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Microstructure and properties of squeeze cast A356 alloy processed with a vibrating slope

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ABSTRACT

The microstructures of A356 alloy parts contained near-round or rosette α-Al grains and eutectics at grain boundaries. Melt processing by vibrating slope could refine grain size and eliminate eutectic phase segregation as well as regional segregation which usually occurred in traditional squeeze casting. Average grain diameter of α-Al grain increased from 44 μm to 64 μm, and grain average roundness decreased firstly from 2.9 to 1.7 then increased to 3.3 with the increase of casting temperature. At casting temperature from 670 °C to 680 °C, crack and cooling shut usually occurred in the products due to poor flow ability of the alloy. When the casting temperature was 690 °C, the alloy had a good filling ability and smooth product with fine near-round or rosette α-Al grains and homogenous eutectics has been obtained. The ultimate tensile strength and elongation of semisolid squeeze casting A356 alloy reached 232 MPa and 7%, which were improved by 12% and 21% respectively as comparing with that of traditional squeeze casting.

1. Introduction

Semisolid metal forming is a preferable process to produce metal part with complex structure for its good filling performance. In addition, aluminum alloy part manufactured by semisolid processing has higher mechanical properties as comparing with liquid metal forming, as reported by Flemings (1991). So semisolid processing attracts more and more attentions in the worldwide for manufacturing high performance part with complex structure. Meng et al. (2014) and Luo et al. (2010) reported that rheo-forming is a type of short semisolid metal forming process, in which semisolid slurry is deformed directly by rolling, extrusion and casting etc. The first key step of rheo-forming process is to prepare semisolid slurry. Up to now, many successful preparing slurry processes have been developed. Liu et al. (2011) and Brabazon et al. (2002) reported that mechanical stirring was successfully applied in production processes. Haghayeghia et al. (2010) developed conditioner direct chill (MCDC) casting and prepared 7075 alloy with fine microstructure. Wannasin et al. (2006) developed gas bubbles and achieved grain refinement during solidification. Lü et al. (2012) prepared excellent semisolid slurry of A356 alloy by indirect ultrasonic vibration method. Walmag et al. (2008) prepared the as-cast steel (or high melting point alloy) with thixotropic properties by hollow jet nozzle. Wang et al. (2010) studied the microstructural evolution of AlSi7Mg alloys during electromagnetic stirring and prepared the good slurry. Ahmad et al. (2014) reported that reciprocating injection screw could produce good thixotropic slurry, permanent magnet EMS could produce an intense stirring in semisolid alloy slurries and refine the microstructure. The results revealed that these methods could prepare slurries of alloys with fine microstructure, and some of them were also successfully applied in production. However, these processes are relatively complex and require accurate controlling of process parameters, and the cost is also higher than conventional liquid forming process by Zoqui et al. (2002), Vieira et al. (2004), and Ghomashchi and Lashkari (2007). Developing low cost process of preparing semisolid alloy is still a key target of semisolid metal forming. Hong and Kim (2006) reported that New Rheocasting was firstly developed by UBE Company in Japan. In this process, a cooling slope was used for casting. Liquid alloy was poured onto the slope, and semisolid alloy could be prepared under the actions of slope cooling and metal flow. Haga (2002), Haga and Suzuki (2003) and Haga et al. (2004) have installed a sloping plate device onto a roll casting mill to develop the semisolid rolling process, and the mechanical properties of the strip prepared by semisolid rolling were obviously improved simultaneously as comparing with casting alloy.

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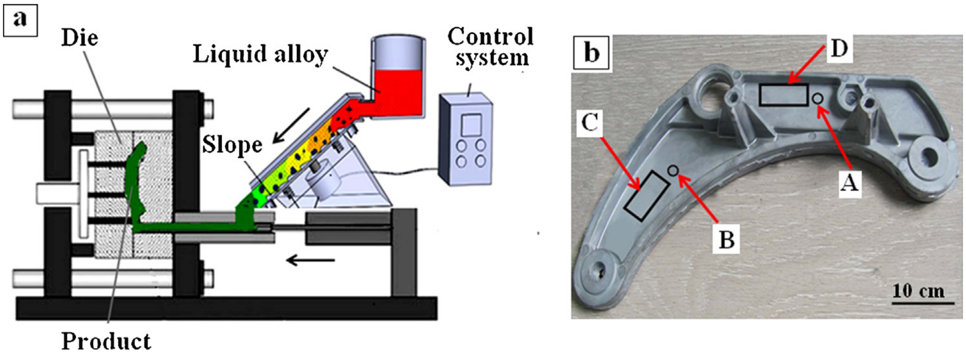


Fig. 1. Self-designed semisolid squeeze casting setup and the product of A356 alloy (A and B are sampling positions for microstructure observation, C and D are sampling positions for tensile test).

Based on the above work, in order to avoid slurry adhesion on the slope surface and improve slurry quality, Guan et al. (2009, 2012) applied vibration on the slope, and combined vibrating slope process and semisolid rolling process, the mechanical properties of the strip obtained by the process were significantly improved. In this paper, in order to develop low-cost semisolid squeeze casting process for producing complex alloy part with high performance, a self-designed vibrating slope device and squeeze casting machine were combined organically for the first time to study semisolid squeeze casting of A356 alloy. In order to evaluate the feasibility of the application of melt processing by vibrating slope on squeeze casting and guide the study of semisolid squeeze casting process, effect of melt processing by vibrating slope on microstructure and properties of squeeze casting A356 alloy were investigated.

2. Experimental procedure

The experimental material was commercial A356 alloy whose main chemical compositions (mass%) are Si 7.00, Mg 0.43, Fe 0.19, and Al balanced. The liquidus and solidus of the alloy are 615 °C and 577 °C respectively. As shown in Fig. 1a, the experimental device was a self-designed semisolid squeeze casting setup that was built through the combination of squeeze casting machine and vibrating slope device. The squeeze pressure of the machine can reach 140 MPa. The alloy was melt in a furnace with the capacity of 200 kg. The melt was heated to 720 °C and then poured onto the surface of the vibrating sloping plate at 670 °C–700 °C, thus the alloy flowed through the slope and filled into the squeeze barrel under gravity. The slurry with fine rosette or near-round primary grains and residual liquids were prepared due to cooling, vibration and melt flow, subsequently, the slurry in the barrel was directly squeezed into product under pressure. The target product with the weight of 2 kg is shown in Fig. 1b. Traditional squeeze casting at casting temperature 700 °C was also carried out for comparison with semisolid squeeze casting. As shown in Fig. 1b, samples were taken from different positions A and B for microstructure observation and phase analysis. Each sample was roughly ground, polished and etched by a solution with 0.5% HF and H_2O, and then microstructure observation was carried out under OLYMPUS DSX500 metallographic microscope. Phase analysis was also accomplished under Ultra Plus SEM. The primary α-Al grain diameter was calculated by using the following equation,

$$d = \frac{L_T}{N \times n}$$

where d is grain diameter, L_T is length of measure line, N is grain number that is covered by the measure line, and n is magnification. The average roundness of α-Al grain was calculated by,

$$S_F = \frac{L_P^2}{4\pi A}$$

where S_F is grain roundness, L_p is the total circumference of measured grains, and A is total grain areas. Mechanical properties of A356 alloy parts were measured by using a CMT5105 tensile machine. The sampling positions are shown in Fig. 1b. The length of the tensile samples is 55 mm, and the thickness is 2 mm, as shown in Fig. 2. The stretching was carried out under the tensile rate of 2 mm/min.

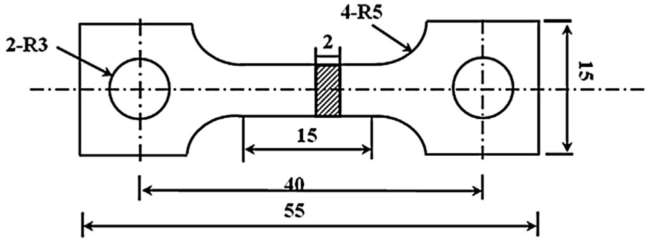


Fig. 2. The dimensions of specimens for tensile testing (mm).

3. Results and discussion

3.1. Effect of melt processing

Fig. 3 shows comparison of microstructures of A356 alloy parts obtained by traditional squeeze casting and semisolid squeeze casting. The microstructures contain α-Al grains and dark structures at grain boundaries. Fig. 4 shows SEM analysis result of dark area in Fig. 3, it reveals that the dark area mainly contains rich Si and Mg elements. Haghshenas et al. (2009) reported that A356 alloy mainly contains Mg_2Si and Si eutectic phases at grain boundaries, so these dark structures can be determined as the same phases. These phases with homogenous distributions can effectively strengthen alloy through pinning dislocations but its segregation can worsen mechanical properties. High casting temperature and rapid solidification usually cause large eutectic phase segregation.

From Fig. 3, it can be found that traditional squeeze casting alloy is composed of big dendrites or nets and large-area eutectic phase segregation, this kind of microstructure would be harmful to mechanical properties. During traditional squeeze casting, liquid metal was adopted. The forming die had a high heat conductivity, which led to a big temperature gradient, so coarse dendrites generated in the alloy. At the same time, eutectic phase could solidify rapidly because of high cooling rate. As a result, the eutectic phase segregation was formed. In addition, the regional segregation also occurred in the product. It can be seen that second dendritic arm at position B is much bigger than that at position A, but eutectic phase segregation at position B is relatively less than that at

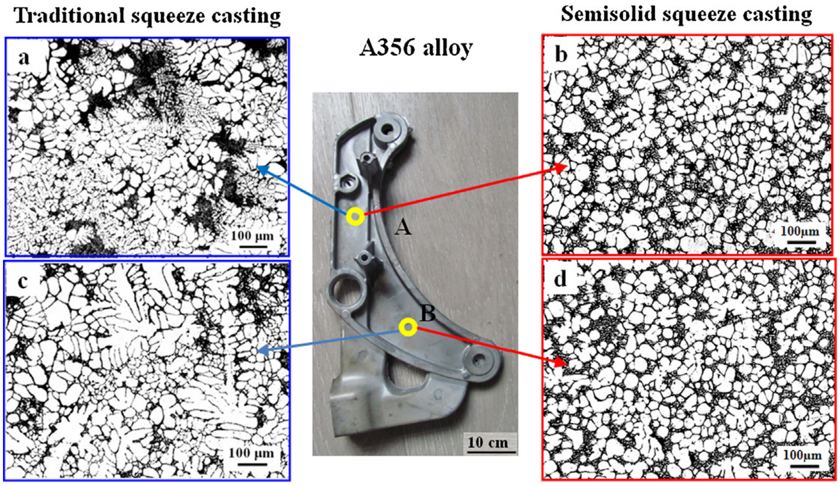


Fig. 3. Comparison of microstructures of A356 alloy parts obtained by traditional squeeze casting and semisolid squeeze casting.

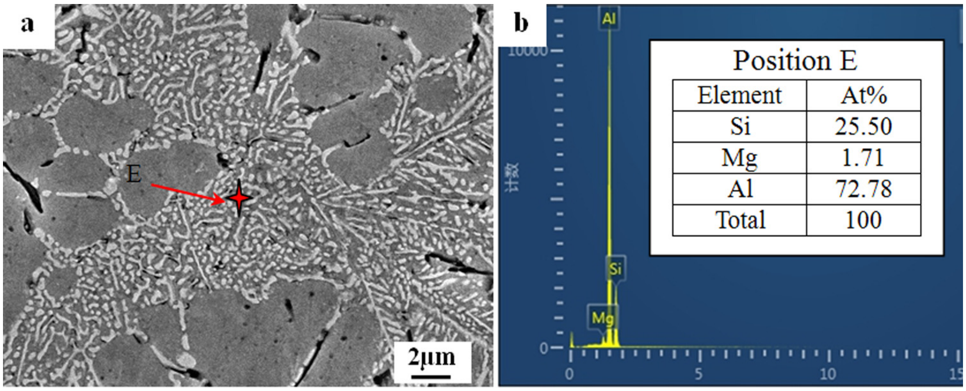
position A. The reason is that the filling route of these positions are different, which lead to different cooling rate and solidification speed. Filling mouth is close to position B. The alloy temperature was higher and the die temperature was lower at position A, so cooling rate at position A was much bigger than that at position B, which resulted to relative faster solidification speed at position A than at position B. Consequently, relative smaller second dendritic arms but larger eutectic phase segregation was remained at position A.

However, it is found that the microstructures of A356 alloy part produced by semisolid squeeze casting at different zones of A and B are all composed of rosette or near-round α-Al grains and eutectics. Grain size of semisolid squeeze casting is much smaller than that of traditional squeeze casting. Both α-Al grains and eutectics in semisolid squeeze casting distribute homogenously. Microstructures at both positions almost have no difference, and the variations of grain shape and size are not obvious, moreover, eutectic phase segregation is not found, which reveals that melt processing by vibrating slope could obviously refine grain size and eliminate eutectic phase segregation as well as regional segregation which usually occurred in traditional squeeze casting. Semisolid squeeze casting process included two solidification stages, the first solidification stage occurred on the slope surface and the second solidification stage was in the die. Guan et al. (2009) reveal that the alloy processed by vibrating slope process was usually composed of near-round primary grains and remnant liquid, and a large quantity of nuclei induced by vibrating, flow and cooling on the slope contributed to semisolid slurry formation. Fine near-round grains were remained in the die. In addition, semisolid alloy had a relative higher solid fraction than liquid alloy, so the cooling speed of the alloy in the die was reduced at the second solidification stage, and the solidification in the die was much closer to equilibrium solidification, thus eutectic phase segregation was avoided.

3.2. *Effect of casting temperature*

Fig. 5 shows the products obtained by semisolid squeeze casting at different casting temperatures. It can be seen when the casting temperature was from 690 °C to 700 °C, semisolid alloy prepared by vibrating slope processing had good flow ability and could fill the die well, and good product with smooth surface has been obtained. However, when the casting temperature was below 690 °C, the alloy flow ability became worse, in this situation, even it could flow down the slope, forming die could not be filled completely, which resulted in incomplete product, and crack as well as cold shut usually occurred, as shown in Fig. 5a and b. So experimental results suggest that semisolid casting temperature should be set from 690 °C to 700 °C in this case.

Fig. 6 shows microstructures of semisolid squeeze casting part at position A under different casting temperatures. Fig. 7 is the variations of average grain roundness and diameter with casting temperature. It can be found that α-Al grain almost kept near-round or rosette shape under different casting temperatures. But average α-Al grain diameter has a slight increase from 44 μm to 50 μm with casting temperature from 670 °C to 690 °C, and the increment becomes obvious when casting temperature is higher than 690 °C.



Position E

Element	At%
Si	25.50
Mg	1.71
Al	72.78
Total	100

Fig. 4. SEM analysis of dark areas in Fig. 3 which mainly contains rich Si and Mg elements.

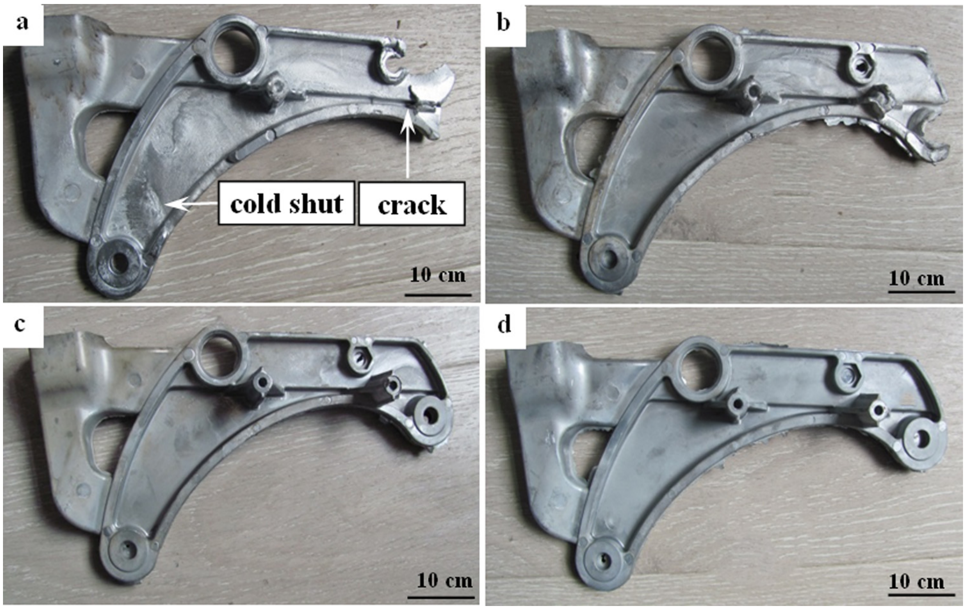


Fig. 5. Products obtained by semisolid squeeze casting at different casting temperatures. (a) 670 °C (b) 680 °C (c) 690 °C (d) 700 °C

The reason is that semisolid alloy at high temperature could provide adequate liquid for primary grain or nuclei growing into large grains in the die. Ahmad et al. (2014) also found that molten aluminum A356 was poured into metallic copper tube molds and cooled down to the semi-solid temperature before being quenched in water at room temperature, the microstructure was more spherical when lower pouring temperatures of A356 alloy.

From Figs. 6 and 7, it also can be found that grain roundness is not a constant value, and it decreases from 2.9 to 1.7 and then increases to 3.3 with the increase of casting temperature. As mentioned above, there are two solidification stages in semisolid squeeze casting process. The first stage is the solidification period on the sloping plate, and the second stage is the solidification process in the forming die. Microstructure formation mechanism in the first stage was studied by Guan et al. (2012). It was believed that near-round grain formation derived from a large number of heterogeneous nuclei that formed on the slope surface and escaped into the melt under metal flow and vibration. Alloy flow ability became better with the increase of casting temperature from 670 °C to 690 °C, so the quantity of nuclei that were flushed by alloy flow and vibration was improved; hence, grain roundness decreases with the increase of casting temperature from 670 °C to 690 °C. But if casting temper-

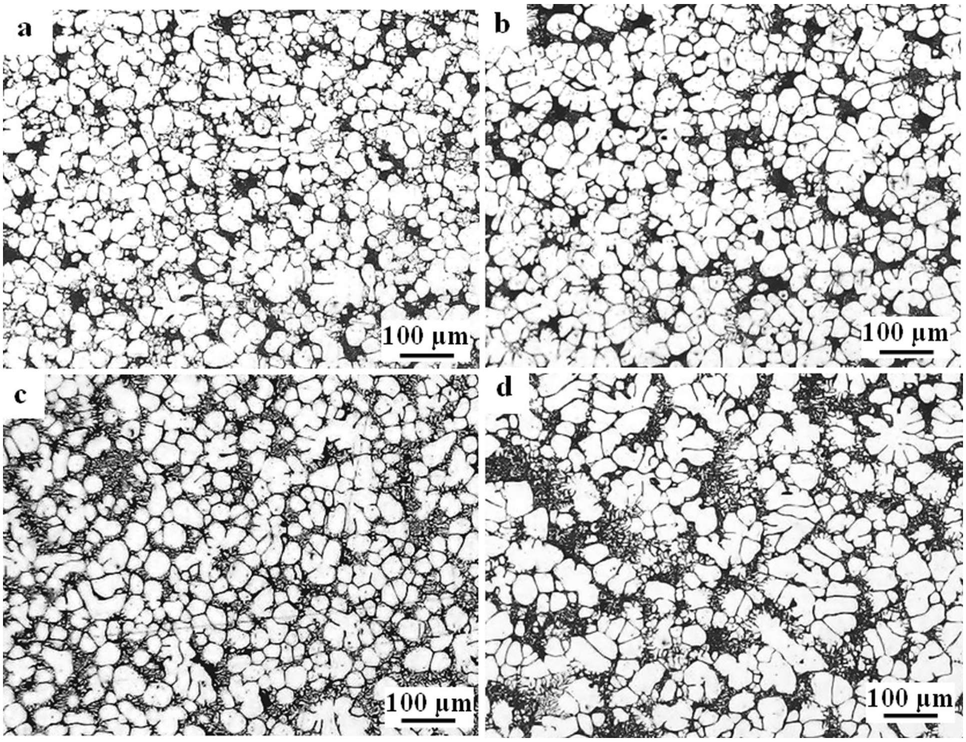


Fig. 6. Microstructures of semisolid squeeze casting part at position A under different casting temperatures. (a) 670 °C (b) 680 °C (c) 690 °C (d) 700 °C

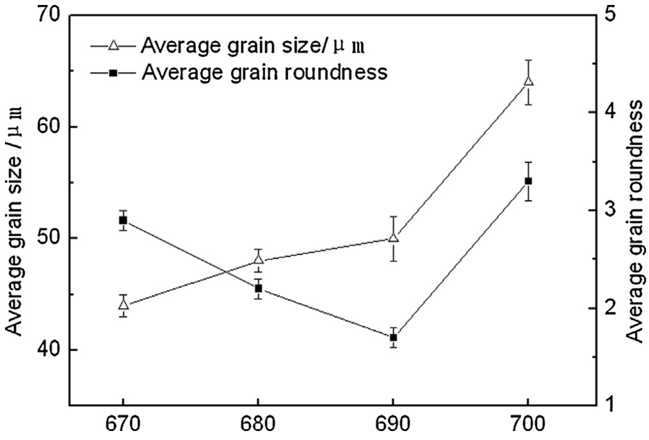


Fig. 7. Variations of average grain roundness and diameter with casting temperature.

ature was over 690 °C, undercooling in the alloy formed on the slope surface was smaller due to high superheat, and fewer nuclei was formed, which resulted much bigger grain roundness and diameter, as shown in Fig. 6d and Fig. 7.

Fig. 8 shows variation of the fraction of eutectic phase with casting temperature. It can be found that the fraction of eutectic phase increases with the increase of casting temperature. When the casting temperature was 700 °C, even slight eutectic phase segregation appeared. This behavior was derived from relative faster solidification speed induced by big thermal gradient due to high casting temperature. When casting temperature was high, the liquid fraction of semisolid slurry was also high. Hence, more liquid phases flowed into forming die. After solidification, more eutectic microstructures formed in the product due to faster solidification. Eutectic phase segregation usually reduces plasticity of the alloy and leads to fracture during service, so it is very important to control the distribution of eutectic phase. As far as the present study is concerned, casting temperature from 670 °C to 690 °C is reasonable for obtaining homogenous distribution of eutectic phase. Fine and near-round grains can be obtained simultaneously.

3.3. Properties of A356 alloy

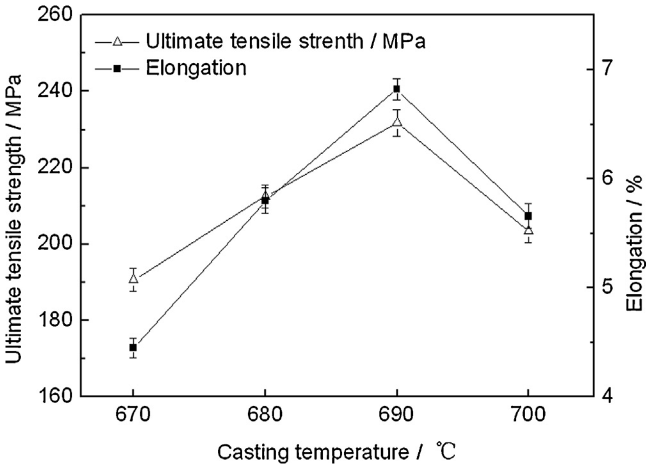


Fig. 9. Properties of semisolid squeeze casting A356 alloy at different casting temperatures.

Fig. 9 shows the properties of semisolid squeeze casting A356 alloy at different casting temperatures. It is found that the ultimate tensile strength as well as elongation of the alloy increase with the increase of casting temperature from 670 °C to 690 °C and then decrease with further increasing of casting temperature. As mentioned above, when the casting temperature was below 690 °C, solidification defects occurred due to poor flow ability of the alloy. Even though the grain size decreased and eutectic phase became homogenous with the decrease of casting temperature from 690 °C to 670 °C, casting defects obviously reduced alloy mechanical properties. Alloy flow ability increased and casting defects were reduced with the increase of casting temperature, so mechanical properties of the alloy were improved correspondingly. Once casting temperature was over 690 °C, casting defects became much less, in this situation, microstructure became the main factor that determined alloy's mechanical properties. Since grain diameter of the product obtained at casting temperature 700 °C is bigger than that at 690 °C, and the eutectic phase segregation at casting temperature 700 °C was also severer than that at 690 °C, the ultimate tensile strength and elongation of the product at casting temperature 700 °C are lower than that at 690 °C. So comprehensively considering the above factors, the reasonable casting temperature 690 °C is suggested.

When casting temperature was 690 °C, the alloy had a good filling ability and smooth product with fine near-round or rosette α-Al grains and homogenous eutectics has been obtained. Fig. 10 shows the ultimate tensile strengths and elongations to failure of A356 alloy parts that were produced by different squeeze cast-

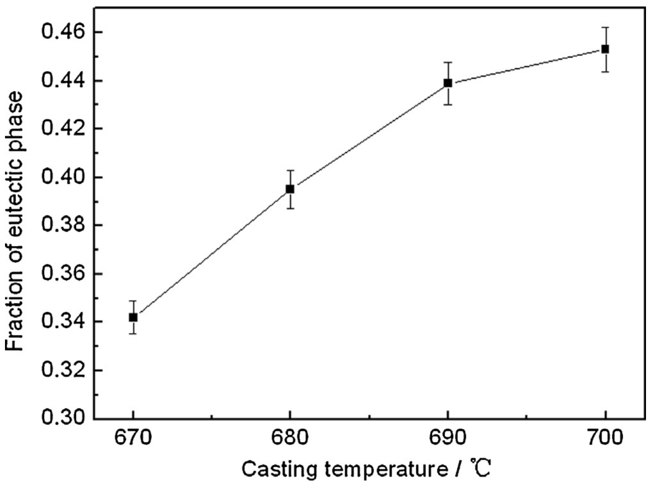


Fig. 8. Variation of the fraction of eutectic phase with casting temperature.

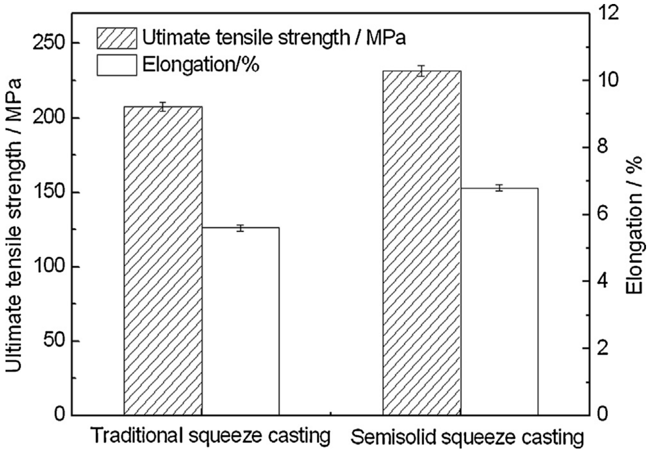


Fig. 10. Ultimate tensile strengths and elongations to failure of A356 alloy parts that were produced by different squeeze casting methods.

ing methods. The ultimate tensile strength and elongation of A356 alloy produced by the semisolid squeeze casting reach 232 MPa and 7% respectively, and that of the same alloy produced by traditional squeeze casting are 208 MPa and 6% respectively, so the ultimate tensile strength and elongation are improved by 12% and 21% respectively as comparing with that of A356 alloy part prepared by traditional squeeze casting. As shown in Fig. 3, coarse α-Al dendrites and eutectic phase segregation appeared in the products prepared by traditional squeeze casting. Eutectic phase is usually quiet brittle, so stress concentration could occur easily between dendrites during stretching. So this kind of microstructure has bad deformation compatibility which would cause crack and rapid fracture failure. While the microstructure of A356 alloy part prepared by semisolid squeeze casting is composed of near-round α-Al grains, and eutectic phase distributes uniformly. Hence, the tensile strength and elongation are obviously improved.

4. Conclusions

A356 alloy was processed by vibrating slope and alloy part was prepared by semisolid squeeze casting through combining vibrating slope and squeeze casting, as well as the effect of melt processing by vibrating slope on microstructure and properties of squeeze casting A356 alloy has been studied. Following conclusions were obtained,

(1.) Melt processing by vibrating slope could refine grain size and eliminate eutectic phase segregation as well as regional segregation which usually occurred in traditional squeeze casting.
(2.) Average grain diameter of α-Al grain increases from 44 μm to 64 μm, and average grain roundness decreases firstly from 2.9 to 1.7 then increases to 3.3 with the increase of casting temperature. The reasonable casting temperature 690 °C is suggested.
(3.) The ultimate tensile strength and elongation of semisolid squeeze casting A356 alloy reach 232 MPa and 7% and they were improved by 12% and 21%, respectively as compared with that of traditional squeeze casting.

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