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ARTICLE

Microstructure and Mechanical Properties of as-Cast Al-5.0Cu-0.6Mn-0.6Fe Alloy Produced by Ultrasonic Vibration and Applied Pressure

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Abstract: The combined effect of ultrasonic vibration (UT) and applied pressure (P) on the microstructure and mechanical properties of the as-cast Al-5.0Cu-0.6Mn-0.6Fe alloy was investigated by optical microscope (OM), scanning electron microscope (SEM) coupled with energy dispersive X-ray (EDX), image analysis as well as tensile test. The results show that the P+UT processing has an significant effect on the morphology and size of α-Al, Fe-rich intermetallics, and Al_2Cu, which promotes the morphology of α-Al transformation from dendritic to globular structure and significantly reduces the size of α-Fe, Al_6(FeMn), and Al_2Cu phase. The P+UT processing is helpful to reduce the degree of bimodal structure which usually occurs during squeeze casting. It is also effective to reduce the segregation along the grain boundary. The best tensile properties of as-cast alloy produced by the P+UT are ultimate tensile strength (UTS) 268 MPa, yield strength (YS) 192 MPa, and elongation 17.1%, which are 64%, 59%, and 307% higher than those of the non-treated alloy, respectively.

Key words: ultrasonic; pressure; microstructure; grain refinement

The Al-Cu-based cast alloys have been widely used in transportation, aerospace, and military industries because of their excellent mechanical properties and low cost. However, Fe is the common and inevitable impurity in Al-Cu alloys, especially in the recycled Al-Cu alloys. Because of the low solubility in Al-Cu alloys[1], Fe usually exists in the form of Fe-rich intermetallics, which are very brittle and deteriorate the mechanical properties of Al-Cu alloys[2]. The morphology, size, and distribution of Fe-rich intermetallics significantly affect the mechanical properties of the alloy. For example, the formation of α-Fe with Chinese script morphology rather than β-Fe with needle-like morphology is less harmful to the mechanical properties of the alloy[3]. Therefore, it is important to develop appropriate methods to modify the morphology of Fe-rich intermetallics, thus minimizing their detrimental effect.

Recently, the application of combined fields, e.g., ultrasonic vibration and electromagnetic fields, in solidification has attracted much attention. Ultrasonic vibration has been proved to be an environmentally benign and efficient method to refine the microstructure and improve the mechanical properties of the alloys during solidification[4]. Zhai et al.[5,6] have shown that the ultrasonic field brings about a striking size refinement effect to the primary phases of Al and Cu alloys and enhance the mechanical properties of these alloys. Haghayeghi et al.[7] and Zhang et al.[8] obtained a refined and uniform microstructure by applying electromagnetic and ultrasonic fields to Al alloys during the solidification. By applying indirect ultrasonic vibration into semi-solid slurry of Al alloy followed by direct squeeze casting, Lv et

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al.[9] reported that the alloy exhibited a uniform microstructure and enhanced mechanical property. Combined magnetic fields can also be used to refine the grains of Al alloy, as demonstrated by Haghayeghi et al.[10], who obtained a more refined microstructure than that obtained using a single field. Jiao et al.[11] investigated the ultrasonic and magnetic coupled field on the TiB_2/7055Al nano-composites, and found that the coupled field promotes the formation of refined, ball shape, and uniform distribution TiB_2 particles and the efficiency of reaction to generate TiB_2 particles is improved. Squeeze casting has a short route, high efficiency, and precise forming, features of casting and plastic processing, which are often used to prepare high-performance Al alloys[12]. Our previous studies[13,14] have found that the P+UT processing is an effective way to refine the microstructure. However, the effect of ultrasonic vibration on aluminum alloys during squeeze casting has been rarely studied. In this study, the effect of combined ultrasonic vibration and applied pressure on the microstructures of the as-cast Al-5.0Cu-0.6Mn-0.6Fe alloy was investigated, and the resulting mechanical properties were evaluated.

1 Experiment

The chemical composition of Al-5.0Cu-0.6Mn-0.6Fe alloys were Cu 5.4%, Mn 0.63%, Fe 0.63%, and Al balance (wt%). First, 6 kg raw materials were melted at 750 °C in an electric resistance furnace; nitrogen was introduced to minimize the hydrogen content. The experimental equipment is shown in Fig.1a. The ultrasonic vibration system consists of a 1000 W generator, 20 kHz transducer, and a Ti alloys horn. The die temperature was set at approximately 200 °C, and the pouring temperature was about 710 °C. The ultrasonic power was 900 W before the horn was preheated to 600 °C, and the applied pressure was 50 MPa. The processes worked simultaneously for 30 s. Finally, the samples with a size of 75 mm×75 mm×70 mm were obtained.

The samples were cut at different positions of the ingots, as shown in Fig.1b. The samples for metallographic observation were taken from the ingot near the horn with a size of Φ10 mm×2 mm, and they were etched with a 0.5 mL HF solution for 30 s. The diameter of the Fe-rich intermetallics, second dendrite arm space (SDAS), and volume fraction of porosity were measured using a Leica light optical microscope equipped with an image analyzer. In quantitative stereology, the measured area fraction is assumed to be equal to the volume fraction. The diameter of Fe-rich intermetallics in this study is defined as follows:

$$d = 2\sqrt{\frac{A}{\pi}} \quad (1)$$

where d and A are the diameter and area of the Fe-rich intermetallics, respectively. Tensile test was carried out using a SANS CMT5105 standard testing machine with a strain rate of 1 mm/min. The dimension of the tensile sample in Ref.[15] was applied in this study.

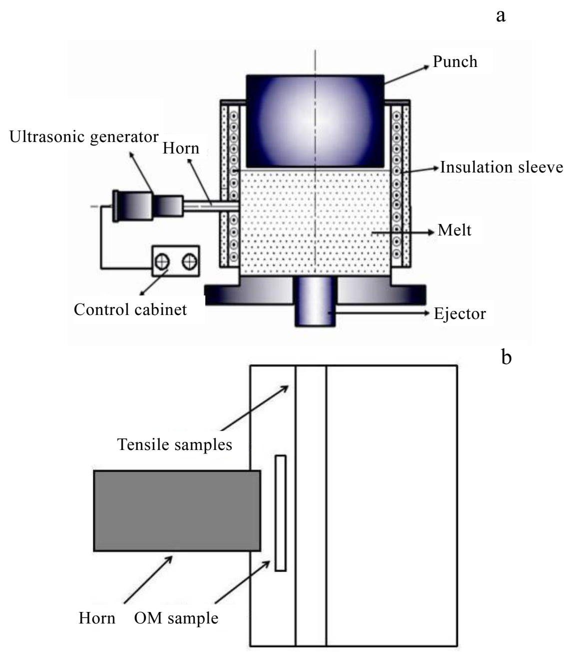

Fig.1 Schematics view of the combined ultrasonic vibration and squeeze casting equipment (a); the positions of sample taken from an ingot (b)

2 Results and Discussion

2.1 Microstructural analysis

Fig.2 shows the microstructures of the alloys obtained by different methods, such as no treatment (non-treated), pressure (P), ultrasonic treatment (UT), and combined applied pressures and ultrasonic treatment (P+UT). The coarse Fe-rich intermetallics with high porosities are dispersed among the fully developed α-Al dendrites in the non-treated alloy (Fig. 2a). Fig. 2b shows that the porosity is difficult to observe, and the α-Al grains are slightly refined under pressure. However, a bimodal structure[16] with distinct regions of poor and rich intermetallics is observed in the alloy. Fig.2c shows that the α-Al dendrite becomes more globular, and the porosity decreases slightly, consistent with what reported by Puga et al. [17] and Lv et al. [18] where UT was applied to the melt during the solidification. As shown in Fig.2d, when the alloy is prepared by combined P and UT, the alloy with significant refined α-Al dendrites and porosity-free is obtained, which indicates that combined treatment promotes the refinement of phases and reduction of porosity.

The SEM images of the samples prepared by different methods are shown in Fig. 3. It is more clear to see the morphology of the second phases. The microstructure of the alloy consists of α-Al dendrites, eutectic phase Al_2Cu and

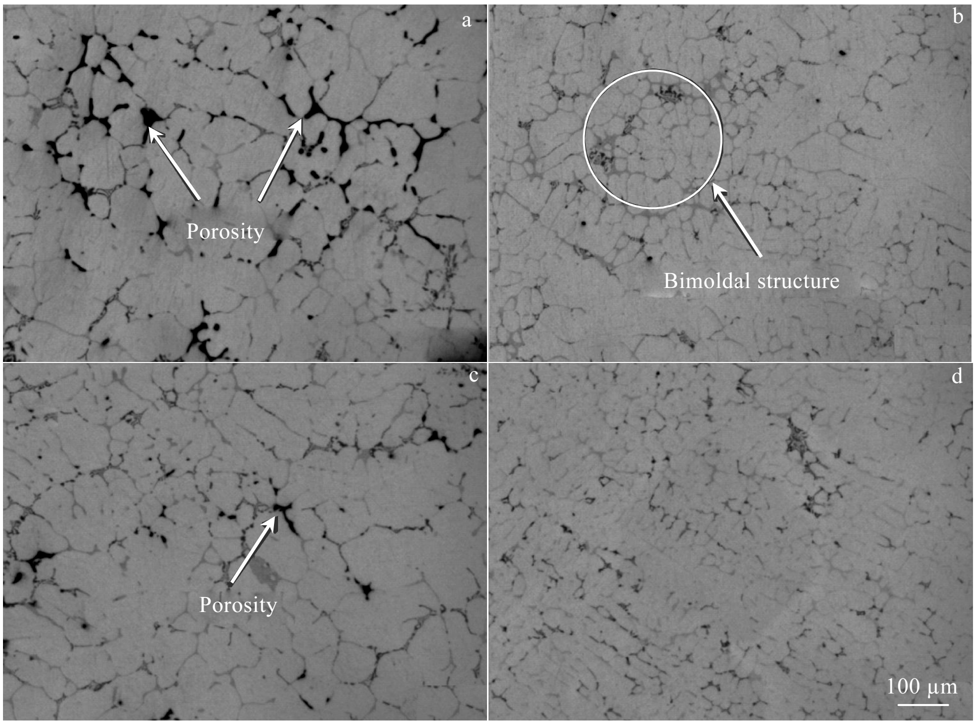

Fig.2 Microstructures of Al-5.0Cu-0.6Mn-0.6Fe alloys prepared by different methods: (a) non-treated, (b) P, (c) UT, and (d) P+UT

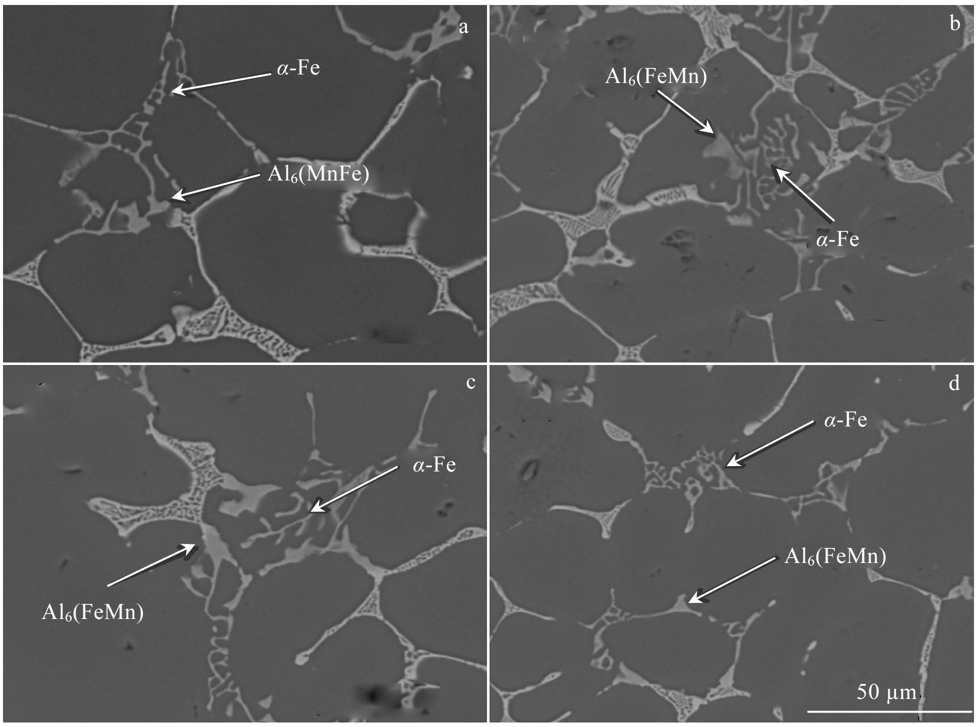

Fig.3 SEM images of Al-5.0Cu-0.6Mn-0.6Fe alloys prepared by different methods: (a) non-treated, (b) P, (c) UT, and (d) P+UT

Fe-rich intermetallics, i.e., mainly α-Fe ($Al_{15}(FeMn)_3Cu_2$) and some $Al_6(FeMn)$. These results are consistent with those obtained by Lin et al. [15]. It can be seen from Fig.2 and Fig.3 that the P+UT processing significantly affects the microstructure of the studied alloy, particularly the morphology and size of α-Al, Fe-rich intermetallics and Al_2Cu. The combined treatment promotes the morphology transformation of α-Al grains from dendritic to a more globular structure and significantly refines the α-Fe, $Al_6(FeMn)$, and Al_2Cu phase.

The quantitative measurements of the Fe-rich intermetallics, the SDAS and porosity results are shown in Fig.4. It is clear from Fig.4a that the diameter of Fe-rich intermetallics of the alloy under P+UT is significantly smaller than those obtained by individual processes, i.e., P or UT. As the processing is changed from the non-treated to P+UT, the diameter of Fe-rich intermetallics decreases from 81 μm to 30 μm, which is around 170 % lower than that of non-treated alloy. Previous studies[15,17] have shown that both ultrasonic vibration and applied pressure have a remarkable influence on the porosity. Fig.4b shows the porosity levels of the alloys prepared by non-treated, P, UT, and P+UT processing methods. The porosity levels are of 2.1%, 0.1%, 0.6% and 0%, respectively. Obviously, the P+UT processing is more effective to obtain the porosity-free microstructure.

The schematic of microstructures of alloys prepared by different methods are shown in Fig.5. In the non-treated alloy, the coarse column crystal nucleates and grow along the vertical direction of the die wall during solidification (Fig. 5a). In the alloy prepared by P, the applied pressure helps the melts to fill into the micro-pores, makes the castings shrink and porosity decrease, reduces the air gap between the melt and die, and increases the cooling rate[19,20] which results in promotion of grain refinement (Fig. 5b). In the alloy treated by UT, the implosion of cavitation bubble induced high pressure is helpful to enhance the homogeneous nucleation and increase the level of local undercooling and the dendrite is fragmented by the acoustic streaming at the same time (Fig. 5c). In the alloy produced by P+UT, the ultrasonic cavitation, acoustic streaming, and applied pressure interactive on the melts simultaneously lead to the final refined and homogeneous microstructure (Fig.5d).

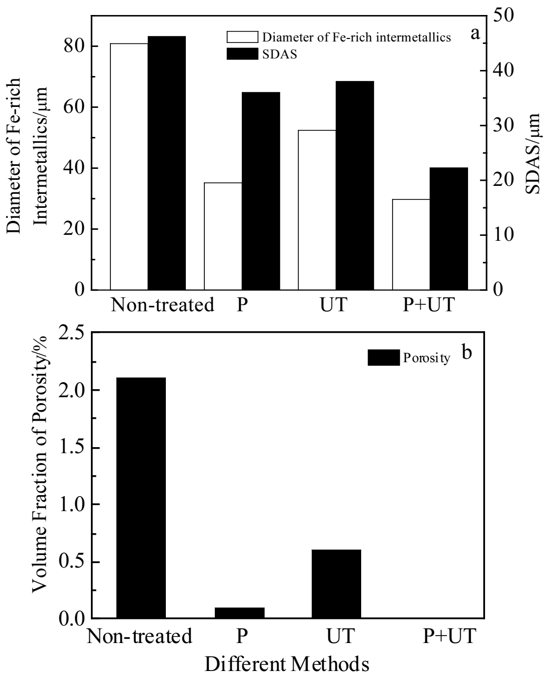

Fig.4 Microstructural characteristics of alloys prepared by different methods: (a) diameter of Fe-rich intermetallics and SDAS and (b) volume fraction of porosity

In order to clarify the mechanism of P+UT which refine the intermetallics, eliminate the porosity, and reduce the segregation, the reasons are explained as the following three aspects in detail. Firstly, the ultrasonic cavitation and acoustic streaming have an important impact on the melts when the ultrasound propagates the melt during solidification. The ever-changing ultrasound waves which lead to alternations of positive and negative pressure field result in the growing and implosion of cavitation bubbles. With the growing of the cavitation bubble, the pre-existing embryo crystals of near the liquid-solid surface grow into crystal nuclei. And the crystal grains can be broken up by high-pressure shock induced by the implosion of cavitation bubbles. Meanwhile, the applied pressure reduces the air gap between the melt and die and increases the cooling rate thus leading to local undercooling. Hence, the alloy produced by P+UT processing often accompanies the changes of temperature, pressure and volume, the Clausius-clapeyron equation can be used to describe their interrelationship:

$$\frac{dT_f}{dP} = \frac{T_f(V_l - V_s)}{L_f} \quad (2)$$

where T_f is the equilibrium melting point, P is the applied pressure, V_l and V_s are the specific volumes of the liquid and solid, respectively, and L_f is the latent heat of freezing. When high intensity ultrasound propagates in the melt, the energy of the collapsing cavitation bubbles is transformed into pressure pulses up to 1000 MPa [4]. The pressure pulse arising from the collapse of bubbles alters the equilibrium melting point T_f. An increase in T_m is equivalent to an increase in the under-cooling, so that an enhanced nucleation event is expected[9]. Thus it leads to the formation of the globular and refined α-Al dendrites and modified α-Fe and $Al_6(FeMn)$ phase[4,18]. Secondly, acoustic streaming stirring is another dominant mechanism to break up the dendrite in the liquid-solid interface and then makes them redistribute homogeneously into the bulk liquid and this is the ideal place for nucleating new grains. Reducing the degree of bimodal structure which usually occurs under applied pressure and reduces the segregation along the grain boundary can be explained by these reasons. Thirdly, the P+UT processing is favorable to eliminate the defects, such as solidification shrinkage and porosity[18, 21] because the applied pressure forces the liquid feeding into porosities.

2.2 Mechanical properties analysis

The mechanical properties of the as-cast alloys for four conditions are presented in Table 1. It can be seen that the optimal properties (UTS: 268 MPa, YS: 192 MPa, and Elongation: 17.1 %) of the alloy could be achieved by the combined P+UT processing. These values are 64%, 59%, and 307% higher than those of the non-treated alloy, respectively. Furthermore, the mechanical properties of the alloy treated by P+UT are also significantly superior to those produced by individual processes, i.e., P or UT. It is well known that the mechanical properties of the alloys depend on the morphology and size of α-Al and Fe-rich intermetallics[4], as well as, the occurrence of porosity[14].

The improvement in the tensile properties of the alloy with P+UT processing could be ascribed to the following points. First of all, the refined and globular α-Al dendrites contribute to a higher strength of the alloys according to Hall-Petch relationship. Moreover, the refined and compacted Fe-rich intermetallics play an important role on the improvement of both strength and ductility because they have prevention effect on the crack initiation and propagation in the alloy during the deformation[21]. Furthermore, the porosity-free microstructure can also make contributions to the improvement of strength and ductility.

The improvement of elongation can also be proved through fracture surfaces of the tensile samples, as shown in Fig.6. Fig.6a clearly shows the Chinese-script α-Fe formed around the α-Al dendrite, forming the porosity area in the non-treated alloy. In the sample with applied pressure,

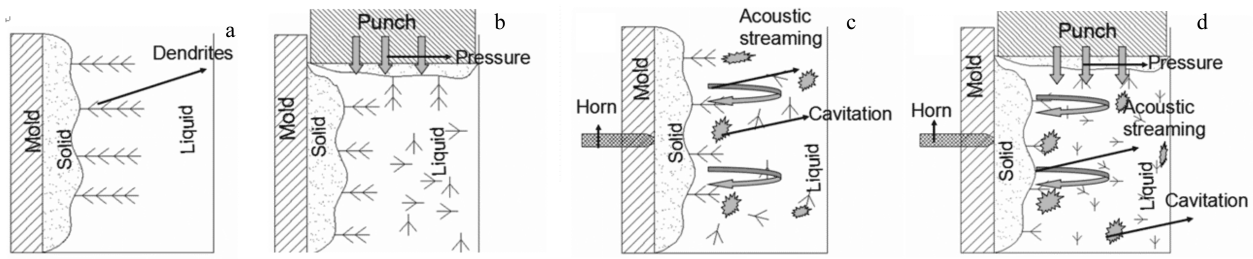

Fig.5 Schematic of alloys under different conditions: (a) non-treated, (b) P, (c) UT, and (d) P+UT

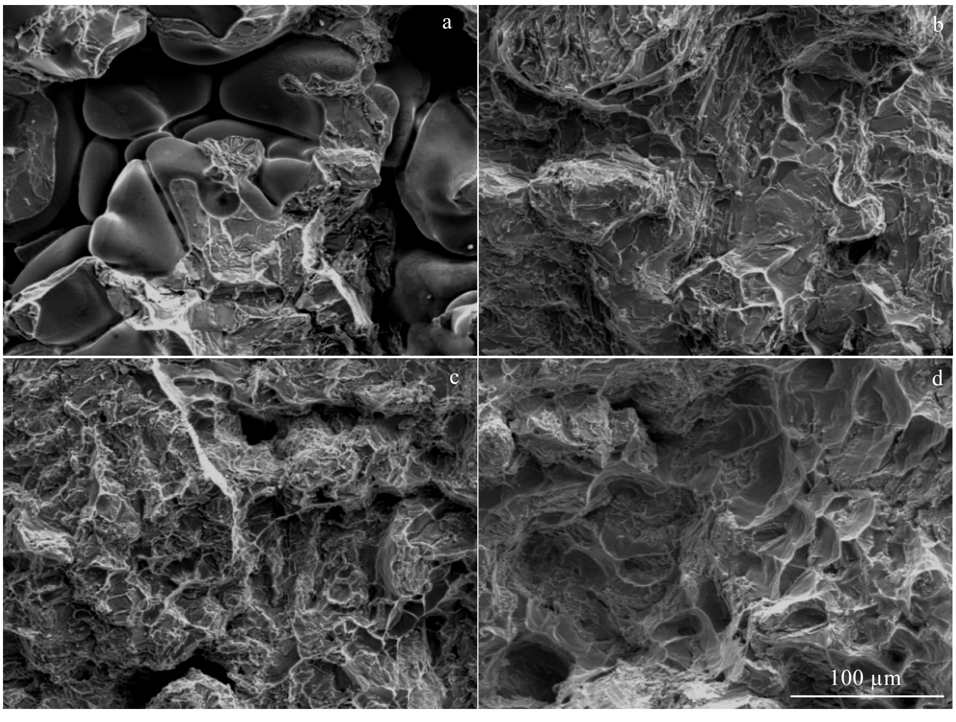

Fig.6 SEM images of the fracture surface of tensile test alloys: (a) non-treated, (b) P, (c) UT, and (d) P+UT

Table 1 Mechanical properties of the as-cast alloy under different conditions

Method	UTS/MPa	YS/MPa	Elongation/%
Non-treated	163±10	121±2	4.2±0.8
P	248±7	182±5	12.8±0.8
UT	232±4	169±9	5.3±0.7
P+UT	268±9	192±1	17.1±1.6

the fracture surface shows extensive irregular cleavage and tearing ridges, indicating quasi-cleavage fracture (Fig. 6b). As shown in Fig.6c, UT increases the number of dimples, and the fracture surface of this alloy shows a combined porosity and dimple morphology. However, deep dimples are distributed uniformly and there is no porosity in the P+UT alloy (Fig. 6d), indicating a significant increase in elongation in this alloy.

3 Conclusions

1) The combined ultrasonic vibration and applied pressure processing has a great effect on microstructure of the as-cast Al-5.0Cu-0.6Mn-0.6Fe alloy, particularly the morphology and size of α-Al, Fe-rich intermetallics, and Al_2Cu. The combined treatment promotes the morphology transformation of α-Al from dendritic to globular structure and significantly reduces the size of α-Fe, Al_6(FeMn), and Al_2Cu phase.

2) The P+UT processing is helpful to reduce the degree of bimodal structure which usually occurs under applied pressure and reduce the segregation along the grain boundary.

3) The tensile properties of the alloys produced by P+UT processing are UTS 268 MPa, YS 192 MPa, elongation 17.1%, which are 64%, 59%, and 307% higher than those of the non-treated alloy, respectively.

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超声振动和加压制备 Al-5.0Cu-0.6Mn-0.6Fe 铸态合金的组织和力学性能

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摘 要：采用金相显微镜(OM)、扫描电镜及能谱(SEM-EDS)、图像分析和拉伸试验等测试方法，研究超声振动(UT)和施加压力(P)耦合作用对铸态 Al-5.0Cu-0.6Mn-0.6Fe 合金组织和力学性能的影响。结果表明：P+UT 工艺对 α-Al、富铁相和 Al_2Cu 的形貌和尺寸有明显的影响，促进 α-Al 的形貌由树枝状向球状结构转变，明显地降低 α-Fe、Al_6(FeMn)和 Al_2Cu 相的尺寸。P+UT 工艺也有助于减少经常出现在挤压铸造中的双峰组织，也能有效地降低晶界偏析。P+UT 工艺制备合金的最佳力学性能为抗拉强度 268 MPa，屈服强度 192 MPa，伸长率 17.1%，分别比未经过处理的合金高 64%，59%和 307%。

关键词：超声；压力；组织；晶粒细化

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