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Effect of ultrasonic melt treatment on structure refinement of solidified high purity aluminum

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Abstract: Effect of ultrasonic melt treatment on the macrostructure of solidified high purity aluminum was studied experimentally using metallographic method and complementary numerical calculations of acoustic pressure and velocity distribution in the melt. The results reveal that the macrostructure is effectively refined within a cone-shaped zone ahead of the irradiating face. Inner crystals along with wall crystals multiply particularly within the effectively refined zone and they contribute equally to structure refining. Isothermal holding after ultrasonic melt treatment results in loss of nucleation potency for nearly a half of nuclei, indicating that ultrasound activated heterogeneous nucleation may be as equal important as homogeneous nucleation for ultrasonic induced structure refining.

Key words: grain refinement; ultrasonic; aluminum; solidification

1 Introduction

Microstructural refinement has been proved to be crucial for industrially used metals to minimise casting defects, improve mechanical properties and hence enhance engineering performance. As a simple and potential physical method, ultrasonic treatment has been proved to be effective to refine metal grains [1−3]. Generally, the application of ultrasound in an overheated melt (namely the ultrasonic melt treatment) or during solidification involves two main refining mechanisms: cavitation activated nucleation [4−6] and grain multiplication, due to dendrite fragmentation caused by cavitation [7−10]. Each mechanism offers a unique perspective and differs in source of nuclei and the following nucleation processes, which complicates assessment of the refining capacity. In the former case, the collapse of a cavity or bubble can generate extremely large pressure spikes to increase the freezing temperature of the liquid and hence promotes homogeneous nucleation, or activate insoluble impurity particles in the melt, e.g. oxides, as effective heterogeneous nuclei to grow grains by the imposition of ultrasound [11−13]. Pioneering works [4,11,14] elucidated that ultrasonic treatment benefits activating nucleants and the potency as melt inoculated, and heterogeneously nucleated wall crystals have marginal refining effect on the final structure. However, little work has aimed to clarify respective contributions of the cavitation induced homogeneous or heterogeneous nucleation to the final refinement and the refining potential of ultrasonic melt treatment. Moreover, most of the previous works conducted in alloys containing a variety of solutes, which are known to promote growth restriction as well as nucleation suppression during solidification and thus complicate refining mechanisms and the assessment.

In the present work, ultra high purity aluminum (99.999%) was employed, the effect of ultrasonic melt treatment on grain density in the solidified structure was studied in order to greatly avoid the potential disturbance of impurity or solutes on nucleation or restricted grain growth, and the role of cavitation induced homogeneous nucleation on the final refinement was directly studied. Based on that, the potency of ultrasonic grain refinement would be demonstrated.

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2 Experimental and numerical modeling

2.1 Experimental

An ingot of 360 g pure aluminum (99.999%) was first put into a clean corundum crucible, melted in a closed resistant furnace at 700 °C for 2 h, and then held at 670 °C. A titanium cylindrical sonotrode of 20 mm in diameter right above the crucible was lowered in the furnace through a hole locating at the center of the furnace lid, which was preheated for about 15 min before immersed to the depth of 25 mm in the melt. The sonotrode was connected to a water-cooled piezoelectric transducer and an ultrasonic generator operating at fixed 20 kHz frequency and power output of 1000 W. After 2 min treatment, the sonotrode was immediately lifted up and the ultrasonicated melt along with the crucible was drew out of the furnace and cooled in the air. Two further contrast experiments were conducted: one sample was obtained by immersing idle sonotrode in melt for 2 min without ultrasonic output and another one was held for 10 min at 670 °C after ultrasonic treatment and before air-cooling. For convenience, the three samples were denoted irradiated, unirradiated and holding sample, respectively.

The resulted samples (~60 mm height) were then longitudinally sectioned into two parts, and one half of each sample was further cross sectioned into four parts every 15 mm in height (as shown in Fig. 1). All of the sections were then ground, polished and etched with a mixed acid solution composed of hydrochloric and nitric acid for metallographic examination.

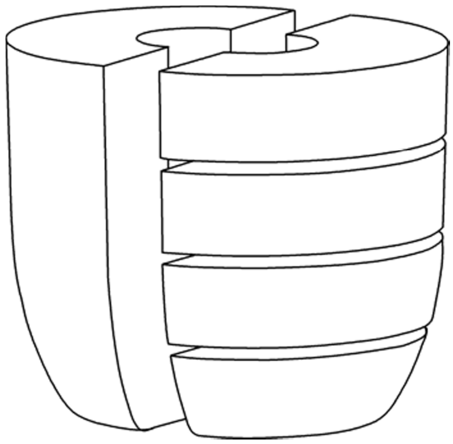

Fig. 1 Sectioning of obtained aluminum ingot samples

2.2 Numerical modeling

Two separate models were applied to calculate the acoustic pressure and acoustic streaming in the melt, respectively. Propagation of time harmonic ultrasound waves in the melt is governed by Helmholtz equation as follows [7]:

$$\nabla\left(\frac{1}{\rho}\nabla p\right)+\frac{\omega^2}{\rho c^2}p=0 \qquad (1)$$

where p is the acoustic pressure, ρ is the melt density, ω is the angular frequency, and c is the sound speed in the melt. Equation (1) was solved for the aluminum melt geometry in Fig. 2 using the commercial finite element software COMSOL Multiphysics. Acoustic power input was transformed to a pressure source boundary as $p_s=p_A\cos(\omega t)$, where $p_A=(2\rho cW/\pi R^2)^{1/2}$, W is the applied ultrasonic power and R is the end face radius of the sonotrode. The melt/air interface is a soft sound boundary, the melt/crucible interface is an acoustic impedance boundary, and others are hard sound boundaries. Modeling details can be found in Ref. [7].

The time-average convection flow induced during the passage of an acoustic wave, namely acoustic streaming, was modelled based on the theory proposed

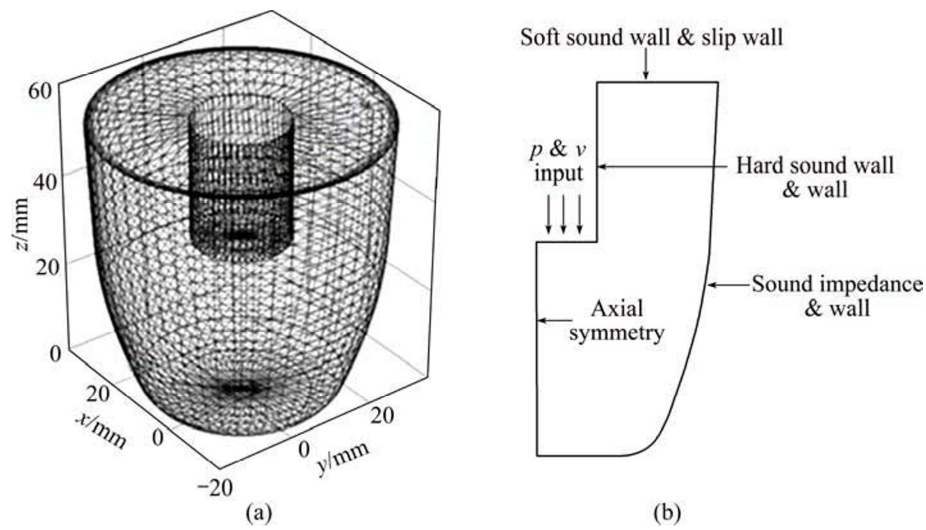

Fig. 2 Schematic diagram of model geometry for calculations (a) and boundary conditions (b)