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Dendrites fragmentation induced by oscillating cavitation bubbles in ultrasound field

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ABSTRACT

The fragmentation of the dendrites of succinonitrile (SCN)-2-wt.% acetone organic transparent alloy caused by ultrasound-induced cavitation bubbles was studied by using ultra-high-speed digital camera with a rate of 40,000 fps. Real-time imaging reveals that the vibrating cavitation bubbles can fragment not only secondary arms but also the primary ones under high ultrasound power. The secondary arms always broke at their roots as a result of stress concentration induced by oscillated cavitation bubble and then ripped off from their primary arms. Generally the fragment process takes tens of milliseconds from bending to breaking, while the break always occurs immediately in less than 25 μs.

1. Introduction

Ultrasonic treatment of metal melt is coming into more and more common use in the field of casting for its effect in refining grains and the avoidance of casting defects so as to improve the performance of metal materials [1–5]. Ultrasonic treatment is a kind of external-field processing, which contributes to the refinement of solidification microstructure mainly through ultrasonic cavitation and streaming [6–12].The proposed mechanism for grain refinement caused by ultrasonic treatment generally falls into three categories: (1) The high transient pressure generated during the implosion of bubbles leads to the increase of the alloy's melting point, due to that, the undercooling of the melt rises, this contributes to the nucleation of homogeneous grains [13,14]. (2) The heterogeneous nucleation is enhanced by "activating" insoluble and impure particles in the melt, such as oxide inclusions, in this way, the wetting ability of the melt is improved, and the agglomeration of particles is avoided or reduced [1,15]. (3) The broken dendrites themselves become the nucleation centers which may grow into new dendrites ahead of the solidification front.

The observation of solidification structures using transparent alloys has been widely used to investigate the dynamics of dendrite evolution under different thermal regimes, mechanical stirring conditions [16,17], and to reveal the mechanism of metal solidification. Photographic observation of ultrasound or cavitation has shown that the cavitation bubbles act as an important factor in the fragment of dendrites [18–20]. Transparent camphene-based alloy solidified in an ultrasonic field [18] tried to study the effect of ultrasound cavitation bubbles on the growth of dendrites at the speed of 500 fps. The fragment of ice dendrites caused by cavitation bubbles in microscale was realized by Rachel Chow [19], who found that the moving cavitation bubbles could break up some existing ice dendrites. The dynamic behavior of ultrasound-induced cavitation bubbles and their effect on the fragmentation of dendrites of SCN-1-wt.% camphor organic transparent alloy was studied by Shu DA [20] using high-speed digital imaging, and it was revealed that the shock waves generated by violent implosion of bubbles was the main factor which caused the dendrites fragmentation. Till now, no high-speed photographic systems, especially with a speed higher than 20,000 fps, have been employed for the observation of dendrite fragmentation under ultrasound field, but it is known to us, the speed of camera is very important for researching the effect of bubble implosion on dendrite fragmentation. It is apparent, only when the behavior of cavitation bubbles is clearly observed, can we discuss the mechanism of dendrite fragmentation under ultrasound treatment correctly. So, in this study, the ultra-high-speed photographic work of 40,000 fps was used to investigate the dendrites fragmentation of SCN-2-wt.% acetone caused by cavitation bubbles in ultrasound field.

2. Materials and methods

The solidification cell is shown schematically in Fig. 1. To investigate the effect of a cavitation bubble on the dendrites, two con-

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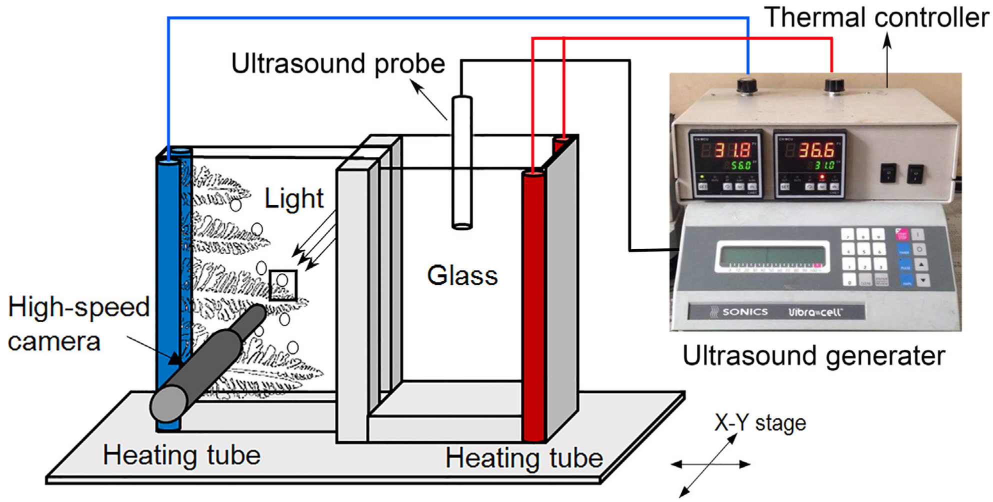

Fig. 1. Schematic diagram of experimental solidification cell.

nected chambers were designed, the left one has a size of 15 mm × 20 mm × 0.3 mm (width × height × thickness) for observation of the solidification of dendrites, and the right one is 15 mm × 20 mm × 3 mm in size for the introduction of ultrasound with the ultrasound probe of 2 mm in diameter dipped ~3 mm inside. The succinonitrile-2 wt.% acetone was used as the analogue for the solidification of alloys. The melting point of the SCN is about 331 K and other physical properties are list in Table 1.The alloy was made by melting pure SCN (99%) and pure acetone (99.7%) with the designed mass ratio in sealed glass bottle using oven at 343 K for ~30 min. Then use a dropper with tip of 2 mm in diameter to fill the cell with the alloy. Both cell and dropper were heated in the oven and all the operation process was taken in the oven to avoid the solidification of the analogue alloy. After the cell was filled with the analogue alloy, the cell was placed onto a 3D-mobile platform for the convenience of camera focusing. The thermal control system in this experiment contains two pairs of heating tubes connected with two-way thermal controller (with controllable silicon), and two PT100 thermal resistances in the melt. One pair of heating pair located at the far right side of the right chamber and the other pair at the far left side of the left chamber. By adjusting the temperatures of the two pairs of heating tubes to generate required thermal gradient conditions. During the experiment, the solidification of the analogue alloy proceeds from left to right in the left chamber, the dendrites grows mainly horizontally. The solidification front in the left chamber is about 15 mm away from the ultrasound probe in the right chamber. By this way it is convenient to capture a single cavitation bubble, and then to investigate its vibration effect on the growth of dendrites. The SONICS VCX 130 ultrasound device was used with adjustable power supply from 30 W to 150 W, and the frequency is 20 kHz. The experiment process contains thermal control, view control and camera control.

Table 1
The Physical Properties of Succinonitrile used in calculation [20–23].

Succinonitrile	Parameters	Value
Melting point	T_M/K	58.081
Density of liquid	ρ_L/kg·m^{-3}	0.970×10^3
Viscosity of liquid	μ/Pa·s	2.66×10^{-3}
Surface energy	γ_{SL}/J·m^{-2}	8.95×10^{-3}
Surface tension	σ/N·m^{-1}	3.85×10^{-2}
Gas polytrophic exponent	γ	1.6 (for air)

Thermal control: The cell containing the alloy together with the ultrasound probe (to avoid the nucleation caused by a cool probe) was firstly heated to 333 K (60 °C) using the thermal control system to fully melt the alloy and then different thermal configurations were used. The temperature of the heating tubes was set at 333 K temporarily as the hot side and the left, as the cooling side, was firstly set at 328 K for ~2 min, to examine if dendrites can form, if not, decrease the temperature of the cooling side by 1 K step by step until dendrites growth can be observed and let them grow freely and see if the dendrite tips can located at the thick cell, or increase the temperature of hot side to see if the dendrite tips grow into the thick cell. In this way, a proper temperature gradient of both cold and hot side can be determined (T_H = 65 °C, T_L = 40 °C) and the solidification front can be fixed in proper position as a consequence of the thermal gradient, which was beneficial for observation, and in our experiment, the dendrite tips were about 10–15 mm away from the ultrasound probe.

View control: The ultrasound generator was turned on for only less than 1 s in order to obtain cavitation bubbles near the tips of dendrites without fragmentation. Then, the 3D-mobile platform can be adjusted to a suitable view area which contains both dendrites and cavitation bubbles, and after that the ultrasound generating system as well as the camera were turned on to capture the vibration of cavitation bubbles, in order to further study its effect on the fragmentation of dendrites.

Camera control: A Nac HX-6 (Nac Image Technology, Tokyo) high-speed digital video camera with an optical microscope (~800 times magnification) was used to film the dynamic interaction between the dendrites and the ultrasound field during solidification. The image acquisition rate was 40,000 fps.

3. Results and discussion

3.1. The fragmentation of dendrite arms in single-dendrite scale

A series of images shows the fragmentation of SCN-2-wt.% acetone dendrite arms caused by an oscillating cavitation bubble under the ultrasonic power of 30 W is shown in Fig. 2, the cavitation bubble is of ~50 μm in diameter near the dendrite tip below the truck. After the ultrasound generating system was switched on, the bubble began to oscillate and the shock wave was generated as shown in Fig. 2b. The first secondary arm away (symbolled as 1) from bubble broke at its root after the treatment for about