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Effect of ultrasonic vibration during casting on microstructures and properties of 7050 aluminum alloy

HuaShan Liu · Xiang Qiao · ZhiHong Chen · RongPiao Jiang · XiaoQian Li

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Abstract The microstructures and properties of ultrasonic and conventional cast 7050 aluminum alloys have been studied. Compared with the conventional cast alloy, the ultrasonic cast ingot (UI) is characterized with a finer microstructure than that in the conventional cast ingot (CI). For the hot-rolled plates, the UI alloy can be aged faster and aging-strengthened easier than the CI alloy. When aged at 120 °C, the UI alloy reaches its peak strength after 8 h, with tensile strength of 602 MPa, yield strength of 547 MPa and elongation of 12.7%, respectively, whereas the CI alloy plate is with its tensile strength, yield strength and elongation of 536 MPa, 462 MPa and 15.0%, respectively, after peak aged for 12 h.

Introduction

Due to low density, high strength, and excellent work ability, 7050 aluminum alloys are used in important parts in the aerospace structural field [1–3]. However, one of the major problems in 7xxx ingot of large size is the crack generating during casting process. Such cracks can be partly eliminated through grain-refining, which improves both the as-cast strength and plasticity [4–8].

Recently, ultrasonic-field was applied to casting process. It was reported that ultrasonic casting process could improve the metallurgical quality of the 7xxx ingot by homogenizing the flow and temperature field thus significantly refining the crystal grain and reducing the macro-segregation of solute elements [9–11]. In this article, two kinds of 7050 aluminum ingots, CI and UI, were utilized to comparatively investigate the effect of ultrasonic vibration on microstructure and properties of as-cast and heat-treated alloys.

Experimental procedure

Conventional and ultrasonic casting 7050 aluminum ingots were included in these experiments. Both in conventional cast and ultrasonic cast, the nominal composition is Al-6.0%Zn-1.9%Mg-2.3%Cu, and the mass of each alloy for melting was about 400 kg. The weighted starting materials were melt and refined at about 780 °C in an electric furnace. After refined, the melt was transferred to a crystallizer of 300 mm in diameter as illustrated in Fig. 1. The sizes of ultrasonic and conventional ingots, separately cast continuously, are both $\Phi 300 \times 2000$ mm.

Details about ultrasonic cast are given here. The setup for ultrasonic sound vibrating mainly consisted of an ultrasonic generator with the frequency of 19 ± 0.5 kHz and the power of 240 W, an air-cooled converter made of piezoelectric lead zirconate titanate crystals, an acoustic radiator made of stainless steel. The 35-mm-in-radius cylindrical radiator was inserted to a depth of 20 mm below the surface of liquid metal to transmit ultrasonic vibration into aluminum melt.

After cast, the ultrasonic cast ingot and the conventional cast ingot were homogenized at 475 °C for 24 h with

H. Liu (✉) · X. Qiao · Z. Chen · R. Jiang
School of Materials Science and Engineering,
Central South University, ChangSha 410083,
HuNan, People's Republic of China
e-mail: hsliu@mail.csu.edu.cn

X. Li
School of Mechanical and Electrical Engineering,
Central South University, ChangSha 410083, HuNan,
People's Republic of China

subsequent hot rolling at 400 °C. Then, the rolled plates of CI and UI were solution treated at 480 °C for 2 h and water quenched followed by 48-h exposure in air at room temperature. Single-stage aging treatment was performed for these two kinds of plates at 120 °C for 4, 8, 12, 16, 20, 24, 28, 32, and 36 h, respectively.

Microstructure was observed through TEM (Tecnai G220ST) and SEM (KYKY2800). Specimens for tensile properties were plates with thickness of 3 mm, a rectangular cross-section and a gauge length of 50 mm. Typical tensile curves were obtained on CSS-44100 Universal materials tensile testing machine. In addition, the data reported here in tensile tests represents the average of at least three independent measurements, and the error of strength is less than 8 MPa.

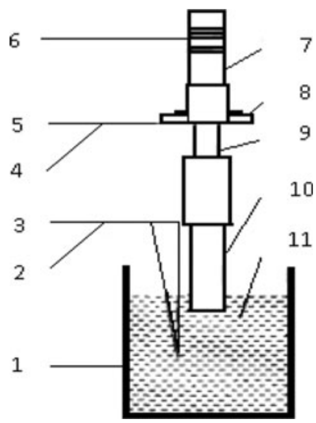

Fig. 1 Sketch of the setup for ultrasonic vibration to the melt. *1* Crystallizer, *2* Thermocouple, *3* Temperature controller and recorder, *4* Gripper, *5* Displacement operator, *6* Ultrasonic generator, *7* Ultrasonic convertor, *8* Flange plate, *9* Amplitude transformer, *10* Radiator, *11* 7050 aluminum melt

Results and discussion

Microstructure of ingots

Microstructures in the CI and UI are shown in Figs. 2 and 3, respectively. It is seen that the microstructure in UI is much finer than that in CI. In addition, from border to center of the ingots, the UI generally consists of fine equiaxed grains while CI shows heterogeneous size distribution of grains.

As illustrated in Fig. 2, when the ultrasonic wave was not applied to casting process, the microstructure from border to center mainly consists of coarse dendritic grains. In addition, distribution of secondary phase in the grains which has not dissolved is easily to be seen. The average size of the coarse grains in conventional ingot is larger than 80 μm. Whereas, UI is dominated with fine equiaxed grains, meanwhile little secondary phase can be observed. The average size is approximately 40 μm, less than half of that in the CI. All these microstructures mentioned above indicate that ultrasonic vibration can refine the grain size of 7050 ingot and improve the ingot quality as reported in Ref [12–15]. The fine grain size can be inherited even after hot-deformation and aging (Fig. 4).

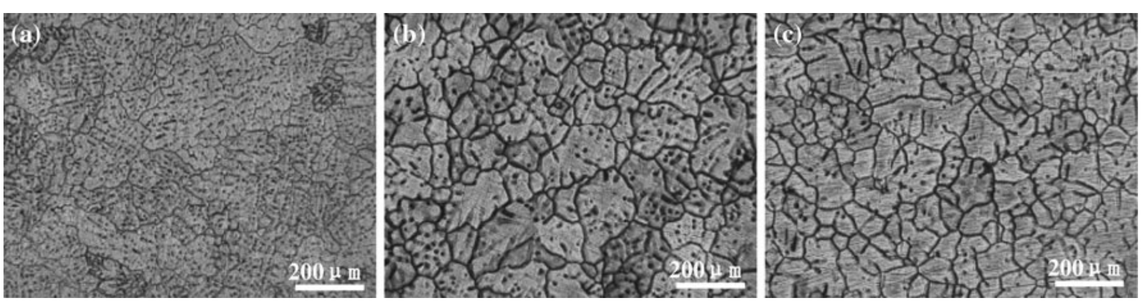

Fig. 2 The as-cast microstructure at various sites of CI. **a** border, **b** 1/2 radius, and **c** center

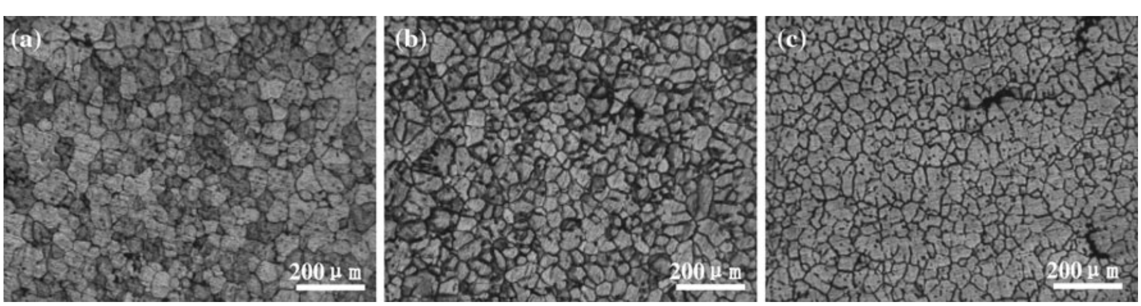

Fig. 3 The as-cast microstructure at various sites of UI. **a** border, **b** 1/2 radius, and **c** center

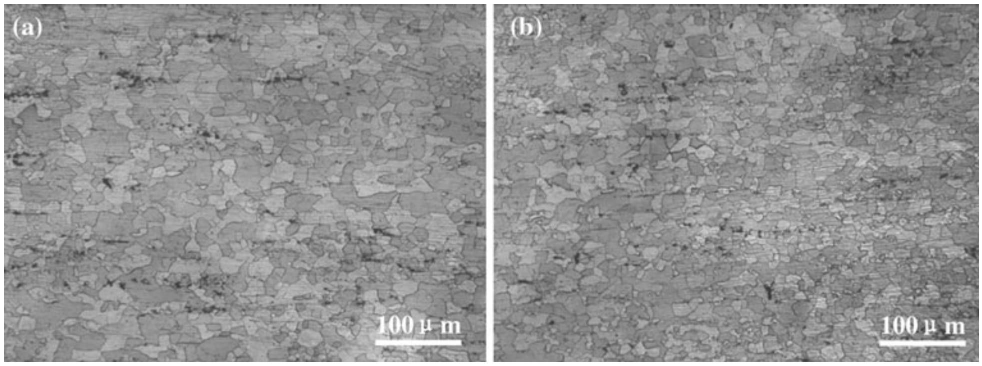

Fig. 4 Microstructure of the rolled plates after aged at 120 °C. **a** CI for 12 h. **b** UI for 8 h

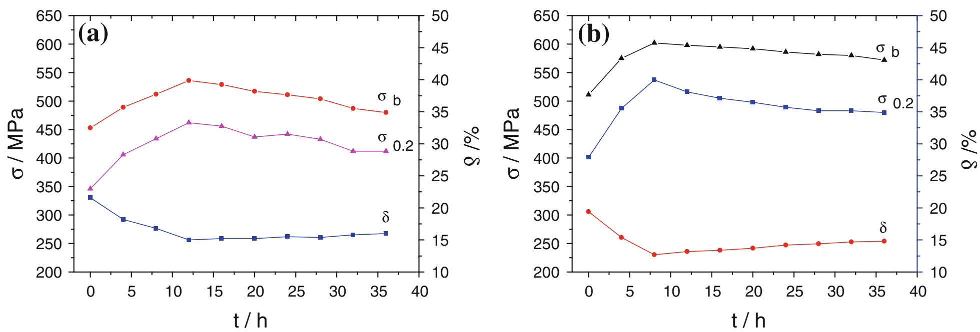

Fig. 5 Mechanical properties changing with aging time at 120 °C for hot-rolled 7050 plate. **a** CI. **b** UI

Researches have been carried out in recent years to the mechanism of ultrasonic vibration to the melt [16–18]. Cavitation effect and acoustic streaming will occur when high intensity ultrasonic sound is applied to the melt. The high amplitude of the acoustic pressure and sound pressure can cause the collapse of cavitation bubbles and melt agitation. What's more, with the effect of ultrasonic vibration, detachment and projection of crystalline particles into the body of the melt. Both these factors result in increase of nucleation rate, leading to a further rise of grain refinement in the as-cast microstructure in the ingot.

Mechanical properties and microstructures after aging

The tensile strength and elongation of 7050 hot-rolled plate after aging at 120 °C for different durations were measured as shown in Fig. 5. Apparently, the fracture strength of the rolled plate of CI reaches 536 MPa after aging for 12 h with the elongation of 15.0%, in comparison with those in the UI rolled plate, strength up to 602 MPa but elongation decreasing to 12.7%. This means that UI after aging can get a higher strength but lower elongation. The dispersed precipitates and the aging process contribute significantly to the strengthening effect [19–21].

Observations of precipitates were performed for the aged CI and UI and the TEM images are given in Figs. 6 and 7, respectively. It is well known that the precipitates in 7050 aluminum alloy may be G.P, η', and η with increasing aging temperature [22, 23]. Here, because the aging temperature is as high as 120 °C, the precipitating should be η' and η, and η' should plays the main role. From the shape of the precipitates, most of them are guessed to be η'. Comparing Fig. 6a with b, it can be seen that the η' phase in UI after aging is finer and more dispersed than that in CI after aging. The same circumstance occurs between Fig. 6c and d. In Fig. 7a and c, minority of cigar-shaped η phase is observed in the aged CI while it also can be seen that the η' phase is much fine after four more hours treatment. From Fig. 7b and d for UI, it can be determined that the precipitates are still fine and dispersed.

As shown in Figs. 6 and 7, wherever precipitates are at grain boundary or in grain, they are finer and more dispersed in UI alloy than those in CI alloy. The finer grain size in hot-rolled UI should at least partly contribute to the finer and dispersed precipitate in aged UI plate. It has been reported that fine-grained microstructure can accelerate the precipitation of new phase, and making precipitated phase more dispersed [24, 25]. Such dispersed precipitates and finer matrix grains will certainly cause aging strength [26–28].

Also from Figs. 6 and 7, we can see that the width of precipitate free zone (PFZ) is narrower in UI alloy than in CI alloy. It is known that the nucleation of precipitate is affected to some extent in the vicinity of grain boundaries, which results in the presence of PFZ. However, the influence factors to the nucleation of precipitate are still

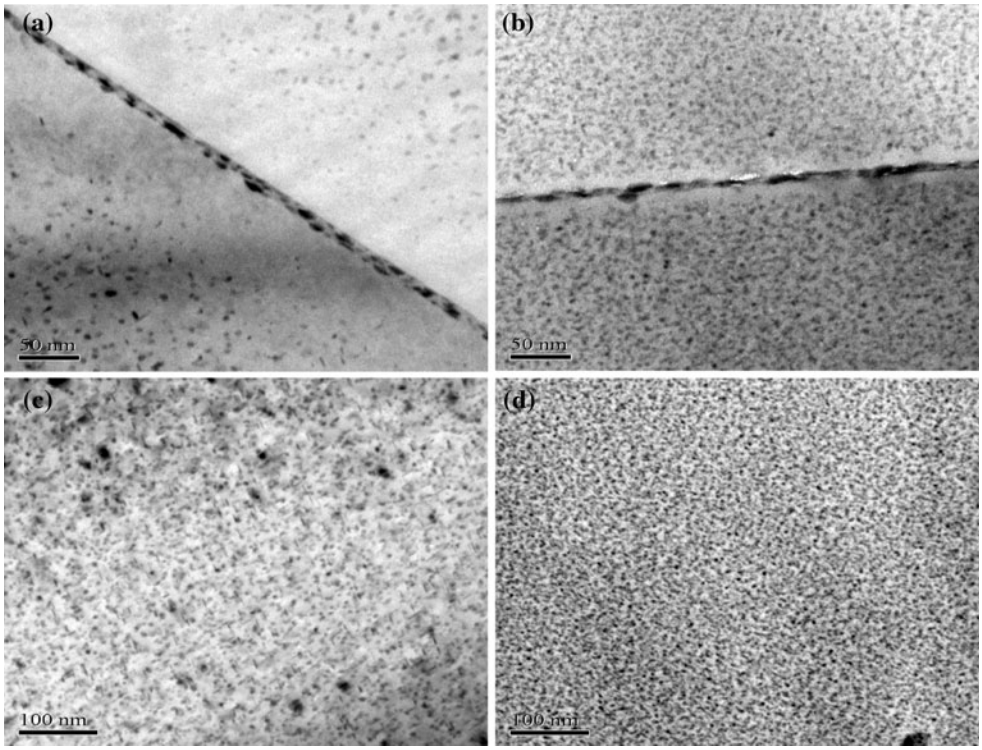

Fig. 6 TEM images of the 7050 aluminum alloy after aging at 120 °C for 8 h. **a**, **c** for CI. **b**, **d** for UI

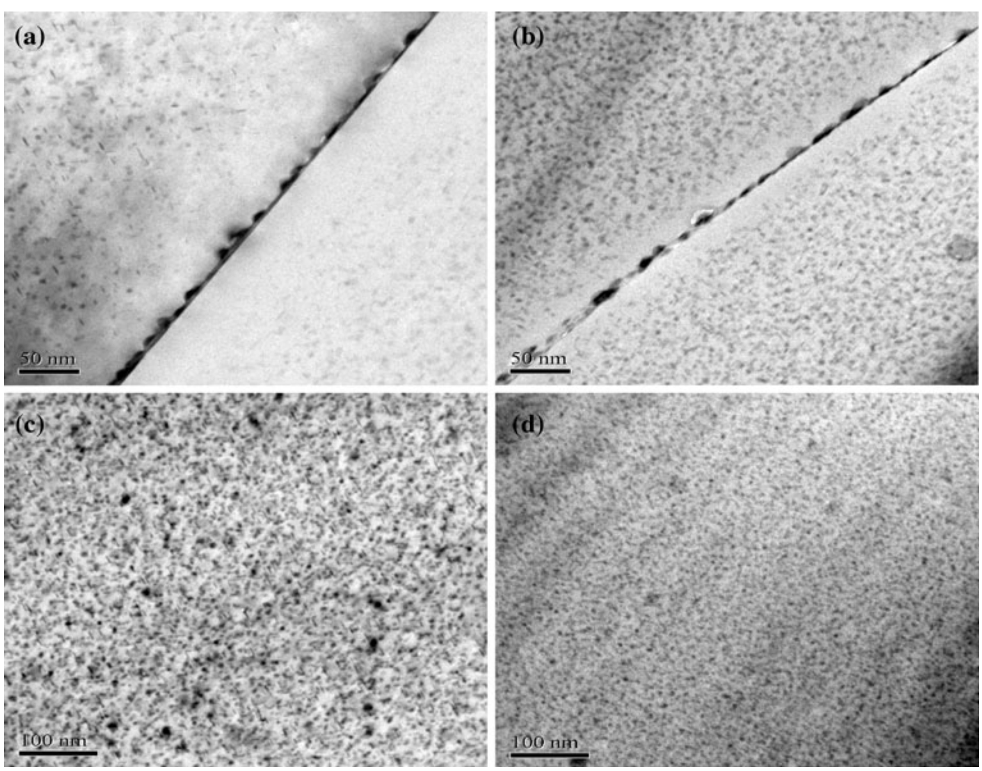

Fig. 7 TEM images of 7050 alloy aged at 120 °C for 12 h. **a**, **c** for CI. **b**, **d** for UI

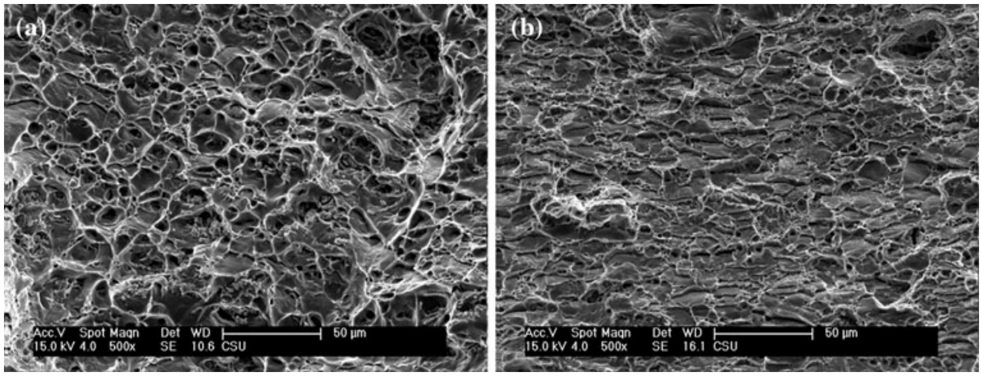

Fig. 8 SEM images of fracture for alloys aged at 120 °C. **a** CI for 12 h. **b** UI for 8 h

controversial. Here, the effect of PFZ on the mechanical properties of 7050 alloy is also not clear.

Tensile fractures of the peak-aged CI and UI alloys are shown in Fig. 8. Apparently, the fracture dimples in UI alloy are smaller, shallower and less obvious than those in CI alloy. This explains why the aged UI 7050 alloy can reach higher strength but is with lower elongation when compared with the aged CI 7050 alloy.

Conclusion

(1) Ultrasonic wave used during casting decreases grain size. The finer grain size can be inherited even after rolling and aging.
(2) The UI alloy has better age-hardening effect than the CI alloy. The tensile strength of peak-aging of UI can be up to 602 MPa in comparison with 536 MPa of CI, but UI shows less plasticity.

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