Materials Transactions, Vol. 48, No. 9 (2007) pp. 2316 to 2318
Special Issue on Solidification Science and Processing for Advanced Materials

EXPRESS RAPID PUBLICATION

Inconel 690 Alloy Crystal Growth Orientation under Different Vibration Waveforms

Che Wei Kuo*, Ming Che Chen*, Jie Hao Chen*, Gen-Huey Lai*, Yung-Tse Chang*, Yu-Che Chen* and Weite Wu

National Chung Hsing University, Department of Materials Science and Engineering, 250 Kuo Kuang Road, Taichung 402, Taiwan, R. O. China

The crystal growth orientation of Inconel 690 alloy solidified under the application of additional kinetic energy was studied. By using an eccentric-mass electric motor for transmitting the kinetic energy to a melting pool, liquid atoms attained kinetic energy that enabled them to strike the solid-liquid interface during solidification. Due to unequal upper and lower amplitudes of the waveform, three types of states of the applied kinetic energy were discussed: (1) the kinetic energy required for the attachment of an atom is greater than that for detachment, (2) the kinetic energy for attachment is less than that for detachment, and (3) the kinetic energy for attachment is equal to that for detachment. The results reveal that unequal kinetic energies for attachment and detachment will encourage epitaxial growth in the (100) direction. Only when the kinetic energies for atom's attachment and detachment are equal will the degree of epitaxial growth in the (100) direction will decrease.
[doi:10.2320/matertrans.MB200719]

(Received June 6, 2007; Accepted July 3, 2007; Published August 25, 2007)

Keywords: *crystal structure, vibration, X-ray diffraction, solidification, Inconel 690 alloy*

1. Introduction

In a nucleation process, base metal grains that exist at the fusion line act as the substrate for nucleation. Since the liquid metal in a melting pool is in close contact with these substrate grains and wets them completely, crystals from the liquid metal easily nucleate onto the substrate grains. During solidification, nucleation occurs by arranging the atoms from the liquid metal upon the substrate grains without altering their existing crystallographic orientations of these atoms; this process is known as epitaxial nucleation. In order to eliminate the inevitable phenomenon, a lot of methods were used to make perturbation motion and improve the fluid convection in melting pool. In order to improve the quality of the metal formed from the melting liquid, vibration techniques are used in this study.

This study is conducted from the viewpoint of the crystal growth theory developed by Chalmers B. in 1954.[1)] According to this theory, the growth rate of a solid-liquid interface reveals that the movement of the boundary separating the liquid from the solid crystalline phase, under a temperature gradient normal to the boundary, may be the result of two different atomic movements. Equivalently, the movement of the interface can be considered as a two-directional diffusion problem in which

$$R_f = R_{f0} e^{(-Q_f/RT)}$$
$$R_m = R_{m0} e^{(-Q_m/RT)}$$

where R_f and R_m are the rates of attachment and detachment, respectively, R_{f0} and R_{m0} are approximate constants, Q_f and Q_m are the activation energies, and R and T have their usual significance. The relationship between the activation energies for attachment and detachment is illustrated in Fig. 1. Q_f and Q_m represent the energies required for moving atoms situated on the liquid and solid sides of the interface, to the saddle point, repectively.[2)]

In the present study, an eccentric-mass electric motor was used to produce a steady-state vibration for supplying kinetic energy to a melting pool. The kinetic energies required for the attachment and detachment of an atom were controlled by the vibration waveforms. Inconel 690 alloy, which nucleates under several steady-state vibration conditions, was used for the study of crystal growth orientation. Inconel 690 alloy is appropriate for this study because of its metallurgical properties. The primary γ-phase of this alloy solidified from the liquid state and cooled to room temperature without any other phase transformation. Therefore, the original crystal structure will be completely retained for follow-up investigation.

2. Experimental Procedure

The dimensions of the Inconel 690 alloy specimen used in the study were 15 × 15 × 5 mm. It was fastened onto a table and heated at the center for 10 s. The heating source was a 200 A, 14 V arc with argon protective gas. In order to prevent the effect of vibrations on the cooling rate because it may lead to a discrepancy in the alloy structure, a water-cooling aluminum steel plate was used for cooling the weld rapidly.

2.1 Vibration system

An eccentric-mass vibrator was used for vibrating the specimen from the melting stage up to the solidification stage. For three kinds of waveforms and near frequencies, 53, 66.9 and 78.6 Hz were selected. These vibration waveforms were determined by a piezo-electric accelerometer and amplified using an amplifier with a gain of 10X. The signals were collected by an HP 54645A oscilloscope. The complete setup of the vibration system is shown in Fig. 2.

2.2 Kinetic energy evaluation

When vibrations are applied to the specimen during the

*Graduate Student, National Chung Hsing University

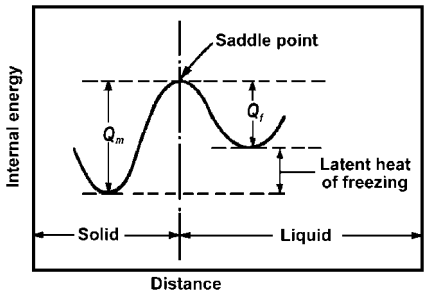

Fig. 1 Relationship between the activation energies for attachment and detachment.

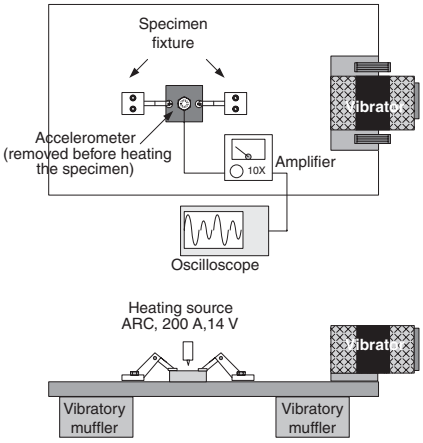

Fig. 2 Vibration system setup.

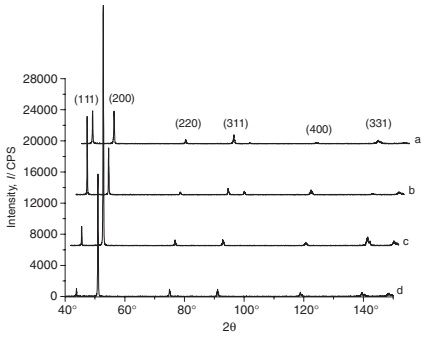

Fig. 3 X-ray diffraction results obtained for (a) 0, (b) 53, (c) 66.9, and (d) 78.6 Hz vibrations (5% offset along the x axis).

Table 1 Upper and lower amplitudes for 53, 66.9 and 78.6 Hz vibrations.

	53 Hz	66.9 Hz	78.6 Hz
Upper amplitude, μm	8.81×10^{-2}	4.56×10^{-2}	2.69×10^{-1}
Lower amplitude, μm	8.79×10^{-2}	5.71×10^{-2}	1.93×10^{-1}
Net amplitude, μm	0.02×10^{-2}	-1.15×10^{-2}	7.6×10^{-2}

melting process, considering the relative velocity between the solid and liquid phases, the motion between the specimen and the liquid atoms can be treated as the liquid atoms striking the specimen. When the specimen is vibrated at a particular frequency, the solid interface moves upward and downward at a rate equal to the selected frequency multiplied by the time in seconds.

The waveforms measured by the piezo-electric accelerometer present the relationship between acceleration and time. Therefore, the energy states required for attachment and detachment are determined by the upper and lower amplitudes of the acceleration-time waveform. The output of the accelerometer is 20 mV per gravity acceleration. By measuring the average acceleration of a wave in half cycle, the upper and lower amplitudes can be calculated. Then, the kinetic energy states for the attachment and detachment of an atom are defined, as listed in Table 1. When the upper amplitude is greater than the lower amplitude, the energy provided by the wave for attachment is greater than that provided for detachment and vice versa.

2.3 X-Ray diffraction

A Mac Science MXP3 X-ray diffractometer was used for crystal diffraction. Its specifications are as follows: X-ray wavelength, 0.154056 nm; X-ray tube voltage, 40 kV; current, 30 mA; and scanning range, 40° to 150° in steps of 0.02°. Since the specimen had a strong crystalline nature, a faster scan speed of 10°/min was selected.

3. Results and Discussion

As shown in Table 1, the net vibration amplitudes at 53, 66.9, and 78.6 Hz are 0.02×10^{-2}, -1.15×10^{-2}, and 7.6×10^{-2} μm, respectively. Due to the vibrations, the kinetic energy is converted into potential energy and the effect of this conversion is reflected in the amplitudes. These net amplitudes indicate the conditions of atom's attachment and detachment is equal, less and over which subject to 53, 66.9 and 78.6 Hz vibration respectively.

Figure 3 shows the X-Ray diffraction results obtained at 0, 53, 66.9, and 78.6 Hz. The diffraction intensity ratios of peaks reveal discrepancies among them. In powder diffraction (random arrangement), the intensity ratio of (111) to (200) should be 5 : 1 (JCPDS 35-1375 standard). When the specimens were solidified by the vibrations of 0, 53, 66.9, and 78.6 Hz, the intensity ratios were 1 : 1, 5 : 3, 2 : 25, and 1 : 15, respectively. Furthermore, the degree of (200) orientated for samples can be recognize as the ratio, 78.6 Hz is the superlative, 66.9 Hz is the next, and then is 0 Hz and the latest is 53 Hz. The ultrahigh intensity of the (200) peak indicates that the crystal is inclined toward the (200) orientation; and the intensity ratios of the (111) and (200) peaks reveal the degree of the (200) orientation in each specimen, which was influenced by the additional kinetic energy.

The effect of the additional kinetic energy is discussed with regard to into three conditions: (1) the kinetic energy required for attachment is greater than that required for detachment, (2) the kinetic energy required for attachment is less than that required for detachment, and (3) the kinetic energy required for attachment is equal to that required for detachment.

(1) Kinetic energy required for attachment greater than that required for detachment.

As shown in Fig. 4(a), the waveform is subjected to a 78.6 Hz vibration. The kinetic energy of the atoms is greater than that in the absence of the vibrations and therefore they strike the solid boundary. The number of atoms that fit into the slack and closed lattice plane will increase significantly due to the additional kinetic energy. Furthermore, the atoms that fit into relatively low energy sites can solidify and release latent heat more easily.

For materials with an fcc crystal structure, the trunks of columnar dendrites (or cells) grow in the ⟨100⟩ direction and each grain grows without changing its ⟨100⟩ direction.[3] Therefore, the deposition rate of the (100) plane is higher than that of the other planes and the latent heat that is released by the solidified (100) plane will decelerate the growth in the

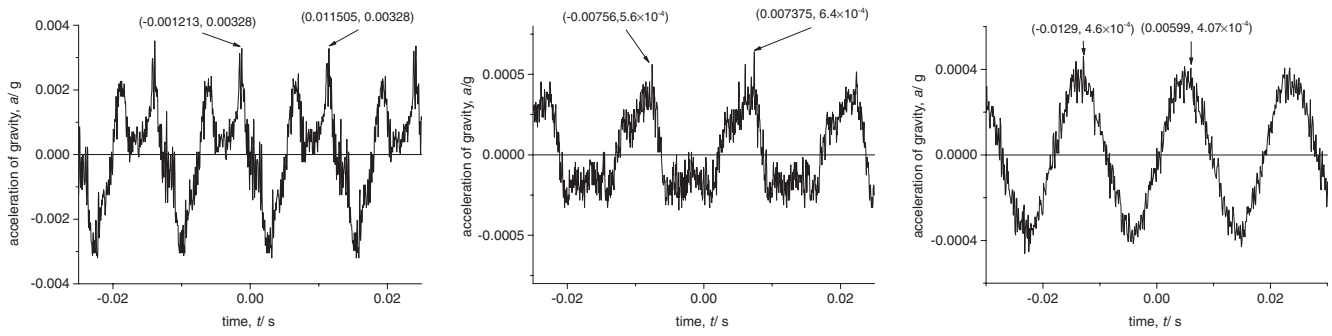

Fig. 4 (a) Waveform for 78.6 Hz vibration. (b) Waveform for 66.9 Hz vibration. (c) Waveform for 53 Hz vibration.

other directions. Finally, a (100) preferred orientation is formed, as indicated by the (200) peak in Fig. 3(d).

(2) Kinetic energy required for attachment is less than that required for detachment.

As shown in Fig. 4(b), the waveform is subjected to a 66.9 Hz vibration. The kinetic energy required for detachment was increased by the vibration; therefore, unstable atoms were easily detached from the solid-liquid interface. Hence, only the atoms present in the low energy site remained attached to the solid-liquid interface. The (100) plane is more slack; hence, in comparison with atoms that fit into the closed plane, the atoms that fit into the site of the (100) plane are more stable. Therefore, crystal growth under this condition still occurs with the (100) oriented structure and results in a high diffraction intensity, as indicated by the (200) peak in the X-ray diffraction (Figure 3(c)).

(3) Kinetic energy required for attachment equal to that required for detachment.

As shown in Fig. 4(c), the waveform is subjected to a 53 Hz vibration. The atoms fit into the solid-liquid interface under the same additional kinetic energy for both attachment and detachment.

Figure 3(b) shows the result obtained for the 53 Hz vibration. Only in this case is the intensity of the (111) plane higher than that of the (200) plane. This result shows that the degree of the (100) orientation is unclear. This result is rather different from that obtained in the previous two cases due to the net kinetic energy (see Table 1). The net amplitude is 0.02×10^{-2}, indicating that the kinetic energies required for attachment and detachment are nearly equal. However, the time for which the atoms are in contact with the solid-liquid interface is shorter than that in the absence of vibrations. In each vibration cycle, the atoms strike the solid-liquid interface at a faster rate only during one half of the cycle, whereas, during the other half cycle, the atoms leave the surface at the same rate. Under such a condition, it is important to solidify the specimen in order to maintain the cooling rate. This is because the water-cooling aluminum steel plate causes the specimen to cool rapidly. In the presence of vibrations, the growth of atoms cannot proceed along the easiest direction due to a low contact time and rapid cooling rate. The atoms solidify on the plane to which they are attached during vibration; this further results in a relatively random arrangement of the crystal structure.

Usually, during solidification, due to an increase in the opportunities for an impact between the solid face and the liquid atoms, the structure of the interface is crucial in determining the crystal growth. However, the waveform of vibrations can strengthen or mitigate the characteristics by applying the vibration kinetic energy for the attachment and detachment of the atom.

4. Conclusions

The relationship between the crystal structure and the applied kinetic energy during solidification has been studied. The additional kinetic energies required for the attachment and detachment of the atom significantly affect the epitaxial growth during the solidification process. Irrespective of whether the kinetic energy for attachment is greater or less than that for detachment, both energies produce a (100) preferred orientation and a highly crystalline structure. A relatively random orientation of the crystal structure is produced only when the additional kinetic energy for attachment equals that for detachment.

REFERENCES

1) B. Chalmers: Trans. A.I.M.E. **200** (1954) 519–532.
2) R. E. Reed-Hill and R. Abbaschian: *Physical Metallurgy Principles*, 3rd ed., (PWS–Kent, Boston, 1992) pp. 434–436.
3) B. Chalmers: *Principles of Solidification* (John Wiley and Sons, New York, 1964) pp. 117.