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Effect of Pouring Temperature by a Novel Micro Fused-Casting on Microstructure and Properties of ZL101 Semisolid Slurry

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Abstract: A novel micro fused-casting (MFC) process is developed for semisolid aluminum alloy slurry. The microstructure evolution and properties of semisolid ZL101 aluminum alloy slurry with different pouring temperature by MFC are investigated in this paper. During the cooling process, the effects of the pouring temperature on microstructure and properties is primarily analyzed. The microstructure of the semisolid ZL101 aluminum alloy is more homogeneous and the grain is smaller under proper pouring temperature. Temperature of liquids and solids of ZL101 aluminum alloy is measured by differential scanning calorimetry (DSC). Distribution and characteristics of the microstructure of samples are examined by optical microscope (OM), scanning electron microscopy (SEM) equipped with energy dispersive spectrometer (EDS). The results show that the ZL101 semisolid slurry fabricated by MFC presents uniform shape and good grain size under the pouring temperature of 594 °C and the stirring velocity of 600 r/min, and the fine grains of the primary α-Al phase with average grain size of 55 μm and shape factor up to 0.67 were obtained. Besides, the ultimate tensile strength and the average Vickers hardness for semisolid ZL101 aluminum slurry are 178.19±1.37 MPa and 86.15±1.16 HV, respectively.

Key words: ZL101 aluminum alloy; semisolid; micro fused-casting; pouring temperature

1 Introduction

As one of super-light metal structural materials, aluminum alloy has attracted significant interest in many applications where the combination of high specific strength, good machinability, and high thermal conductivity is of prime concern[1,2]. ZL101 aluminum alloy parts with complex structure have been widely used in the field of aviation, aerospace and military industry[3]. Among varieties of processing techniques, direct forming complex metal parts by additive manufacturing (AM) technique is an eye-catching topic in the research field[4-6]. Micro fused-casting (MFC) without mold molding is a pioneering metal processing technology, which usually needs the semisolid metal liquid as raw material[7-9].

Compared to the traditional liquid forming of metals, the semisolid metal processing for the form of parts offers lots advantages such as dropped processing temperature, prolonged die, reduced solidification shrinkage, and improved mechanical properties[10,11]. Generally, the semisolid metal processing is mainly consisted of three prime processes including semisolid material production, remelting, and forming. The target of semisolid forming technology is to produce semisolid metal slurry with non-dendritic microstructure[12]. There are various methods to achieve it, such as electromagnetic stirring, spray deposition, mechanical stirring, strain-induced melt activation and semisolid isothermal heat treatment[13,14]. In order to make full use of the advantages of semisolid metal forming technology, searching for new preparation methods with low-cost has been an object for many experts and manufacturers. Recently, some new semisolid forming technologies, such as controlled crystal method, liquidus casting method and controlled nucleation method, have turned up. Now, a pioneering semisolid metal slurry processing named micro fused-casting (MFC) is produced[15], and in the processing, the semisolid metal is pressed out from the base of

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crucible with a horizontal movable plate assembled near the outlet.With aid of 3D software, the semisolid metal is solidified and formed layer by layer.

In this paper, an innovative processing technology of semisolid metal slurry, namely the MFC, is introduced. The effect of pouring temperature by MFC has been studied in detail, and it plays a key role on the microstructure and mechanical property of ZL101 semisolid alloy.

2 Experimental

2.1 Experimental process

The principle of the MFC semisolid slurry experimental equipment is shown in Fig.1. The experimental equipment is made of high-strength graphite, and it consists of melting crucible and channel. During the process, the uniform semisolid-slurry was continuously prepared in crucible heating due to the strong shearing and cooling provided by the stirring, the temperature of metal slurry was controlled between the liquidus and the solidus phases, and the melt nucleation transformed into spherical primary grains gradually. In the channel, α-Al grains gradually became round under the cooling conditions and the scouring of graphite channel wall. The semisolid slurry with fine non-dendrites was obtained. In the process, the pouring temperature has great influence on the morphology of the primary α-Al phase and mechanical properties of undercooled semisolid ZL101 aluminum alloy slurry.

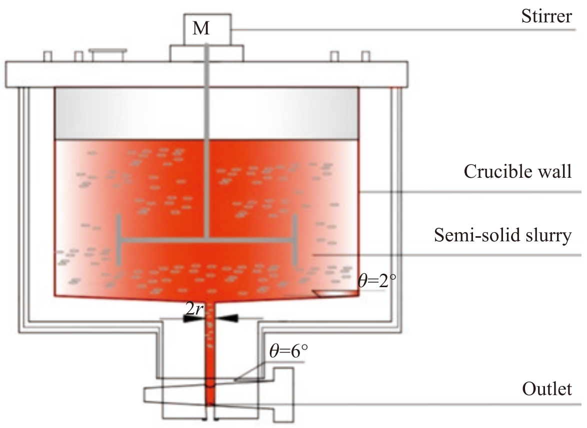

Fig.1 Micro fused-casting for semisolid metal

The experimental material was a commodity ZL101 aluminum alloy and the liquidus and the solidus of this alloy were 627.86 and 558.65 ℃, respectively.

2.2 Marterials

A commodity ZL101 aluminum alloy was used with density of 2.73 kg/m^3. Its main chemical compositions (wt%) were Si 7.36, Fe 0.27, Zn 0.21,Mg 0.25 and Al balanced.

2.3 Semisolid slurry preparation

In order to obtain fine and globular microstructure, the ZL101 aluminum slurry was heated to a temperature zone between liquidus and solidus, which is a sufficient condition for requiring semisolid metal slurry processing. In this experiment, we chose the stirring velocity with 600 r/min and different pouring temperatures. The samples for microstructure observation were prepared by standard metallographic techniques. For microstructures observation, samples were cut off from the quenched slurries, roughly ground and polished and etched by an aqueous solution of 0.5% HF for 15 s, the etched samples were cleaned with an alcohol and dried, then analyzed by optical microscopy (OM), and the representative microstructure of the slurry can be obtained. All the metallographic samples were examined by OM, SEM and EDS. T1 thermal treatment of the samples involved artificial aging. Fig.2 shows the schematic drawing of the sample location for ZL101 semisolid slurry microstructure analysis.

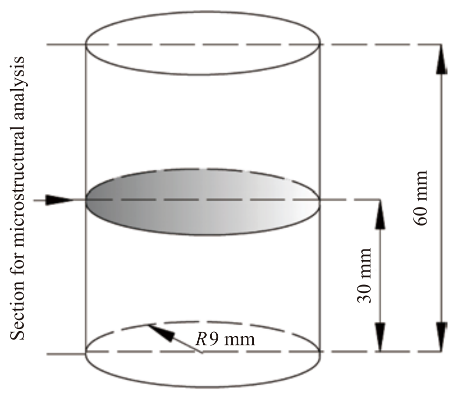

Fig.2 The semisolid sample of ZL101 aluminum

2.4 Testing methods

The average grain size was calculated by

$$S = \frac{L_p^2}{4\pi A_p} \tag{1}$$

The average roundness of the grain shape was calculated by image analysis software. S is the average roundness, L_P and A_P are total circumference of measure grains and grain areas value of globule, respectively.

The average roundness of the grain shape was calculated by

$$D = \frac{L_f}{N_f \times \mu} \tag{2}$$

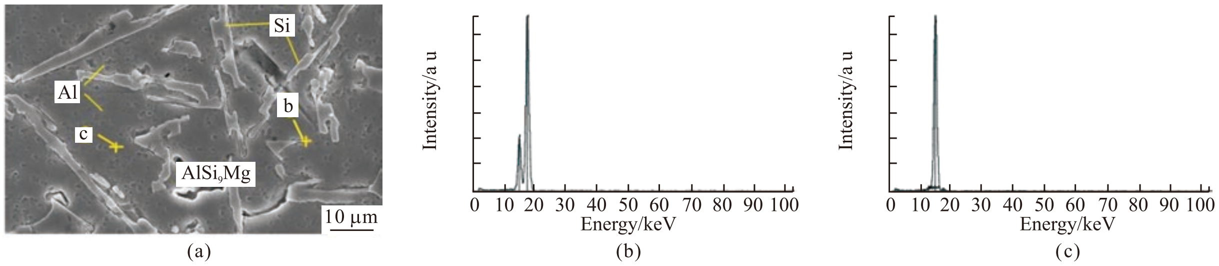

Fig.3 BSE and EDS image of ZL101 alloy material

D is the average grain size, N_f is the grain count, L_f is the length of measure line that is covered by the measure line and μ is the magnification value.

The hardness was test by a XHB-3000 Brilled duromete. The samples were conducted by using a 62.5 kg load and 5 mm diameter indentor, and the loading time was about 30 s.

ZL101 semisolid sample has been used for making tensile samples. The samples for mechanical property tests were obtained from middle region, the samples were machined to standard specimens, and the tensile test was carried out by a CMT5105 tensile machine. The results reported in this work were the average number obtained from five tensile test samples.

3 Results and discussion

3.1 Microstructure of the ZL101 alloy material

Fig.3 shows electron (BSE) image and EDS spectra backscattered of two regions on the ZL101 aluminum alloy material, which exhibits typical dendritic microstructure. Furthermore, BSE image indicates that grey precipitates is α-Al (point b), the white needle-shaped precipitates is Si (point c), the shine precipitates is $AlSi_9Mg$, and the microstructure of ZL101 alloy material is mainly composed of matrix α-Al and eutectic Si phase. According to the EDS results of ZL101 aluminum alloy, it is confirmed that region "b" (white needle-shaped precipitates) and region "c" (grey precipitates) in Fig. 3 are eutectic α-Al and eutectic Si phases, respectively. It is found from Fig. 3 that the ZL101 aluminum alloy has microstructure in complex irregular shapes, in which α-Al is grey precipitates alloy of large block shape and the Si phase is with needle-shape.

3.2 Effect of pouring temperature on the microstructure and properties of the semisolid ZL101 slurry

In order to further understand the formation of spherical primary α-Al grains, the effects of pouring temperature on the microstructure and properties of semisolid ZL101 alloy slurry were discussed. During the MFC process, the preparation of semi-solid melts was conducted by using the temperature control and mixing system, and the dendrite became short under the action of cooling conditions and shear force in the crucible bucket.

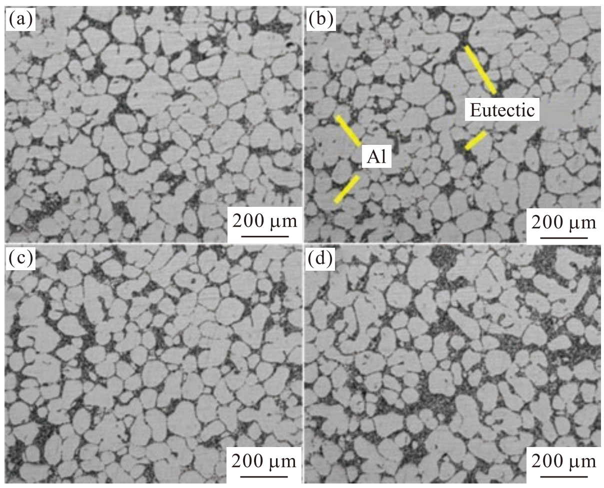

Fig.4 OM images of the ZL101 experimental alloy treated at different pouring temperature: (a) 590 ℃, (b) 594 ℃, (c) 598 ℃, (d) 602 ℃

Fig.4 shows the optical microstructure images for semisolid ZL101 alloys prepared under the conditions including the stirring velocities of 600 r/min, the channel diameter of 3mm, and different pouring temperatures (590 ℃ (Fig.4(a)), 594 ℃ (Fig.4(b)), 598 ℃ (Fig.4(c)), and 602 ℃ (Fig.4(d))), respectively. All samples were cooled at room temperature (T1 state). The average roundness of the grain shape was calculated by image analysis software. It was found that the pouring temperature has great influence over morphologies of ZL101 semisolid slurry. The grains becomes more rounded and smaller. Pouring temperature combined with melt undercooling can affect the dendrite fusing and grain shape of the melt. Therefore, proper pouring temperature was the key factor to achieve smaller grains. The sample prepared under the pouring temperature of 594 ℃ is with the most uniform microstructure and fewest dendrites.

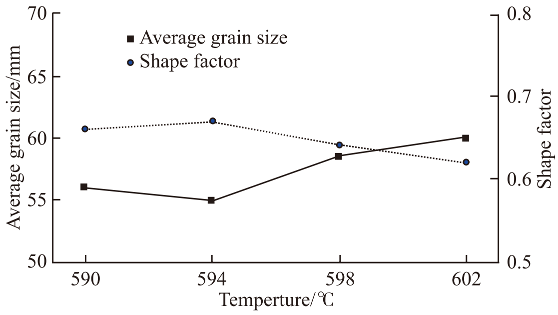

Fig.5 Average grain size and shape factor at different pouring temperature

Fig.5 shows the relationships of average grain size and shape factor with pouring temperature. The primary grain size is the best for the experimental alloy developed at pouring temperature of 594 ℃. The pouring temperature can affect the nucleation rate and undercooling of the semisolid slurry, and further influence the final grain size of the ZL101 semisolid alloy slurry. The shape factor decreased with enhancing the pouring temperature, and then increased from 594 ℃. For average grain size, it was increased with enhancing the pouring temperature, and then decreased from 594 ℃. As stated, the undercooling in the melt is determined by the pouring temperature, so the undercooling was enhanced with the increase of the pouring temperature of ZL101 semisolid slurry. For this reason, a low pouring temperature can cause the fine undercooling and good nucleation rate, which was beneficial to the formation of fine grain. On the other side, the higher pouring temperature made the ZL101 semisolid alloy slurry segregate, as shown in Fig.4(d). For these reasons, we suggest a reasonable pouring temperature to be 594 ℃, and under which , the average shape factor and average grain size were 0.67 and 55 μm, respectively.

3.3 Effect of pouring temperature on the properties of the semisolid ZL101 slurry

Fig.6 shows the relationship between the tensile strength and Vickers hardness with different pouring temperature. The tensile strength and Vickers hardness are best for the semisolid ZL101 alloy developed at 594 ℃, because the pouring temperature can affect the undercooling strength and nucleation rate of the semisolid melt in the crucible bucket, and further influence the tensile strength and Vickers hardness. The nucleation rate decreased with the temperature increasing from 594 ℃. Furthermore, the liquid fraction of the semisolid ZL101 slurry increased with the increasing increments of the pouring temperature, and viscosity decreased correspondingly. As stated, the melt undercooling is determined by pouring temperature, so the reduced pouring temperature led to the increase of the crystal size of ZL101 semisolid slurry. For this reason, a high pouring temperature could cause a low nucleation rate, which caused dendritic crystals formation. When the pouring temperature of MFC was 594 ℃, many obvious big dendrites disappear in the microstructures of the ZL101 semisolid slurry, as shown in Fig.4(b). On the other side, the melt undercooling was increased and the nucleation rate was enhanced as reducing the pouring temperature, and thus the tensile strength and Vickers hardness were increased respectively. Nevertheless, the melt flowing ability of the ZL101 slurry became poor if the pouring temperature was lower than 590 ℃, and thus the operation procedure was usually failed.

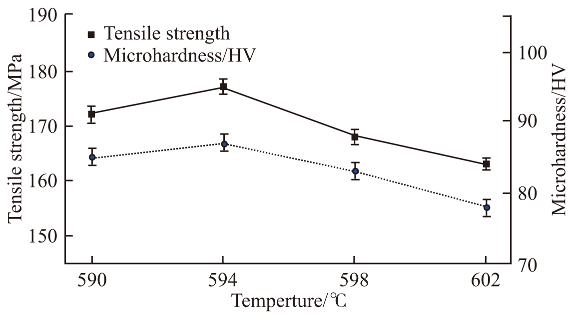

Fig.6 Average grain size and shape factor at different pouring temperature

Therefore, the highest tensile strength and Vickers hardness were obtained for the ZL101 semisolid slurry produced with the pouring temperature at 594 ℃ and the stirring velocities at 600 r/min. The ultimate tensile strength and Vickers hardness for the optimal ZL101 semisolid slurry are 178.19±1.37 MPa and 86.15±1.16 HV, respectively. Obviously, the pouring temperature at 594 ℃, the stirring velocity at 600 r/min and the channel diameter at 3 mm are the key parameters for obtaining the high quality ZL101 semisolid slurry.

4 Conclusions

a) Semisolid ZL101 alloy was produced by a novel MFC technology, through which the primary grains are easily crushed due to the undercooling. The paper studied the influences of pouring temperature on the microstructure evolution and properties of ZL101 semisolid slurry alloy prepared by MFC.

b) Under the pouring temperature at 594 ℃ and the stirring velocities at 600 r/min, the average shape factor and average grain size reached 0.67 and 55 μm, respectively, and its ultimate tensile strength and Vickers hardness are 178.19±1.37 Mpa and 86.15±1.16 HV, respectively.

Conflict of interest

All authors declare that there are no competing interests.

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