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The influence of vibration & shock on the crystal growth during solidification

WANG FENG-QUAN, HAN XIAO-LING
Southeast University, Nanjing, People's Republic of China

Based on the single-phase solidification experiment of alloy Al-4.5% with lateral single-phase vibrating & shocking on it, the article studies the influence of vibration & shock on the crystal growth and reveals the phenomenon that the dynamics effects only occur near the solid/liquid interface in crystal growth on the basis of vibration reai-time method to locate the solid/liquid interface.

1. Introduction

Since mid-1800s, many researches have been on solidification of metals under the exciting of vibration. But most of the researches stressed the influence of the variation of vibration parameters to the solidification of metals. On the basis of vibration real-time method to locate the solid/liquid interface during solidification of metals and the experiment of solidification under the exciting of single-phase sine vibration and shock, the author makes further research on the influence of vibration & shock on crystal growth and reveals the phenomenon that the dynamics effect caused by vibration and shock only occurs near the solid/liquid interface.

2. Solidification experiment under the exciting of vibration & shock

The experiment is carried out with the Bridgman one-way solidification device. The experiment system, which mainly comprises of three parts: the one-way solidification device, the vibration exciting system and the control system, is showned in Fig. 1.

The force-exciting is supplied in the direction of perpendicular to the direction of crystal growth. The types of exciting signals are sine and pulse respectively. The exciting force is exerted on the outside of the crystallization utensil and transered to the sample by crystallization utensil and the crucible. This kind of vibration-exciting can effectively imitate the influence of circumstance vibration and general vibration interfering solidification.

The intensity and frequency of sine excitation are controlled by the unit of sine signal generator and the intensity of force is regulated by the power-amplifier. The spectrum and the energy level of pulse exciting are controlled by the pad and the weight of the hammer. The exciting force signals is measured by the force transducer and charge amplifier send to the measurement amplifier to be measured or to one channel of the double-channel analyzer. The response signals are measured by the accelerometer, sent to the other channel of the analyzer by charge amplifier. The characteristics of signals and the time-varying characteristics of the dynamic parameters of solidification system (such as transient force spectrum, response spectrum, transfer function, correlation and coherence function etc.) are real-time analyzed by the double-channel analyzer. The transfer function of solidification system under impulsive exciting is shown in Fig. 2.

3. Sin and impulse exciting

3.1. Single-phase sine exciting

Multi-point single-phase excitation is adopted to simplify the research of vibration of solidification system. Deveuveke's theory showes that N single-phase exciting forces (phases are 0° or 180°) can excite the single-phase forced vibration of N-degrees straggling linear-structure. To excite the single-phases vibration which is in proportion to the rth order natural modal shape of solidification system:

$$x(t) = a_r \sin(\omega t - \theta) \tag{1}$$

Here α_r is amplitude factor, it is required that the exciting force can surmount the inertial force, the elastic force and the damping force:

$$\begin{aligned}\{f(t)\} = ([k] - \omega^2[M_\mathrm{s} + M_\mathrm{f}]\{\varphi_r\}\sin(\omega t - \theta)\\ +\omega[C]\{\psi_r\}\cos(\omega t - \theta)\end{aligned} \tag{2}$$

Here M_s is the mass of the test sample and M_f is the mass of the solidification utensil, K is regarded as the stiffness of the utensil and the solid-phase of the sample.

When the exciting frequency ω is equal to the natural frequency ω_r of the system the single-phase force is:

$$\{f(t)\} = \{F_r\}\sin\omega t \tag{3}$$

$$\{F_r\} = j\omega_r[c_r]\{\varphi_r\} \tag{4}$$

Here $\{\varphi_r\}$ is rth order modal shape; C_r is rth order modal damping of the solidification system.

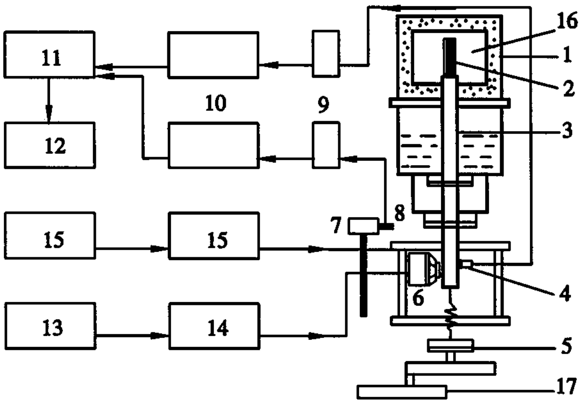


Figure 1 Lest instruments. 1. Furnace: 2. Specimen: 3. Crystallizer: 4. Electrometer: 5. Transfer machine: 6. Magnetoelectric exciter: 7. Snmer: 8. Force transducer: 9. Charg amplifiers: 10. Voltmeter: 11. Final analyser: 12. X-Y plotter: 13. Signal generator: 14. Power amplifier: 15. d.c. power supply: 16. Crucible: 17. Electrometer.

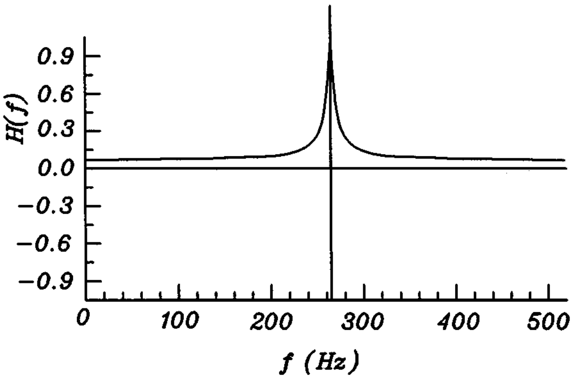


Figure 2 The transmitting function of the vibration solidification system.

In general, the damping of solidification systems is proportional. According to Bishop's theory, the amplitude of force reaches its climax when the exciting frequency is equal to natural frequency of the solidification systems and its expression is showed as follows:

$$\{F_r\} = a_r \left(\frac{c_r}{k_r}\right)^2 \omega_r^2 [M_s + M_f]\{\varphi_r\} \tag{5}$$

Here k_r is rth order modal stiffness of the system.

In this experiment, two-point exciting is adopted, and the distance between the two exciting points is seven centimeters. In order to excite the first two orders principal modal shapes, each exciting force of each excitation is less than $5N$. To reduce the influence of additional mass and stiffness of the exciter to the system, the experiment adopts non-contact electromagnetic vibrator, as shown in Fig. 1 (6). The phase of each force are identical (or reverse), and the amplitude can be regulated and the expression is:

$$F_{rj} = \frac{B_{rj} S_r}{2\mu_0} \qquad j = 1, 2, \ldots \tag{6}$$

Here, B_{rj} is the average intensity of magnetic induction of each pole; S_{rj} is the area of each pole of the magnetic core; μ_0 is the magnetic conductivity coefficient in vacuum.

TABLE I Frequency range of force spectrum of different hammer cap materials

Hammer cap materials	Rubber	Nylon	Aluminum alloy	Steel
upper limit of force spectrum (Hz)	400	800	1500	2000

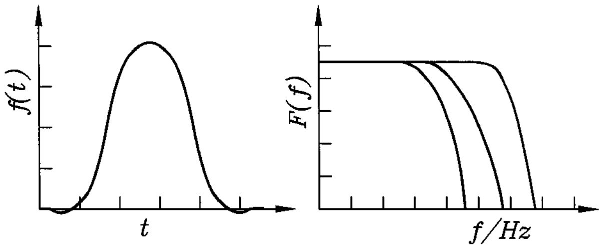
Sine-wave vibration experiment is carried out under exciting of harmonic vibration with the first two natural frequencies, and its distribution of the amplitude is determined by expression 5.

3.2. Impulse excitation

The response of impulse excitation during solidification is achieved by hammer striking. The ideal frequency band width unit pulse force $\delta(t)$ should be ∞ and we can get all modal shapes and natural frequencies of the system. But the experiment indicates it is impossible to get a impulse force whose duration is naught by striking. Fig. 3 shows the frequency band width in this experiment when the stainless steel crystallization utensil is struck by a steel hammer with different packing. The upper limits of frequency are listed in Table I and it is the frequency corresponding to the −3dB on the force spectrum.

4. The result of the experiment

Fig. 4 indicates the tree-shape crystal of one-way solidification on the condition of vibration insulation. In this situation the intensity of surrounding vibration dis-



(a) (b)

Figure 3 Pulse signal and it's force spectrum. (a) Pulse time signal, (b) Force spectrum, 1. Nylon, 2. Aluminium, 3. Steel.

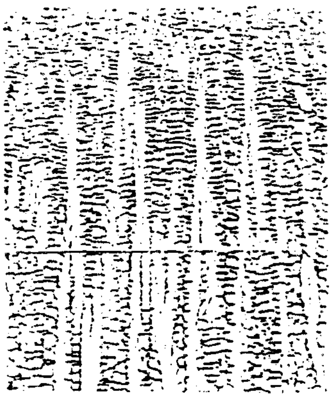
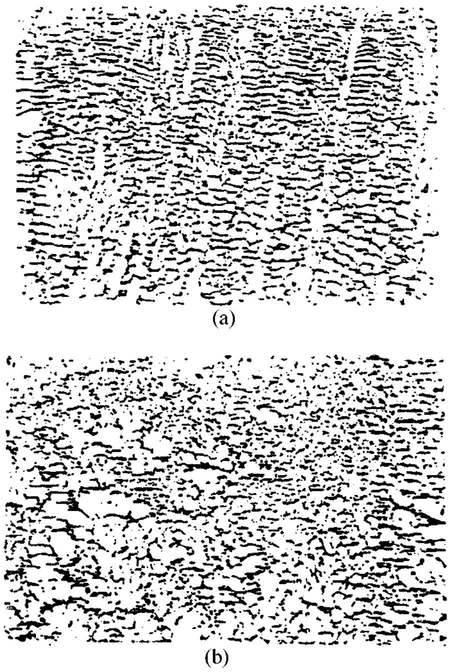


Figure 4 The tree-shape crystal structure of static solidification. Cooling water level = −1.00 mm, pulling down speed = 0.1 mm/s; $G_L = 6.1810\,^{\circ}$C/mm; $R = 0.0363$ mm/s; $G_L/R = 170.5796\,^{\circ}$C s/mm^2.


(a)

(b)

Figure 5 The broken tree-shape crystal looks caused by transverse sine wave vibration.

turbance is approximately one thousandth of the virtual intensity of the driving vibration, so it can be regarded as static solidification.

Fig. 5 shows the damaged tree-shape crystal of solidification under the single-phase sine wave exciting with the first order harmonic vibration frequency. In Fig. 5, besides the break caused by vibration (Fig. 5a), there are transverse movement or freeing of the column-shape crystal particles caused by transverse force of the liquid (Fig. 5b).

The looks of the interface under the instantaneous shock is shown in Fig. 6. The looks is achieved by rapid quench and the experiment denotes that this kind of structure only occurs at the interface r at the shocking instant and the structure of other parts is basically the same as the tree-shape crystal structure of static solidification.

5. The real-time identification of solid/liquid interface during solidification

At the moment of shocking, the force and response signals are transferred to analyzer by the force transducer on the hammer and the accelerometers respectively by charge amplifier and the real-time frequency-response function of the solidification system can be gained and shown in Fig. 2. From Fig. 2 we can know the first order natural frequency of the system at the moment is ω_0.

According to the instantaneous solid/liquid interface location discernment theory:

Figure 6 The looks of the interface excited by pulse.

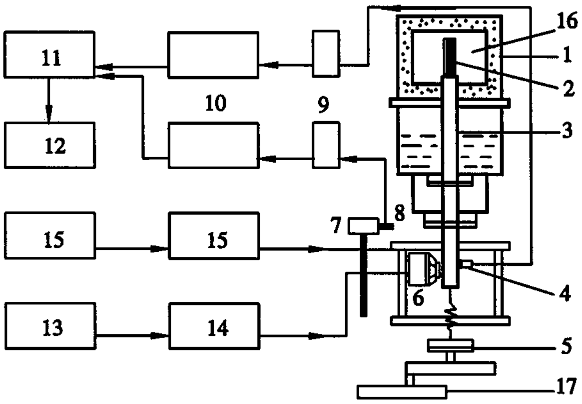


Figure 7

Here, ω_0—the first order natural frequency of the solidification system at the beginning of the experiment ($r = 0$), q—the ratio of the inner diameter to the outer diameter of the solidifying utensil column shell

$$q = \frac{d}{D} \quad 0 < q < 1$$

r—the ration of the solid-phase length to the total solid-liquid length at the moment of impulse excitation.

$$0 < r < 1$$

The expression (7) describes the relation between the instantaneous interface location and the natural frequency of the system at that moment, which is shown in Fig. 7.

From expression (7) and Fig. 7, the location r of solid/liquid interface can be determined at the moment of impulse excitation.

The analysis of experiment indicates that at the pulse instant the crystal looks makes a sudden change at the interface location. The tree-shape crystal generates distinct break and freeing (shown in Fig. 6) at this location, but at the other location the tree-shape crystal still maintains the tree-shape looks of the static solidification as shown in Fig. 4.

$$\lambda = \omega/\omega_0 = \sqrt{\frac{[1 - q^4(1-r)^5]\left[1 + \frac{45}{104}(t-1)q^2\left(\frac{104}{45} - 7.2r^5 + 8r^6 - 4r^7 + r^8 - \frac{1}{9}r^9\right)\right]}{(1-q^4)/[1+(t-1)q^2]}} \qquad (7)$$

6. Conclusions

According to the analysis of this article, conclusions can be drawn as follows:

(1) The transverse vibration and shock excitation can cause break and freeing of tree-shape crystal during the solidification.

(2) The dynamic effect caused by vibration and shock only occurs near the solid/liquid interface at the instant of excitation during the solidification.

References

1. WANG FENQUAN and HE DEPING, *Journal of Materials Science* (1994).
2. WANG FENQUAN and ZHU ZHENGHUA, *Journal of Materials Science* **28**(2) (1993).

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