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Effect of power ultrasound on solidification of aluminum A356 alloy

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Abstract

The present investigation attempted to evaluate the effect of ultrasonic vibration on the nucleation and growth of aluminum alloy A356 melt. A356 melt was treated at various solid fractions isothermally with ultrasonic vibrations by dipping the acoustic radiator into the melt. Experimental result confirmed that globular grains could be effectively obtained when the melt was ultrasonically treated at the temperature close to its liquidus and subsequently cooled quickly. It further illustrated the difficulty to form globular grains when the specimens were treated at isothermal temperatures in the mushy zone. It may imply that in the given experiments cavitations-induced heterogeneous nucleation plays a more important role than dendrite fragmentation in the formation of globular grains.

Keywords: Solidification; Aluminum alloy; Ultrasonic vibration; Nucleation; Dendrite fragmentation

1. Introduction

The research of ultrasonic vibration for metallurgical applications can be dated back to 1878 when Chernov proposed the original idea of improving cast metal quality by elastic oscillations [1]. The injection of ultrasonic energy into molten alloys brings about nonlinear effects such as cavitation, acoustic streaming, emulsification, and radiation pressure [2], which are used to refine microstructures, reduce segregation, and improve secondary phase formation and distribution.

Ultrasonic treatment of aluminum alloys, in general, has been studied extensively [1,3–6]. It has been shown that the introduction of high intensity ultrasonic vibration into the melt can eliminate columnar dendritic structure, refine the equiaxed grains, and under some conditions, produce globular non-dendritic grains [1]. Mechanisms for grain refinement under ultrasonic vibrations have been proposed [7,8]. They are related to ultrasonically induced cavitations, which produce large instantaneous pressure and temperature fluctuations in the melt. These pressure and temperature fluctuations are likely to induce heterogeneous nucleation in the melt. They are also likely to promote dendrite fragmentation by enhancing solute diffusion through acoustic streaming. However, there is no convincing evidence in the literature as to which mechanism, i.e. heterogeneous nucleation or dendrite fragmentation, is more important for grain refinement under ultrasonic vibrations. This article reports some results of the carefully designed experiments in which ultrasonic energy was injected in the melt at various stages of solidification.

2. Experiments

The raw material used in this study was aluminum alloy A356 (Al–7.0 wt.% Si–0.4 wt.% Mg–0.1 wt.% Fe). The ultrasonic system used for this research consisted of a 1.5 kW acoustic generator, an air-cooled 20 kHz transducer made of piezoelectric lead zirconate titanate crystals (PZT), and an acoustic radiator made of titanium alloy Ti–6Al–4V. A pneumatically operated device was installed to move the radiator. The time to preheat the radiator and to dip it into the melt can be precisely controlled.

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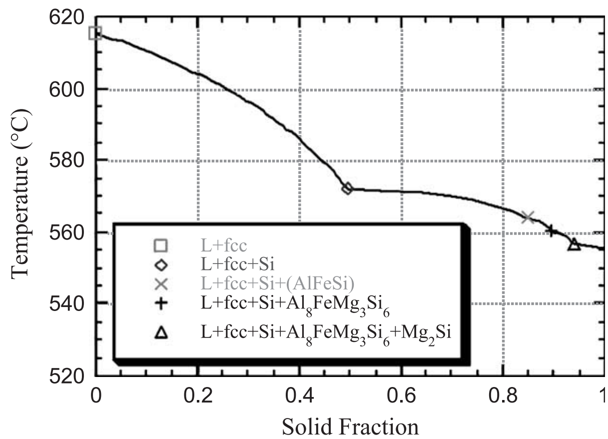

Fig. 1. Temperature versus solid fraction curve of A356 aluminum alloy.

The temperature versus solid fraction curve of this material was determined by thermodynamic simulations ahead of the experiments. As is shown in Fig. 1, the liquidus temperature of this alloy is 614 °C and the solidus temperature is 554 °C. The primary fcc aluminum dendrites start to form at 614 °C and the binary eutectics at 574 °C. Tertiary eutectics and complex intermetallics form at the late stage of solidification.

Three types of experiments were carried out, namely continuous processing, intermittent processing, and isothermal processing. In the continuous processing, ultrasonic energy was injected into the molten aluminum over a range of temperature that covered from 634 to 574 °C as the alloy cooled in the furnace. The ultrasonic system was not able to function when the melt temperature was lower than 574 °C since the solid fraction was too high. The second approach, intermittent processing, was the stepwise application of acoustic power coupled into the melt at different temperature intervals from 614 to 574 °C. Temperature intervals were 5 °C and the time of each isothermal treatment was varied over, 5, 10, and 20 s. The third approach consisted of isothermally applying acoustic energy into the melt at different solid fractions. The isothermal processing time varied from 5, 10, and 20 s. Experimental results reported in Ref. [9] indicate that 20 s is enough to produce globular grains during solidification of aluminum alloys.

In the experiments, aluminum A356 alloys were heated up to 650 °C and cooled to predetermined temperatures for ultrasonic processing. Meanwhile the ultrasonic radiator was also preheated to the same temperature as the aluminum melt. The radiator was then inserted into the melt. The specimens thus treated were cooled in the furnace to room temperature. The microstructure of the specimens was characterized.

3. Results and discussion

Fig. 2 shows the comparison of the obtained microstructure without (a) and with (b) the continuous application of acoustic power. Without acoustic vibration, the microstructure was dendritic and its average grain size was several millimeters. Upon the application of acoustic power, the dendritic structure was broken up into a somewhat globular grain structure. The average grain size was about 200 μm. This result is in accordance with previous work [7].

Microstructures corresponding to different intermittent time processing are presented in Fig. 3. The comparison between Figs. 2a and 3 reveals a very large difference in the resultant microstructure. In particular, the application of intermittent acoustic energy makes the microstructure more globular and destroys the dendritic microstructure. The comparison of Figs. 2b and 3 shows little difference in terms of grain morphology between the application of intermittent and continuous acoustic power. However, the average grain size appears to be reduced by intermittent acoustic vibration. Fig. 3 indicates that the intermittent treatment is more efficient than the continuous treatment in terms of grain size reduction. This is due to the fact that the cooling rate in the specimen treated with intermittent vibration is faster than that treated with continuous vibration. Cooling rate has a major effect on the resultant grain size.

Isothermal processing was then carried out in the melt. Fig. 4 shows the microstructure obtained for five conditions: without acoustic power applied (a); acoustic power applied 10 s at 614 °C (b), at 610 °C (c), at 605 °C (d). Isothermal processing reduces the average grain size compared with that without acoustic vibrations. The

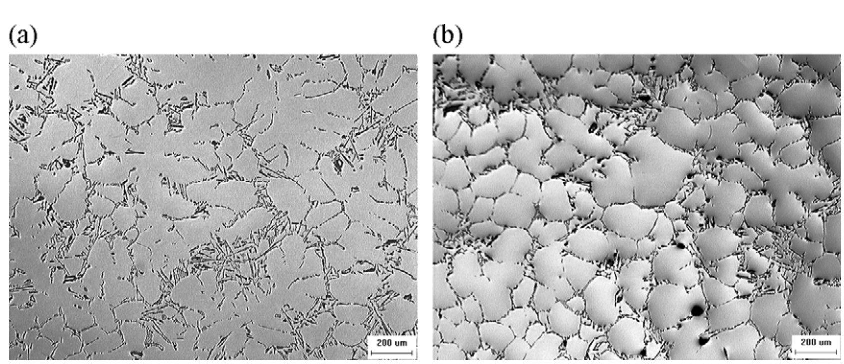

Fig. 2. A comparison of microstructures obtained without (a) and with (b) the application of continuous acoustic power.

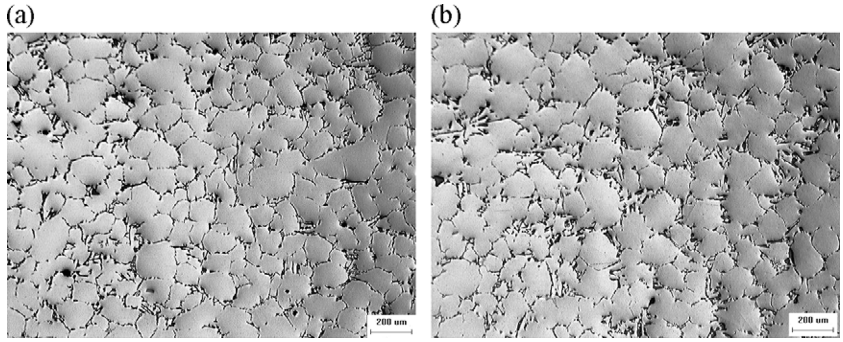

Fig. 3. A comparison of microstructures obtained with the application of intermittent acoustic power for (a) 10 s and (b) 20 s at each isothermal temperature step.

comparison of Fig. 4b with c shows little effect of processing temperature on the average grain size using isothermal processing. No globular structures were obtained for isothermal processing for various times and temperatures in the range of 614 to 574 °C.

Note that 614 °C is the liquidus temperature of the alloy; 610 and 605 °C are the temperatures where the corresponding solid fraction is about 0.1 and 0.18, respectively.

Finally, the isothermal processing time was increased. Fig. 5 shows the resultant microstructure of a specimen subjected to ultrasonic vibrations for 20 s at 614 °C (a) and 610 °C (b). The extended isothermal vibration time seems to have little effect on breaking up dendritic structures further and forming globular structures.

It is well known that isothermal coarsening can be used to produce a globular microstructure in aluminum alloy if the specimen is held at a semi-solid temperature for an extended time. Electromagnetic stirring can also be applied to a solidifying alloy to obtain globular grains at fairly short processing times. In fact, both isothermal coarsening and electromagnetic stirring have been successfully used for the production of globular/non-dendritic microstructures. The results shown in Figs. 4 and 5 suggest that it is difficult to obtain globular grains, in a short time frame, by injecting acoustic energy into aluminum A356 alloy in the semi-solid temperatures (mushy zone temperatures). This may imply that the temperature/pressure fluctuations induced by acoustic vibration are not efficient in breaking up dendrites in the mushy zone. Dendrite fragmentation requires the remelting of the secondary dendrite at their roots. Remelting of a solid is usually slow because latent heat is needed to remelt the secondary dendrites at their roots. The temperature/pressure fluctuations occur at a frequency of 20 kHz, which may be too fast for dendrite fragmentation. Some limited dendrite fragmentation occurred in our experiments since the grain size is reduced with acoustic vibration. The

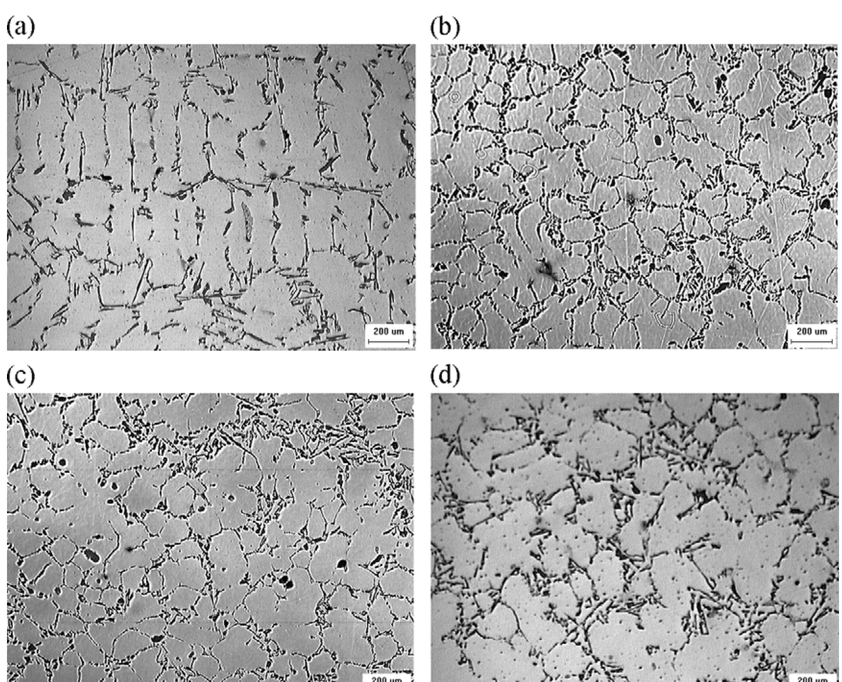

Fig. 4. A comparison of microstructures obtained without (a) and with isothermal processing for 5 s at 614 °C (b), at 610 °C (c) and at 605 °C (d).

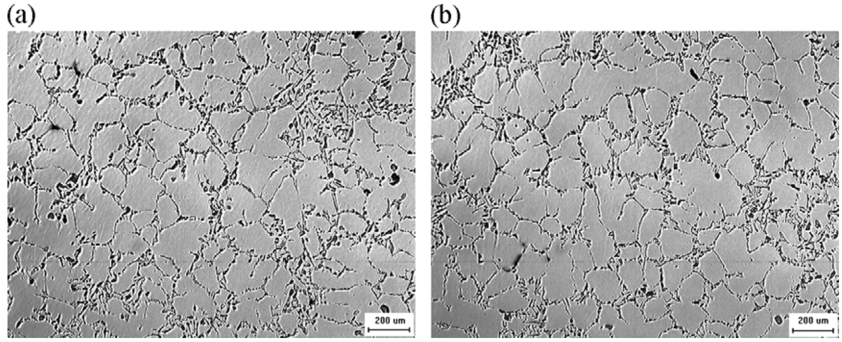

Fig. 5. The microstructures of specimens subject to ultrasonic vibration for 20 s under isothermal processing conditions at (a) 614 °C and (b) 610 °C.

limited dendrite fragmentation can be related to the acoustic streaming in the slurry, which promotes mass transfer and thus the remelting of dendrites at their roots.

Having excluded the effect of dendrite fragmentation on the formation of globular/non-dendrite microstructure in the acoustically processed melt, in this situation acoustically induced heterogeneous nucleation seems to be the dominant mechanism for the formation of a globular microstructure. With ultrasonic vibration applied to the melt, cavitations form, which give rise to the formation of a large number of tiny discontinuities or cavities. These cavities expand and collapse instantaneously. During the expansion stage of the small cavities, the temperature of the cavity surface drops. As a result, undercooling occurs on the cavity surfaces and results in the formation of nuclei of the solid phase. The formed nuclei can be distributed throughout the melt by the acoustically induced streaming. A large number of nuclei can be produced during the expansion stage, resulting in the formation of globular grains.

4. Summary

A globular/non-dendritic microstructure was obtained and grains were refined in the melt subjected to a continuous acoustic vibration when the melt was cooled from 634 to 574 °C. Better results were obtained by intermittent injection of acoustic energy in the melt. Isothermally ultrasonic treatment with a short time in the mushy zone reduced the average grain size but failed to produce a globular microstructure. This may suggest that in the given experiments the dominant mechanism for grain refinement using acoustic vibrations is likely not due to dendrite fragmentation but cavitation-induced heterogeneous nucleation.

Acknowledgments

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