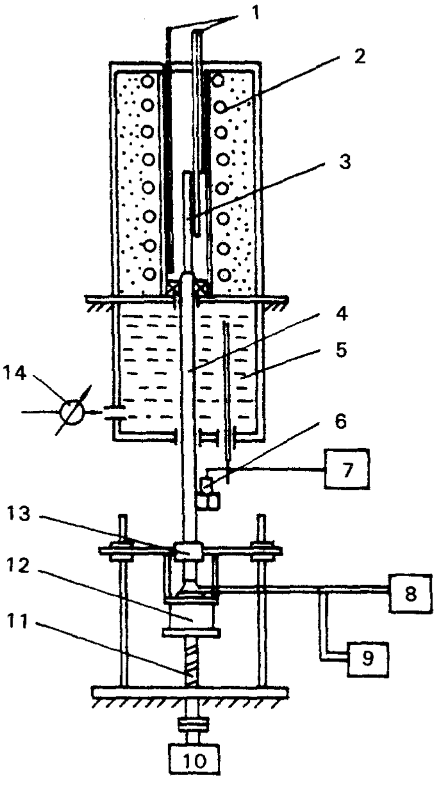

Figure 1 Vibrational Bridgman arrangement. 1, Thermocouple; 2, resistance-heated furnace; 3, crucible; 4, pulldown rod; 5, cooling tank; 6, accelerometer; 7, detecting meter; 8, signal generator; 9, frequency detector; 10, electromotor; 11, screw; 12, electromagnetic vibrator; 13, jig; 14, flowmeter.

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unchanged over the long intervals during solidification with or without vibration applied.

The vibrational parameters were controlled at will. The exciting force and the response of the solidification system to vibration were recorded and analysed in real time. The first, second and third resonant frequencies (470, 1050, 1736 Hz, respectively) of the solidification system were used as exciting frequencies in order to make the response of the solidification parameters of the S–L interface more evident and easier to measure. After taking insulating measures, the response of external unexpected vibration was only 10^{-2} to 10^{-4} the forced vibration and its frequency was only 10–50 Hz; thus it was negligible.

For simplicity, an Al–3.0% Mg alloy was studied first. The main stalk of the low solute dendrites was parallel with the crucible axis and thus perpendicular to the S–L rough interface. The growth rate, R, of the S–L interface and the temperature profile of liquid in front of the S–L interface were directly measured from the top of the crucible. The diameter of the measuring rod was more than fifteen times the spacing between two neighbouring dendritic stalks. The values of solidification parameters of the S–L interface measured were statistical, because the measuring holding time was much longer than the vibrational cycle. The same solidification control technique and measuring method were adopted in order to obtain high precision.

3. Results and discussion

3.1. Temperature profiles of liquid in front of the S–L interface

The effects of vibration on the temperature of the liquid in front of the S–L interface during crystal growth with and without vibration, are shown in Fig. 2, in which S is the temperature curve of the liquid in front of the S–L interface measured under the conditions of static crystal growth. Its regression equation and relative coefficient are $T_1 = 797–181.25e^{-0.0339z}$ and $r = 0.9984$, respectively. (a–c) are measured under conditions of applied stable longitudinal sinusoidal vibrations with the first, second and third resonant frequencies of the solidification system, respectively, the regression equations and the relative coefficients of which are $T_1 = 799–168.96e^{-0.0241z}$, $r = 0.9984$; $T_1 = 799–178.981e^{-0.0250z}$, $r = 0.9984$; and $T_1 = 829–211.75e^{-0.0260z}$, $r = 0.9993$; respectively.

Fig. 2a shows that the temperature curves of the liquid in front of the S–L interface under conditions of vibrational and static crystal growth are different; the curvature of the former is smaller than that of the latter. The two curves intersect at a certain point z, below which the temperature of the liquid under vibration is higher than that in the static state. This indicates that the vibration induces a slight increase in the temperature of the liquid in front of the S–L interface. Above point z, the temperature of the liquid under vibration is lower than that in the static state; this indicates that the vibration promotes heat transfer in the liquid.

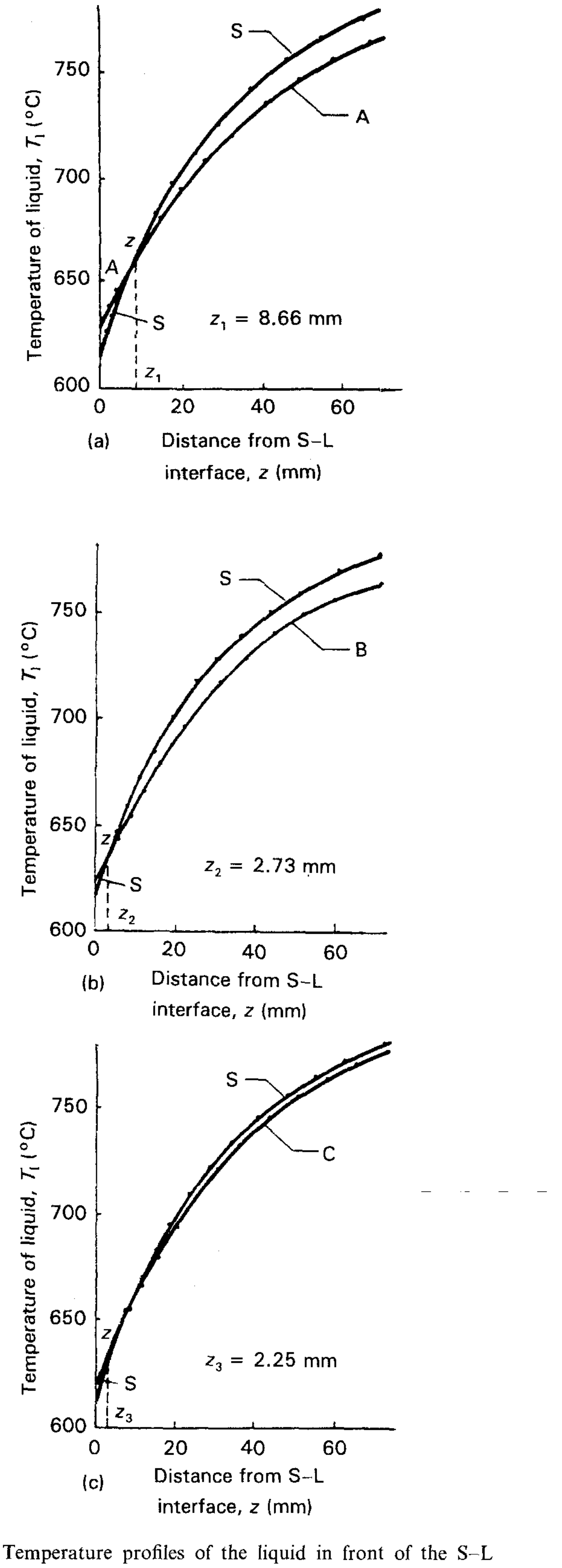

Figure 2 Temperature profiles of the liquid in front of the S–L interface: S, under the static state; (a) with the vibration of the first resonant frequency applied; (b) with the vibration of the second resonant frequency applied; (c) with the vibration of the third resonant frequency applied.

From Fig. 2b and c we can see that the temperature profiles of the liquid with the vibration of the second or third resonant frequencies of the solidification system, are similar to that of the liquid with the first resonant frequency, while the vibration of first resonant frequency introduced changes the temperature

TABLE I

Conditions of vibration	Without vibration	First resonant	Second resonant	Third resonant
Temperature gradient, G_l (°C mm^{-1})	6.13	4.24	4.45	5.57
Relative temperature gradient	1	0.692	0.726	0.909
Growth rate of S–L interface, R (mm s^{-1})	0.0363	0.0255	0.0280	0.0294
Relative growth rate	1	0.702	0.771	0.81
Relative temperature near S–L interface	1	1.016	1.014	1.013

profile more drastically than the other two. The position of the intersection z changes with the order of resonant frequency of the solidification system; the distances between intersection z and the S–L interface for the first, second and third resonant frequencies are 8.67, 2.73, and 2.25 mm, respectively. These values also show that the temperature profile changes when the first resonant frequency is introduced.

3.2. Relations between solidification parameters and exciting frequencies

The temperature gradients G_l, of the liquid in front of the S–L interface and the growth rates, R, of the S–L interface with and without vibration applied are shown in Table I. It can be seen that G_l decreases due to vibration, and it is obviously reduced when the vibration of the first resonant frequency is introduced.

The macroscopic average growth rate, R, of the S–L interface also decreases due to vibration. Both the values of the reductions of G_l and R decrease with increasing order of resonant frequency. It should be pointed out that the results were obtained under conditions of crystal growth with a microscopically rough interface.

These results are similar to those reported elsewhere [1, 3], i.e. the microscopic growth rate at the off-faceted region of the growing crystal obtained from vibrational striation changed due to the mechanical vibration introduced. On the other hand, it has been pointed out [1, 3] that the microscopic growth rate in the faceted region is unaffected by vibration.

3.3. The relation between the vibrational striations in the dendritic crystals and the measured macroscopic growth rates, *R*, of the S–L interface

It was found that there were several periodic vibrational striations, like a bamboo joint, in the specimen when a stable longitudinal sinusoidal vibration with the first resonant frequency of the solidification system was applied, see Fig. 3. The spacing between two neighbouring "vibrational striations" is 1.6 mm, corresponding to a period of 62.745 s. The average macroscopic growth rate, R′, calculated from the above values is 0.0255 mm s^{-1}, while that directly measured from the S–L interface under the same conditions is also 0.055 mm s^{-1}. It shows that these two values are identical.

Figure 3 Periodic vibrational striation.

4. Conclusions

1. In crystal growth, the vibration introduced makes the temperature of the liquid near the S–L interface increase slightly.

2. The temperature gradient, G_l, in front of the S–L interface and the growth rate, R, decrease due to vibration.

3. Both G_l and R are obviously reduced when the first resonant frequency is applied, but as the order of resonant frequency was increased the reductions of G_l and R decreased slightly.

4. The crystal growth rate calculated from the "vibrational striation" is identical to that measured.

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