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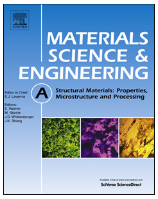

Combined effects of mechanical vibration and wall thickness on microstructure and mechanical properties of A356 aluminum alloy produced by expendable pattern shell casting

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ABSTRACT

In the present work, the combined effects of mechanical vibration and wall thickness on the microstructure and mechanical properties of A356 aluminum alloy produced by the expendable pattern shell casting process were investigated. It has been found that with the increase of wall thickness, the morphologies of the α-Al primary phase and eutectic silicon phase of the samples obtained from the conventionally cast evolved from a fine dendrite to a coarse dendrite and from a fibrous structure to a plate-like structure, respectively, and the mechanical properties of A356 aluminum alloy decreased continuously. After the mechanical vibration was applied, the coarser dendrites transformed into the fine equiaxed grains, and the size, morphology and distribution of the α-Al primary phase and eutectic silicon particles as well as SDAS were improved significantly. Meanwhile, the mechanical properties and density of A356 aluminum alloy increased greatly, and the tensile strength, yield strength, elongation as well as hardness of the sample with 40 mm wall thickness were 35%, 42%, 63% and 29% higher than that of the conventionally cast under the T6 condition, respectively. The effect degree of the mechanical vibration on the microstructure and mechanical properties increased with increasing wall thickness. Furthermore, the mechanical vibration changed the fracture mode of A356 aluminum alloy from a transgranular fracture mode of the conventionally cast to an intergranular fracture mode.

1. Introduction

Complicated and thin-walled aluminum-silicon alloy precision castings are widely used in the aircraft and automotive industries due to their excellent castability, weldability, corrosion resistance as well as high strength to weight ratio [1–4]. Generally, die casting, permanent mold casting, sand casting and lost foam casting (LFC) are used for producing aluminum alloy precision components [5]. The die casting process is a precision casting method with a high productivity. However, the die components usually contain a substantial amount of gas porosity due to the high speed injection of the molten metal. As a result, the heat treatment of the die components is not possible due to the blister formation on the casting surface [6,7]. Meanwhile, the permanent mold casting method is usually difficult to manufacture thin-walled castings because of the high solidification rate of the molten metal. In addition, the sand casting method is not easy to meet the demands of dimensional accuracy and surface finish required in precision castings. On the other hand, the LFC process has been regarded as a near net shape method for manufacturing complicated aluminum alloy precision castings [8–10]. However, the decomposition of the foam pattern during the pouring process may result in the gas porosity and slag inclusions [11,12], and its pouring temperature is higher than that of traditional cavity casting to overcome the heat absorption from the decomposition of the foam pattern. Moreover, the cooling rate of the molten metal is slow due to the adoption of dry sand molding, resulting in coarser grains, serious porosity defects and poorer mechanical properties.

The expendable pattern shell casting process is a compound precision casting technology and suitable for producing complicated and thin-walled aluminum alloy precision castings [13–15]. It was first proposed by Ashton, named Replicast CS process [16]. This compound casting process adopts the foam pattern preparation of the LFC method and thin shell precision fabrication of the investment casting method. And it has some advantages, such as the flexible design and low cost of the foam pattern, high precision of investment casting and good forming ability. The porosity and slag inclusion defects in the LFC process from the decomposition

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of the foam pattern during the casting process can be fully avoided because the foam pattern has been removed before pouring. On the other hand, the filling ability and feeding capacity of the molten metal can also be improved because the filling and solidification of the molten metal are carried out under the vacuum pressure. Unfortunately, the microstructures of aluminum alloy precision castings obtained using the expendable pattern shell casting process show a coarse dendrite with an inhomogeneous distribution, and the eutectic silicon particles form a coarse plate-like structure, especially the castings with the larger wall thickness, leading to a sharp decrease of the mechanical properties. It has been noted that the cooling rate of cast samples and their microstructures are greatly influenced by the wall thickness of castings during the solidification process [17].

Generally, the refinement of microstructure mainly has the following methods, such as chemical elements modification [18], electromagnetic vibration [19], ultrasonic vibration [20] and mechanical vibration [21]. The mechanical vibration has the potential to be a simple, economic and effective method to refine the microstructure and improve mechanical properties [22], which was first applied on the steel by Chernov [23].

In the present work, the mechanical vibration was first introduced into the expendable pattern shell casting process to produce the A356 aluminum alloy in order to improve the microstructure and mechanical properties of A356 aluminum alloy. Meanwhile, the effect of the wall thickness of castings on the microstructure and mechanical properties of the A356 aluminum alloy were also considered. The object of the present work is to investigate the combined effects of mechanical vibration and wall thickness on the microstructure and mechanical properties of the A356 aluminum alloy produced by the expendable pattern shell casting process.

2. Experimental procedures

In this experiment, the foam pattern samples with a step shape were first prepared using the foaming molding process, and the wall thicknesses of the foam pattern samples are 10 mm, 20 mm, 30 mm and 40 mm, respectively, as shown in Fig. 1. The ceramic shell was then produced by coating the foam pattern with the ceramic slurry and using refractory to form the stucco on the coated pattern. The foam pattern was heated in a furnace at 250 °C for 30 min, and melted off the ceramic shell. The ceramic shell was then heated at 500 °C for 30 min to remove any residual foam. And, the ceramic shell was roasted at 800 °C for 60 min for strength enhancement. Subsequently, the ceramic shell prepared was placed inside a sand box. The sand box was filled with a 40/50 unbonded loose-sand. The loose-sand was compacted using a three-dimensional (3D) vibration table. Next, the sand box was covered with a plastic film.

The chemical composition of the A356 aluminum alloy used in this study is shown in Table 1. The crucible was first preheated at 300 °C, and the preheated aluminum ingot was placed inside the crucible. When the temperature of the molten metal reached 740 °C, the melt was refined using argon gas, and the slag was then skimmed. Afterwards, the molten metal was ready for casting, and the pouring temperature of the molten metal was 730 °C. Before the molten metal was poured, the mechanical vibration and vacuum equipments were simultaneously opened. According to our previous studies, when the vibration frequency and amplitude were 100 Hz and 1 mm, respectively, the mechanical vibration has an optimal effect on the microstructure and mechanical properties of the A356 aluminum alloy. Therefore, the vibration frequency and amplitude used in this study were 100 Hz and 1 mm, respectively, and the vacuum level was 0.03 MPa.

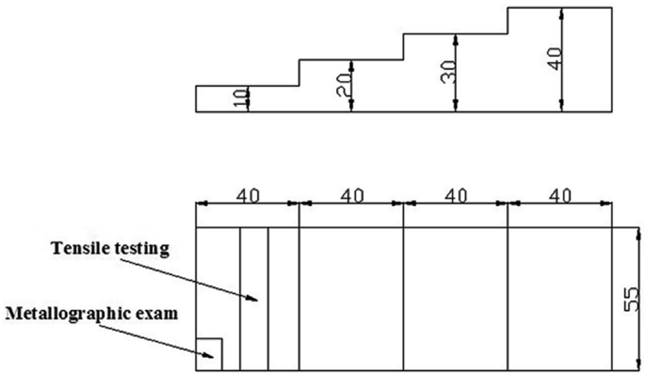

Fig. 1. Schematic for step sample (unit: mm).

Table 1
The nominal chemical composition of experimental alloy (wt%).

Element	Si	Mg	Ti	Fe	Al
Content	7.10	0.31	0.23	0.17	Balance

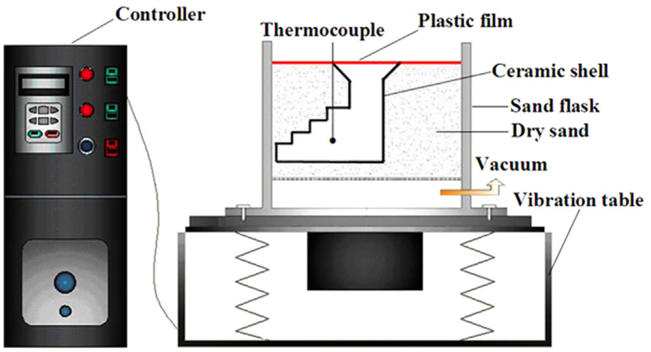

Fig. 2. Schematic illustration of experimental apparatus for the mechanical vibration during the expendable pattern shell casting process.

Fig. 2 shows a schematic illustration of experimental apparatus for the mechanical vibration during the expendable pattern shell casting process. Meanwhile, the comparative castings obtained from the conventionally cast (without vibration) were also poured with the same A356 aluminum alloy and pouring temperature to the vibration method.

The metallographic samples were etched using 0.5% hydrofluoric acid solution after polishing, and its sampling position is shown in Fig. 1. Microstructures were observed using an OLYMPUS-MG3 metallographic microscope. The secondary dendrite arm spacing (SDAS), average length of silicon particles as well as average width of eutectic silicon particles were measured by using the Image Tool metallographic analysis software. The SDAS was measured by averaging the distance between adjacent side branches on the longitudinal section of a primary arm. The measurement was done on 50 different areas of each microstructure in order to minimize the errors. The aspect ratio of eutectic silicon particles was taken as the ratio of the average length of silicon particles to the average width of silicon particles. The grain size and shape factor of the α-Al primary phase were defined according to the following equations [24, 25].

$$D = 2\sqrt{\frac{A}{\pi}} \tag{1}$$

$$F = \frac{4\pi A}{P^2} \tag{2}$$