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Annulus electromagnetic stirring for preparing semisolid A357 aluminum alloy slurry

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Abstract: The effects of pouring temperature and annulus gap width on the microstructure of the semi-solid A357 aluminum alloy slurry prepared by annulus electromagnetic stirring(AEMS) technology were investigated. The results show that low pouring temperature and narrow annulus gap are advantageous to obtaining the small spherical primary α(Al) phase. The lower the pouring temperature is and the smaller the annulus gap width is, the more uniform, the smaller and the more spherical the microstructure is. The microstructures obtained by the ordinary electromagnetic stirring and AEMS were compared. The results indicate that the primary α(Al) particles are globular, small and distribute homogeneously in the slurry obtained by AEMS. But in the slurry obtained by the ordinary electromagnetic stirring, the primary α(Al) particles are small dendrites in the edge of the slurry and they are large and rosette-like or dendritic in the inner of the slurry.

Key words: electromagnetic stirring; semi-solid slurry; A357 aluminum alloy

1 Introduction

As a near-net shape forming technology, the semi-solid processing(SSP) of metals has received considerable attention and more researches and explorations have been carried out since 1970s, when SPENCER and FLEMINGS[1] conducted the hot tearing test leading to the discovery of rheocasting metal at MIT. After developing for several decades more approaches to prepare the semi-solid slurry have been exploited. These approaches include electromagnetic stirring[2], mechanical stirring[3], twin screw rheomoulding[4], new rheocasting[5], melt mixing[6], semi-solid rheocasting [7], continuous rheoconversion process[8], SEED process[9], low super-heat pouring and weak electro-magnetic stirring[10], controlled nucleation method[11], etc. Among them only the electromagnetic stirring is widely accepted for production of non-dendritic feedstock on a commercial scale. Because of non-pollution, easy process control and continuous production, it has been a main method for producing the semi-solid slurry or billets. However, it has some shortcomings. In the stirring process, the stirring force exerted in the slurry is different between the surface layer and inner of the slurry because of the skin effect resulting from electromagnetic induction; and the force exerted in the surface layer is much larger than that in the inner of the slurry. So, the microstructure distributes inhomogeneously; the primary phase is small and dendritic in surface layer but it is large and rosette-like or dendritic in inner of the slurry; and the slurry is in poor quality.

To avoid the above shortcomings existing in the ordinary electromagnetic stirring, an advanced semi-solid metal processing technology, namely, the annulus electromagnetic stirring(AEMS) process[12], has been developed and the effects of the process parameters on the microstructure are investigated in this work.

2 Experimental

The alloy used in the experiment is commercial A357 aluminum alloy, and its composition is shown in Table 1. Its liquids temperature and the solids temperature are about 613 ℃ and 553 ℃, respectively.

The schematic diagram of the home-made AEMS apparatus is shown in Fig.1. In the apparatus a cooling pipe with closed bottom is set in the center of the

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Table 1 Chemical composition of A357 aluminum alloy used in experiment (mass fraction, %)

Si	Cu	Mg	Al
7.2	0.1	0.6	Bal.

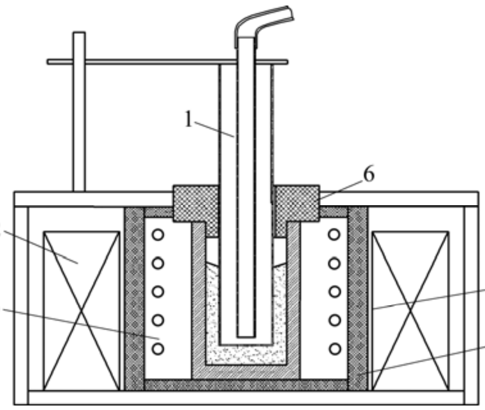

Fig.1 Schematic diagram of annulus electromagnetic stirring apparatus (1—Inner cooling pipe; 2—Electromagnetic stirrer; 3—Outer cooling controller; 4—Slurry-preparation house; 5—Heat-preservation materials; 6—Cover of slurry-preparation house)

slurry-preparation house. A narrow annulus gap between the inner wall of the slurry-preparation house and the outer wall of the cooling pipe is designed innovatively in order to weaken the skin effect and obtain the strong magnetic fields. The annulus gap width may be adjusted by changing the outer diameter of the cooling pipe.

The A357 aluminum alloy was melted to scheduled temperature in an induction furnace, then the molten metal was poured into the slurry-preparation house made of stainless steel, whose dimension is 160 mm in height and 80 mm in diameter and its preheat temperature is 200 ℃. The room-temperature air was input to the inner cooling pipe and the outer cooling controller to uniform the temperature of the slurry. The alternating inductive rotating electromagnetic stirrer was adjusted with 30A input current and 30 Hz frequency. When the slurry temperature was cooled to 600 ℃, the slurry-preparation house with the semi-solid slurry was put into the room-temperature water and quenched immediately, and then the semi-solid billet was obtained. The specimens cut from billet was observed with the Zeiss-type optical microscope after grinding, polishing and etching by 0.5% HF acid to investigate the effects of the processing parameters on the microstructure. The position where the samples were cut is shown in Fig.2.

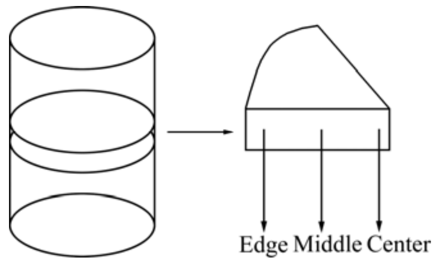

Fig.2 Schematic diagram of position of sampling

3 Results and discussion

3.1 Effect of pouring temperature on microstructure

Fig.3 shows the microstructures at different pouring temperatures with 20 mm in annulus gap width. The microstructure is obtained from the middle of the cut sample, as shown in Fig.2. The white phase is primary α(Al) particle and the dark continuous matrix is the quenched eutectic.

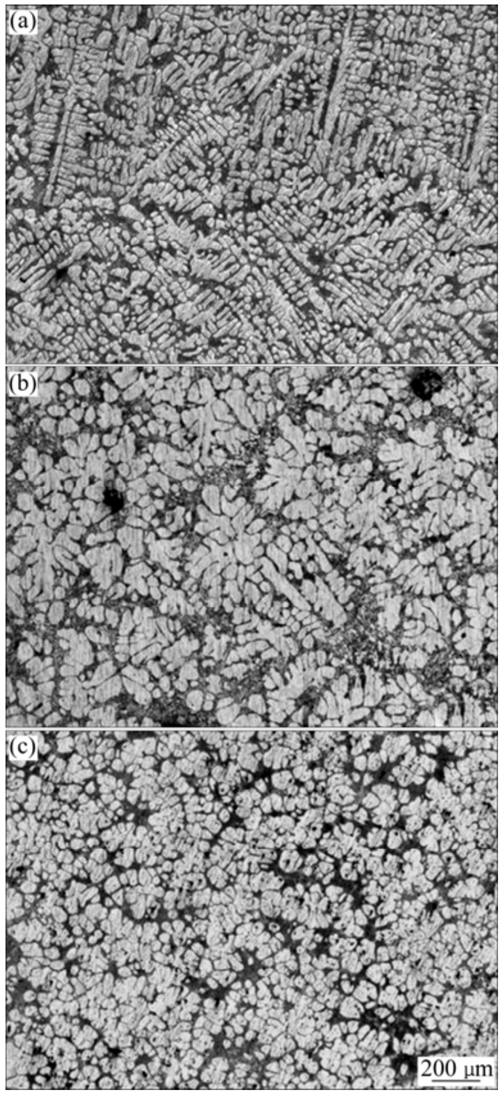

Fig.3 Microstructures of A357 AEMS samples at different pouring temperatures: (a) 670 ℃; (b) 650 ℃; (c) 630 ℃

From Fig.3, it can be seen that the pouring temperature has an important effect on the microstructure morphology and particle size of the primary α(Al) particles. With the pouring temperature decreasing, the morphology of the primary α(Al) particle changes significantly from dendritic to rosette-like and finally to globular, and the particle size turns small. When the pouring temperature of 670 ℃ is adopted, the primary α(Al) particles are dendritic with large size, as shown in Fig.3(a). But when the pouring temperature is decreased to 650 ℃, most of the primary α(Al) particles are rosette-like and the particle size becomes large, as shown in Fig.3(b). If the pouring temperature continues to decrease to 630 ℃, most of the primary α(Al) particles are globular with small particle size, as shown in Fig.3(c). The microstructures in Fig.3 indicate that the morphology and particle size of the primary α(Al) particles are sensitive to the pouring temperature. When the pouring temperature is high, the primary α(Al) particles are dendritic and the particle size is large, and they are globular and small when the pouring temperature is low. It is advantageous to obtaining the small globular primary α(Al) phase at a low pouring temperature.

It has been demonstrated that the pouring temperature has an important effect on the semi-solid microstructure. CARDOSO et al[13] has proved that the ultimate microstructure is sensitive to the superheat degree and low pouring temperature can improve the spheroidicity of the primary α(Al) particle of the semi-solid A357 alloy in the NRC process. The early research results carried out by FLEMINGS[3] have shown that the microstructure with rosette-like shape may be obtained at a appropriate cooling rate when the pouring temperature is near to the liquid temperature, about 20 ℃ above the liquidus temperature. The liquidus casting method[14] developed by Northeastern University of China has also indicated that low pouring temperature is advantageous to non-dendritic microstructure with spherical shape and small grain size. So, it is advisable to lower the pouring temperature to near to the liquidus temperature. However, it is not convenient and uneasy to control in the operation. Therefore, 630 ℃ of pouring temperature is advisable in the annulus electromagnetic stirring method in this work.

3.2 Effect of annulus gap width on microstructure

Fig.4 shows the microstructures obtained at different annulus gap width with pouring temperature of 630 ℃. The microstructure is obtained from the middle of the cut sample, as shown in Fig.2.

From Fig.4, it can be seen that the annulus gap width has an obvious effect on the semi-solid microstructure. When the annulus gap width is 30 mm, the primary α(Al) particles are rosette-like and the particle size is large, as shown in Fig.4(a). If the annulus gap width is decreased to 24 mm, the particle size of the primary α(Al) is small and most of the particles are globular, as shown in Fig.4(b). And when the annulus gap width continues to decrease to 20 mm, the primary α(Al) particles are much smaller and globular, as shown in Fig.4(c). That is to say, the primary α(Al) particles turn smaller and more globular with the annulus gap width decreasing.

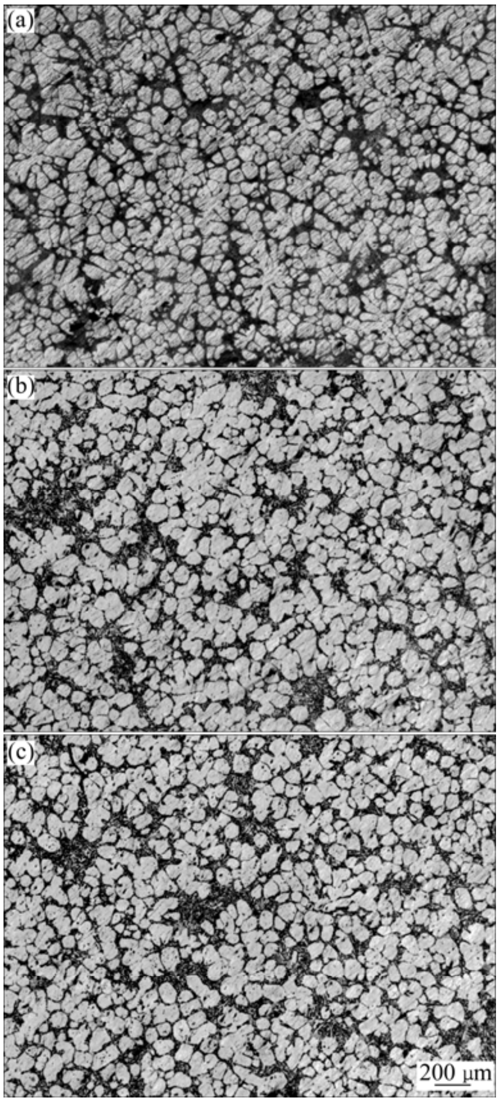

Fig.4 Microstructures of A357 AEMS samples at different annulus gap width: (a) 30 mm; (b) 24 mm; (c) 20 mm

The main reason is that the cooling intensity and shear rate are different in the semi-solid slurry. With the annulus gap width decreasing, the metal flows through the narrow annulus gap in a much thinner film manner, and the cooling intensity becomes much larger. Moreover, the smaller the annulus gap width is, the thinner the film is and the more uniform the slurry temperature is. The more uniform temperature contributes to the increase of the number of effective nuclei and the small globular semi-solid microstructure is obtained. DOHERTY et al [15] suggested that high particle density played an important role in the forming of semi-solid microstructure. FLEMINGS and JONSON[16] believed that the particles grew to dendrite in the early stage; and if the particle density was much larger, the particles exhibited globular morphology; but if the particle density was small, the particles turned rosette-like or dendritic. CHALMERS [17] also believed that the free nuclei came mainly from the molten metals near the cooling body and the vast free nuclei favored the fine semi-solid structure. So, it is appropriate to employ the small annulus gap width in the annular electromagnetic stirring in order to obtain the effective nuclei. On the other hand, the shear rate exerted in the slurry is different at different annulus gap width. According to the calculation method applied by SPENCER and FLEMINGS[1], the average shear rate $\dot{\gamma}$ may be calculated by Eq.(1):

$$\dot{\gamma}=\frac{2Rr}{R^2-r^2}\cdot\frac{2\pi n}{60} \tag{1}$$

where $\dot{\gamma}$ is the average shear rate; R is the inner radius of the slurry-preparation house; r is the outer radius of the cooling pipe; n is the rotation speed of the magnetic field and it is determined by Eq.(2):

$$n=\frac{60f}{p} \tag{2}$$

where p is the pole number; and f is the frequency.

In this experiment, the pole number p is 1, the frequency is 30 Hz and the annulus width is 30 mm, so the average shear rate $\dot{\gamma}$ exerted in the slurry is calculated to be 101 s^{-1}. Similarly, when the annulus gap widths are 24 mm and 20 mm, the average shear rates are 179 s^{-1} and 251 s^{-1}, respectively. That is to say, the shear rate increases with the annulus gap width decreasing. When the annulus gap width is 30 mm, the slurry is sheared in a relatively wide gap and the shear rate is low; and when the annulus gap width is 20 mm, the slurry is sheared in narrow gap and the shear rate is large. The large shear rate is advantageous to restraining dendrite growth and accelerating dendrite fragmentation. Moreover, the strong electromagnetic stirring makes the slurry temperature more uniform. Also it thins down the heat diffusion layer and the diffusion boundary layer of the solute, and decreases the undercooling of the solute, which is advantageous to changing the microstructure morphology from dendrite to the globosity and obtaining the small and spherical microstructure.

3.3 Microstructure obtained by annulus electromagnetic stirring method and ordinary electromagnetic stirring method

Fig.5 and Fig.6 show the microstructures obtained by the ordinary electromagnetic stirring method and the annulus electromagnetic stirring method, respectively. The parameters used in the ordinary electromagnetic stirring are as follows. The pouring temperature is 630 ℃. The parameters used in the annulus electromagnetic stirring method are as follows. The pouring temperature is 630 ℃, and the annulus width is 20 mm.

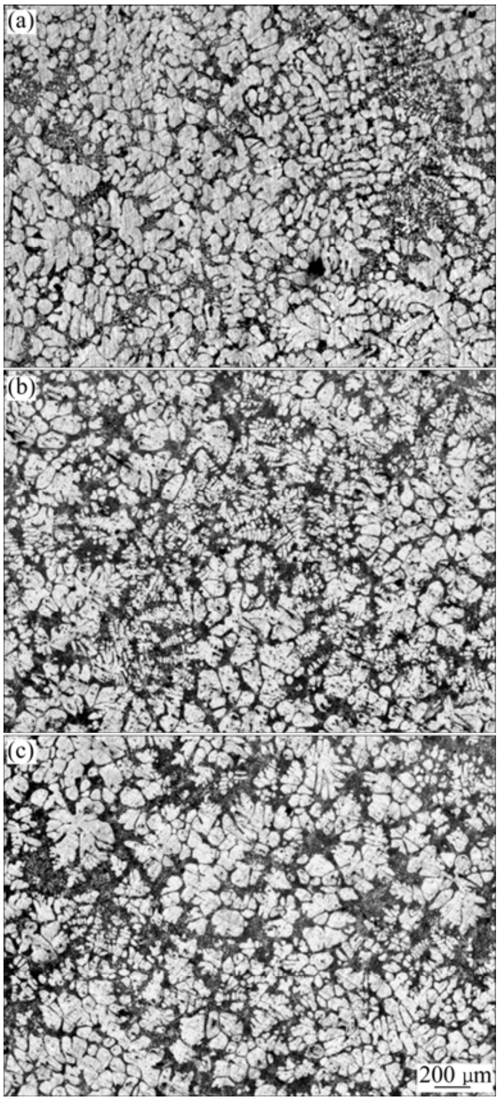

Fig.5 Microstructures of A357 alloy obtained by ordinary electromagnetic stirring: (a) Edge; (b) Middle; (c) Center

From Fig.5, it can be seen that the microstructure morphology and particle size obtained by the ordinary electromagnetic stirring are different from the edge to the center of the semi-solid slurry. At the edge, the primary α(Al) particles appear dendritic, as shown in Fig.5(a). In the middle, the primary α(Al) particles change

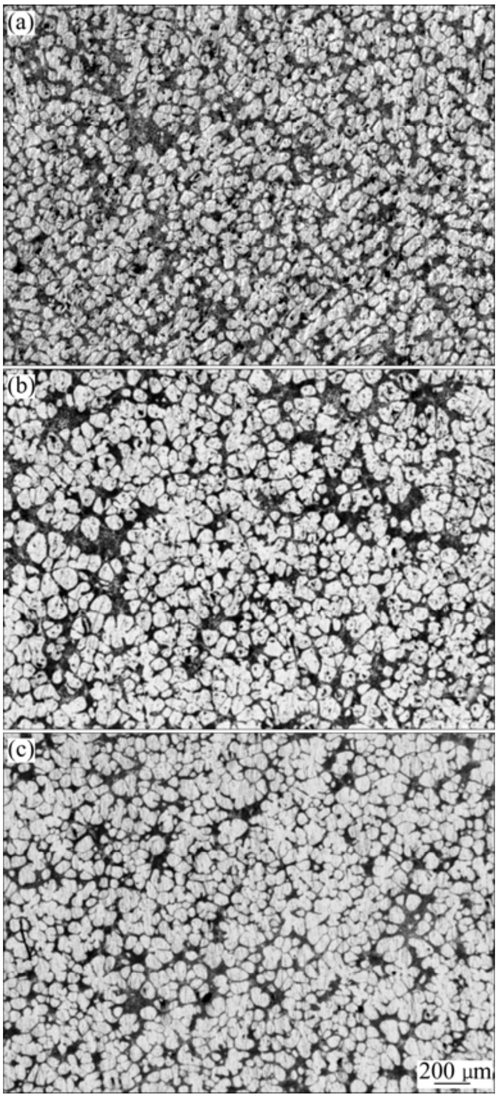

Fig.6 Microstructures of A357 alloy obtained by annulus electromagnetic stirring: (a) Edge; (b) Middle; (c) Center

towards rosette-like and the particle size is large, as shown in Fig.5(b). In the center, most of the primary α(Al) particles are rosette-like and the particle size is still large, as shown in Fig.5(c). But the microstructures obtained by the annular electromagnetic stirring are fine and the primary α(Al) particles distribute uniformly from the edge to the center of the slurry, as shown in Fig.6. The primary α(Al) particles are small and spherical in the edge of the slurry, as shown in Fig.6(a). Similarly, the primary α(Al) particles are still small and spherical in the middle and center of the slurry, as shown in Figs.6(b) and (c).

The main reason of the different microstructure is resulted from the different shear rate and cooling rate in the slurry. If the ordinary electromagnetic stirring is used, the shear rate exerted in the edge and center of the slurry is different because of the conductor skin effect, that is, the magnetic induction intensity and shear rate are strong in the edge of the slurry, but they are weak in the center of the slurry. Moreover, the cooling rates in the edge and the center are different. The cooling rate is large in the edge of the slurry but it is small in the center of the slurry, so the microstructure morphology and particle size are not completely homogeneous in the slurry. The microstructure obtained by the annular electromagnetic stirring is homogeneous in the semi-solid slurry. The semi-solid A357 alloy slurry is sheared greatly in the narrow annular gap and the shear rate is great; moreover, the slurry is cooled by the cooling pipe and the slurry-preparation house and the annular gap is narrow. So, the slurry temperature distributes uniformly, which contributes to obtain the small, globular and homogeneous microstructure.

4 Conclusions

1) The annular electromagnetic stirring is advantageous to increasing the shear rate and obtaining the small, spherical and homogeneous microstructure.

2) Compared with the ordinary electromagnetic stirring, the microstructure obtained by the annular electromagnetic stirring is small and globular, and the microstructure is homogeneous in the edge and the center.

3) The low pouring temperature and narrow annulus gap are advantageous to obtaining the small spherical primary α(Al) particles. The lower the pouring temperature is and the smaller the annulus gap width is, the more uniform, the smaller and the more spherical the microstructure is.

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