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Microstructure characteristics and tensile property of ultrasonic treated-thixocast A356 alloy

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Abstract: Billets of A356 aluminum alloy were treated using ultrasonic vibrations during solidification. The billets were reheated to the semisolid state at different routes to optimize the procedure. Billets were, then, thixocast using a die casting machine. The results showed that the ultrasonic-treated billets exhibited finely distributed α(Al) globules after reheating and thixocasting. The thixocast ultrasonic-treated billets showed higher ultimate tensile strength and elongation compared with the untreated billets. Moreover, the thixocast parts showed a tendency to ductile fracture under tension when made from ultrasonic-treated billets, while those made of untreated billets showed brittle fracture with obvious straight facets. These results revealed the feasibility and competence of ultrasonic melt treatment as a potential route for preparing billets for thixocasting.

Key words: A356 alloy; semi-solid forming; ultrasonic treatment; reheating; thixocasting; tensile property

1 Introduction

Various techniques have been developed recently for the production of high performance aluminum components, such as gravity die-casting, pressure die casting, squeeze casting and liquid metal forming. One of the major drawbacks of these processes, however, is the dendritic evolution of the microstructure which leads to defects and cracking. Many other difficulties are porosity, turbulent filling of mould and shrinkage. Research for overcoming these problems gave rise to a new forming process, namely the semisolid manufacturing (SSM) developed by FLEMINGS [1], for production of commercial components of extremely high casting integrity and excellent properties. In contrast with the conventional casting processes, SSM relies on the production of slurry which has the physical state between solidus and liquidus temperature (mushy state). According to the review of FAN [2], the billets for thixoforming processes can be prepared by several techniques such as mechanical stirring, magneto-hydrodynamic (MHD) stirring, spray casting, chemical grain refining, and ultrasonic treatment (UST). The MHD stirring is the most widespread practice for feed stock production. The main disadvantages of this technique are the high production cost, the microstructure non-uniformity in the cross section of the cast billet, and the non-spherical particle morphology.

Ultrasonic treatment of molten metal, on the other hand, can effectively produce metal slurry with fine, non-dendritic and homogeneous microstructure suitable for SSM processing. ESKIN [3] and BRODOVA et al [4] reported that the technology of UST is not complex and offers other advantageous such as degassing and enhanced grain refinement effects. HUANG et al [5] also found that ultrasonic treatment of aluminum melt can increase the number of wall crystals and inner crystals, contributing equally to a final refined structure in the solidified part. In addition, MEEK et al [6] observed a significant energy saving by use of UST. Moreover, the effective treatment time can be considerably short. Ultrasonic treatment of 15 s at 1−10 °C above the liquidus temperature provides fine non-dendritic structure in the research of KHALIFA et al [7,8]. The ultrasonic treatment showed potential effects in refining the primary silicon and Fe-intermetallic phases in hyper-eutectic Al−Si alloys, as well. This effect superseded

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that of phosphorous addition (50×10^{-6}) on both Si-particle refining and wear resistance [9].

In the current work, non-dendritic A356 billets were prepared using ultrasonic waves. The effect of ultrasonic treatment on the microstructure of the billets before and after reheating was investigated. The tensile property of the UST-thixocast product was evaluated and explained in terms of the influence of UST on the final microstructure of the samples.

2 Experimental

2.1 Processing of billets by UST

Ingots of A356 alloy (Table 1) were heated to a temperature of 730 °C, and then degassed with dry Ar using hollow lance for 20 min. Ultrasonic treatment was performed at different pouring temperatures (630−680 °C) in order to select the optimum UST temperature of the alloy. Crucible was made from stainless steel with 40 mm in diameter at the bottom, and 44 mm in diameter at the top, and 70 mm in height, 3 mm in thickness. Ultrasonic treatment of the solidifying alloy was carried out continuously from the pouring temperature up to solidification using the ultrasonic system shown in Fig. 1. Ultrasonic vibrations are transferred through a horizontal guide rod and vertical guide plate to the mold, which is made of stainless steel in the form of crucible. The vibrations are, thus, transferred to the solidifying alloy through the bottom and walls of the crucible horn. The ultrasonic system provides a power of 2 kW, frequency of 19.5 kHz, and vibration amplitude of 25−30 μm at the bottom of crucible. The capacity of the crucible is about 1.3 kg liquid aluminum. The crucible temperature was kept at room temperature during all experiments. The microstructure of some samples was qualitatively investigated to decide the optimum UST condition.

Table 1 Chemical composition of A356 alloy (mass fraction, %)

Si	Mg	Fe	Ti	Zn	Mn	Cr	Cu
7.01	0.38	0.70	0.02	0.01	<0.01	<0.01	<0.01

Sr	Sb	Ca	Na	P	Bi	Al
<0.0005	<0.002	0.003	0.0005	0.0004	<0.001	Bal.

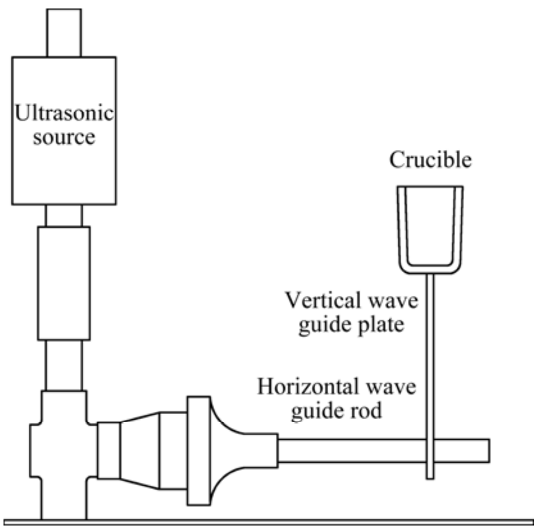

Fig. 1 Setup for ultrasonic treatment of solidifying alloy

2.2 Reheating to semisolid state

In order to decide the optimum reheating condition, cubic samples were prepared from the billets and then reheated for 6 min and a cube was drawn at different temperatures. A reheating temperature of 582 °C for 6 min showed the most homogeneous structure with fine globules. The prepared billets (UST-630 °C) were then preheated at the optimum reheating condition (582 °C for 6 min), in an induction furnace. Reheating crucible was made from porous alumina, and a graphite coated vertical split-type crucible for easy feeding into the die casting machine. The upper surface of billet was made flat by machining and a hole was drilled to the center of the billet. The typical preheating curves were shown in Fig. 2. For the investigated alloy, at a slurry temperature of 583 °C, the solid fraction was found to be 0.5 [10]. This fraction is expected not to change that much between 582 and 586 °C since these alloys have a small temperature sensitivity of solid fraction [2].

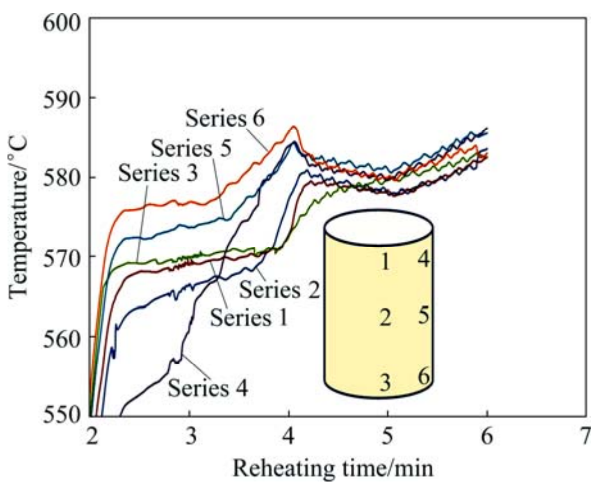

Fig. 2 Typical reheating curves at six positions during induction heating of billets for 6 min (temperature range is 582.5−586.6 °C)

The experimental setting shown in Fig. 3 was used for thixocasting. A stainless steel die was used. The preheating temperatures of the sleeve and the die were 450 °C and 270 °C, respectively. Plunger tip moving speed was 63 mm/s and the maximum applied force applied to the plunger tip was 2 t.

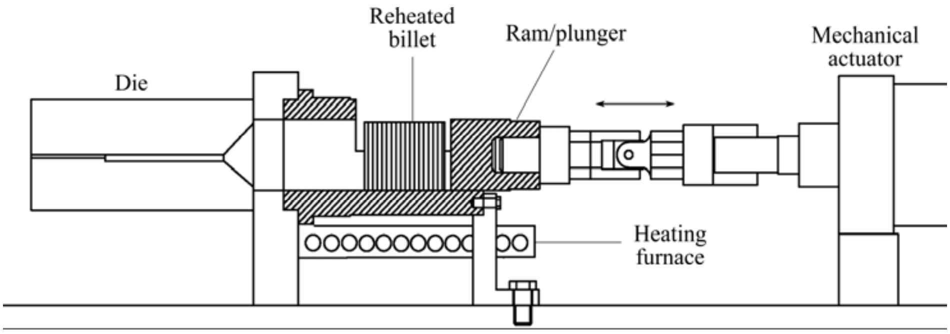

Fig. 3 Experimental set up for thixocasting

2.3 Investigation of samples

The flat surface (i.e., half of the ingot cross-section) of each sample was polished and etched with Keller's reagent. The microstructure features were investigated at three stages: after UST, after billets reheating and finally after thixocasting. The effect of ultrasonic treatment on the microstructure of the processed billets was studied based on the grain size and globularity of the *α*(Al) grains. Tensile test was carried out using the standard sample shown in Fig. 4.

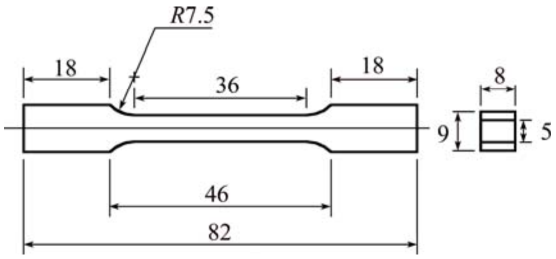

Fig. 4 Dimensions of tensile samples (unit: mm)

3 Results and discussion

3.1 Effect of processing by UST

The ultrasonic treatment in the current work was carried out from the pouring temperature and down to 560 °C. The billets prepared by ultrasonic treatment at different pouring temperatures (630−680 °C) showed different degrees of microstructure modification. However, the samples ultrasonically treated at 630 °C showed the most homogeneous and refined structure among all the other samples. Figure 5 shows the cooling curves of A356 alloy without and with UST at 630 °C.

The optical micrographs of the untreated and ultrasonically treated billets with optimum treatment condition (630 °C) are shown in Figs. 6(a−d). As presented in Fig. 6, treatment by ultrasonic vibrations in the liquid state results in continuous refining of the *α*(Al) grains (from 145 to 100 μm) and partial elimination of dendritic structure (Fig. 6(b,d)) compared with untreated melt as shown in Figs. 6(a) and (c). This leads us to expect more globular Al grains in the reheated billets.

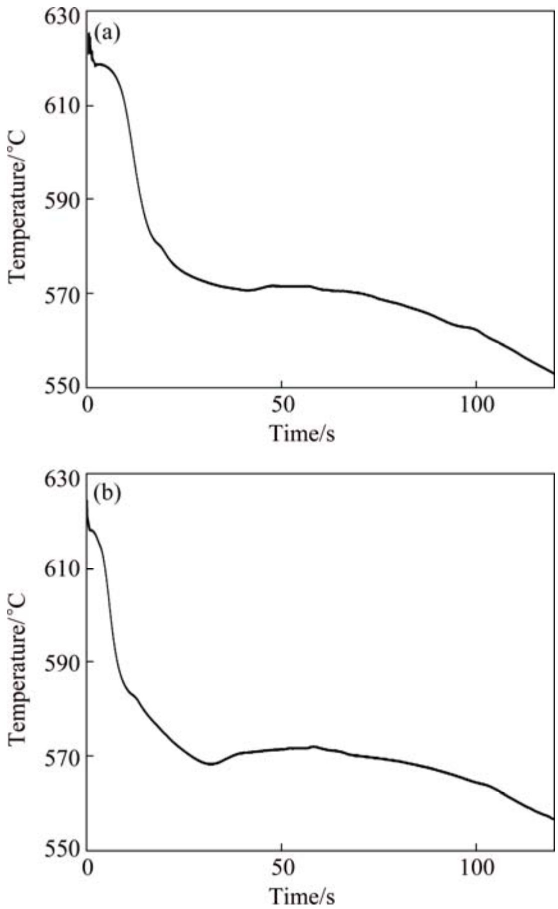

Fig. 5 Cooling curves for pouring at 630 °C: (a) Without UST; (b) With UST

The observed microstructure refinement by UST was previously discussed by many researchers. ESKIN [3] owed the refining effect of ultrasonic vibrations to two main mechanisms: cavitation-enhanced heterogeneous nucleation and dendrite fragmentation. Cavitation-enhanced heterogeneous nucleation as explained by AGHAYANI and NIROUMAND [11] occurs when ultrasonic vibrations cause local random compression–expansion cycles in the melt. When the local pressure in the melt becomes less than its vapor pressure during the half-period of expansion, a cavity is formed. The cavity continues to grow until collapses

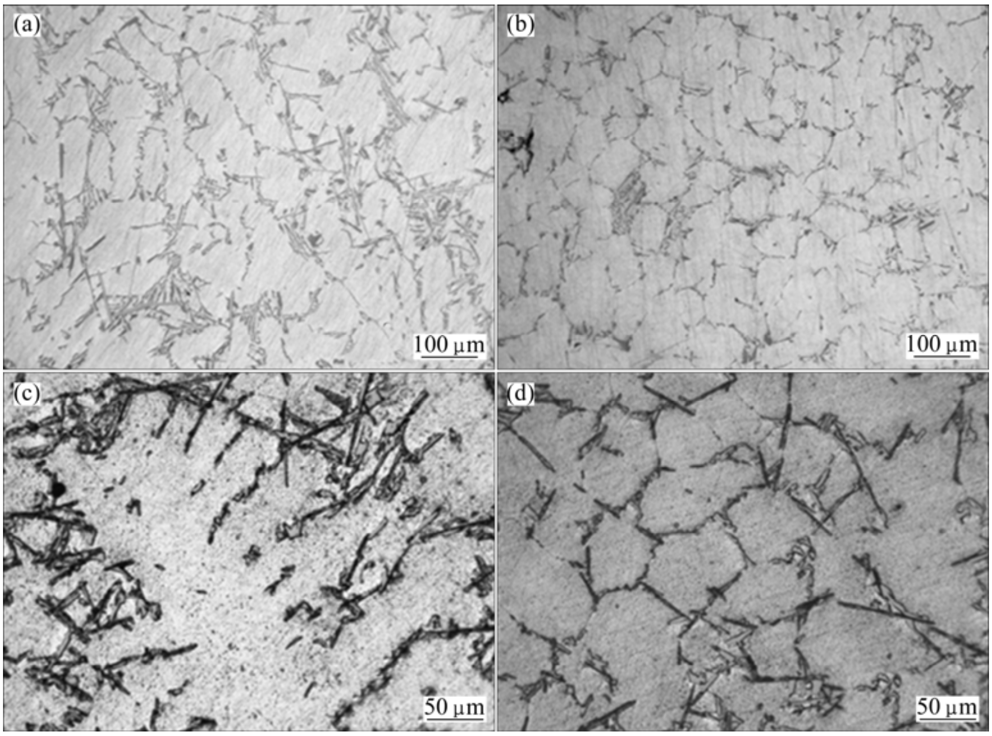

Fig. 6 Microstructures of untreated and ultrasonically treated billets with optimum treatment condition (continuous treatment from pouring at 630 °C down to 560 °C): (a) Without UST; (b) With UST; (c) Without UST (etched); (d) With UST (etched)

during the half-period of compression, thus producing a high intensity shock wave in the melt. Under the action of high intensity of shock, as reported by PUGA et al [12], the insoluble solid impurities throughout the melt become active and involve in the solidification of process, promoting heterogeneous nucleation. Cavitation-enhanced heterogeneous nucleation is the expected refining mechanism in our experiments and it seems to be the most valid hypothesis, as claimed by JIAN et al [13] and QIAN et al [14].

According to ATAMANENKO et al [15] and NIE et al [16], these acoustically induced nuclei are highly thermodynamically unstable and their survival time depends strongly on the melt temperature. In the current work, therefore, we tried ultrasonic treatment at different temperatures in order to decide the optimum treatment condition of this alloy. It is observed that, as the melt temperature increases, more coarse grains evolve. Figures 7(a) and (b) represent the optical microstructure of the samples treated at 640 °C and 680 °C, respectively. The coarsening of microstructure with increasing UST temperature is because the survival time of the nuclei decreases as the treatment temperature increases and hence number of available nucleation sites for the new grains decreases. This is also in agreement with our previous work on a B390-hyper eutectic Al−Si alloy [9], where the primary Si particles became smaller in size as the pouring temperature decreases.

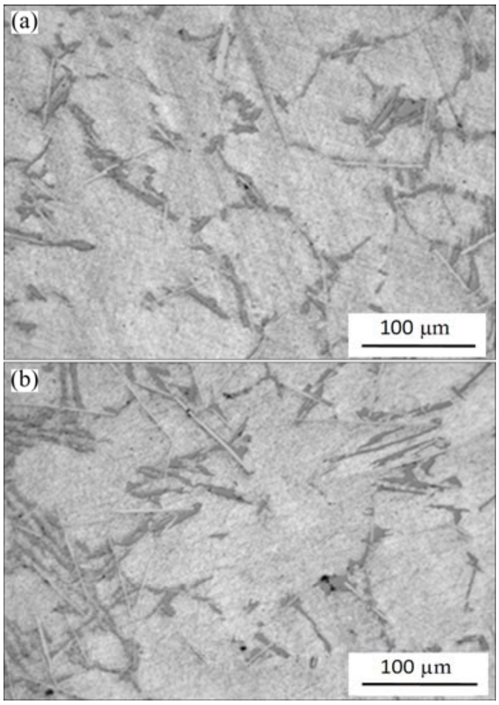

Fig. 7 Optical microstructures of ultrasonically treated A356 billets at 640 °C (a) and 680 °C (b)

3.2 Microstructure of reheated billets

According to HIRT et al [17], subsequent to the production of billets with non-dendritic microstructure, the process of reheating the billet to the desired semisolid temperature is also a challenging task. It was reported that the evolved microstructure after reheating depends strongly on the initial as-cast microstructure [18]. Since the initial microstructure shown in Fig. 6(b) for the ultrasonic treated billet (630 °C) is composed of fine non dendritic grains, it is expected that this billet will have globular structure after reheating to the semisolid state.

The selection of induction heating parameters is of utmost importance in obtaining a sound casting with desired microstructure and mechanical properties as stated by LAKSHMI et al [18]. Regarding the reheating time, WANG et al [19] reported that the time taken for the material to be globular upon reheating depends on the initial grain morphology and grain size. It changes from 10 min for a fine dendritic structure to 8 min for a fine rosette-like structure and 5 min for a fine globular structure. In the current work, where we have a fine non-dendritic structure, 6 min were applied. Figures 8(a)−(d) represent the microstructure of the reheated cubes at 578, 580, 582 and 600 °C, respectively. It is obvious that the globules size and distribution vary with the reheating temperature. Finer and more homogeneous structure is obtained in the case of reheating to 582 °C. A globule size of around 50 μm with a roundness of 0.7 was obtained at the optimum reheating condition of the billet as shown in Fig. 9.

3.3 Microstructure and mechanical properties after thixocasting

The microstructure refinement is known to play an essential role in the mechanical properties of the Al−Si alloys. The microstructure of the thixocast parts has further confirmed the structure refinement by ultrasonic treatment. Figure 10 shows the microstructure of the deformed billet, which was reheated at the optimum temperature (582 °C). The deformed structure is characterized by globular-nondendritic structure with

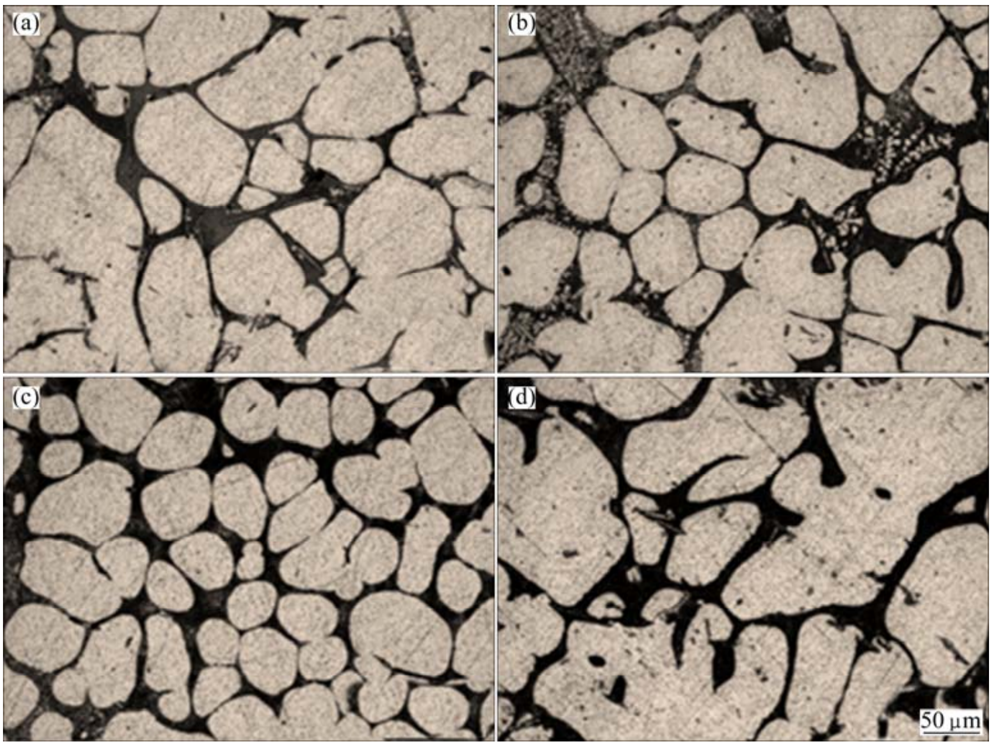

Fig. 8 Microstructures of billets reheated at 578 °C (a), 580 °C (b), 582 °C (c) and 600 °C (d)

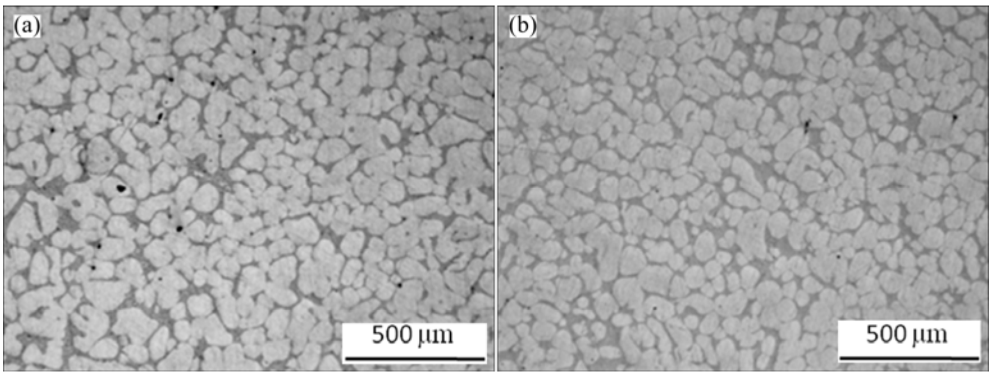

Fig. 9 Microstructures of billet reheated at 582 °C: (a) Center of billet; (b) Surface of billet

finer grain size as shown in Figs. 10(a) and (b). On the other hand, the untreated billet maintains its original dendritic structure after thixocasting, as shown Figs. 10(c) and (d).

Figure 11 shows the SEM images, EDS line scannings and EDS elemental mappings of Si and Fe after thixocasting with and without UST respectively at pouring temperature of 630 °C. A significant refinement of α(Al) grains is observed. Moreover, the long Fe-intermetallic platelets in the sample without UST are relatively broken into a highly desirable fine compacted form as shown in Fig. 10(b).

This deformed microstructure constituting of globular Al grains along with relatively fine Fe-intermetallics is expected to show a notable difference in the mechanical properties. The tensile test results show that the ultimate tensile strength and elongation of the thixocast-UST billets are 147 MPa and 3.6% compared with 125 MPa and 2.5% for the untreated billets. LÜ et al [20] have also observed that the tensile properties of the rheocasting samples, where the semisolid slurry was prepared by ultrasonic vibrations are considerably higher than those of the conventional casting ones. The beneficial results of ultrasonic vibration on the mechanical properties of the treated alloy as confirmed by GAO et al [21] are usually due to its effect on grain

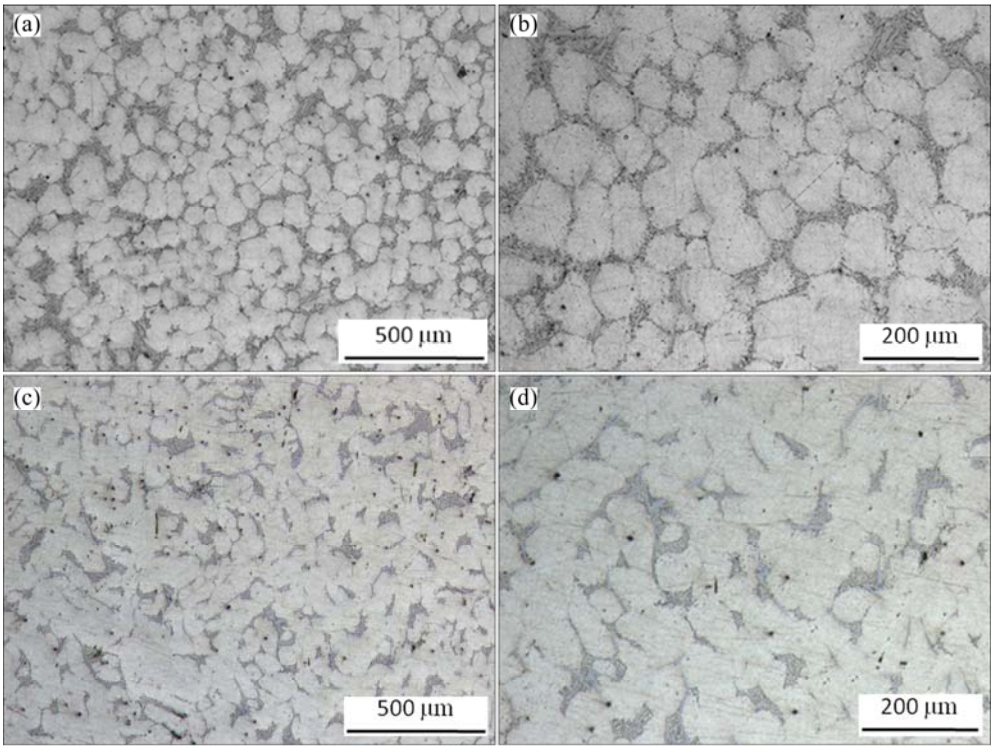

Fig. 10 Microstructures of thixocast parts: (a, b) With UST; (c, d) Without UST

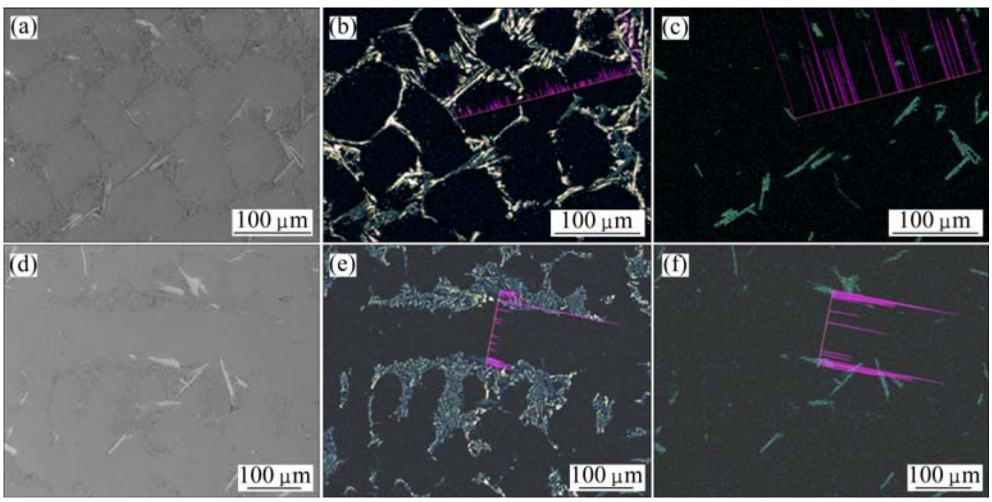

Fig. 11 SEM images and EDS elemental mapping of A356 alloy after thixocasting: (a−c) With UST; (d−f) Without UST; (a, d) SEM image; (b, e) Si mapping; (c, f) Fe mapping

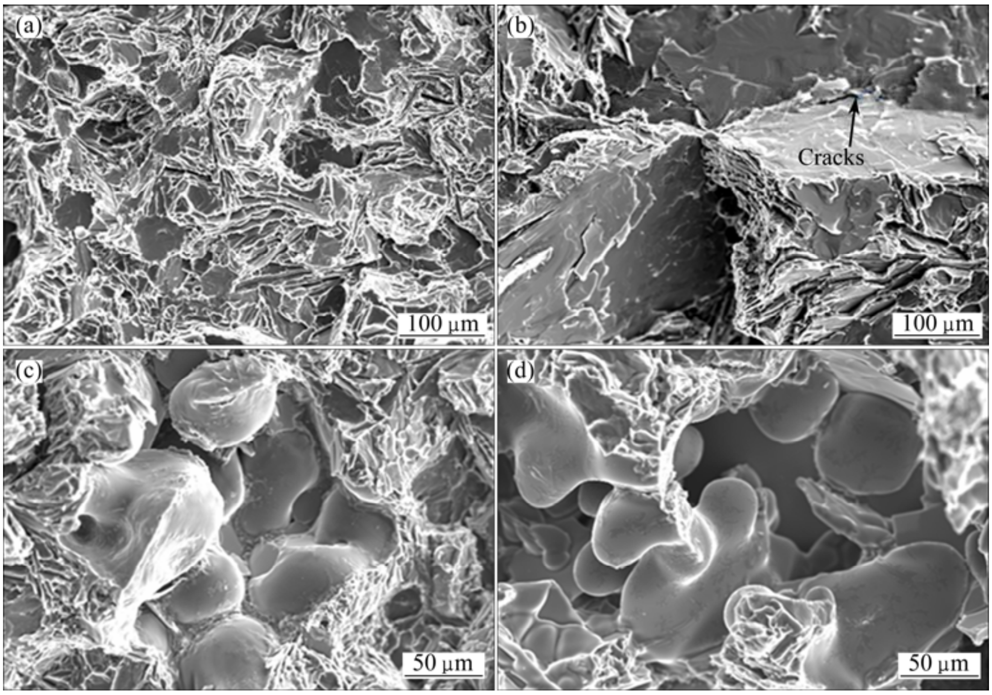

Fig. 12 Fractographs of tensile samples with (a, c) and without (b, d) UST

refinement during the solidification of the alloy.

Here, it is worth mentioning that the tensile properties are not high since the tensile test bars were machined from the die cast pieces and then tested for mechanical properties. The machining of cast sample pieces is not recommended and usually cast alloys are cast into tensile-specimen shape for testing. In addition, the tensile test was performed on the as-deformed samples without any prior heat treatment. If heat treatments were performed, higher tensile strength values would be expected.

The fractographs of the tensile samples were investigated by SEM and represented in Fig. 12. In the case of ultrasonic treated billets, as shown in Figs. 12(a) and (c), the fracture surface was composed of fine dimples indicating tendency to ductile fracture mode. The surface of untreated billets, as shown in Figs. 12(b) and (d), showed coarse dimples and the fracture was brittle with entire cracks.

4 Conclusions

1) Ultrasonic treatment in the liquid state is an efficient method for preparation of refined grain non-dendritic billets for thixocasting.

2) Ultrasonically treated billets exhibited finely distributed α(Al) globules after reheating and thixocasting.

3) The thixocast-UST billets showed higher ultimate tensile strength and elongation (147 MPa, 3.6%) compared with (125 MPa, 2.5%) the untreated billets. Moreover, thixocast-UST billet showed tendency to ductile fracture upon testing for tensile strength while the untreated billets showed brittle fracture with straight facets.

4) These results reveal the feasibility and competence of UST as a potential route for processing and grain refinement of billets for thixocasting.

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超声处理触变铸造 A356 合金的显微组织特征和拉伸性能

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摘　要：在 A356 合金凝固过程中，对锭坯进行超声振动处理。采用不同工艺将锭坯重新加热至半固态，然后采用模铸机进行触变铸造。结果表明，经重新加热和触变铸造后，超声处理的锭坯具有均匀分布的细小球状 α(Al)。与未进行超声处理的锭坯相比，经超声处理的触变铸造锭坯具有更高的拉伸强度和伸长率。经超声处理的触变铸造锭坯在拉力作用下表现出韧性断裂倾向，而未经处理的锭坯则呈现出明显的小刻面，表现为脆性断裂。超声熔体处理作为一种触变铸造的处理方法具有可行性和竞争力。

关键词：A356 合金；半固态成形；超声处理；重新加热；触变铸造；拉伸性能

(Edited by Yun-bin HE)