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Characterization on morphology evolution of primary phase in semisolid A356 under slightly electromagnetic stirring

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Abstract: The effects of slight electromagnetic stirring on morphology of primary phase in semisolid A356 prepared by low superheat pouring and slight electromagnetic stirring were researched, and some characteristic parameters characterized the morphology and grain size of the primary phase were calculated. The results indicate that the stirring power has an important effect on the morphology and the grain size. The characteristics of the morphology could be characterized by the fractal dimensions and the shape factors. The fractal dimension and the shape factor change when the morphology changes with processing conditions. Both increase with the increase of the stirring power, but the fractal dimension is still affected by the grain size. The increase of stirring power could obviously improve the grain size, fractal dimension and shape factor of the primary phase.
Key words: semisolid; A356; primary phase morphology; fractal dimension; stirring power

1 Introduction

The amount and morphology of primary phase in semisolid alloy have great effects on the processing ability and the mechanical properties of semisolid alloys[1−2]. The research has indicated that one of the microstructural characteristics of semisolid alloy with good forming properties has certain amount of nondendritic primary phase[3]. At present, shape factor is a more accurate analysis method to quantitatively describe the phase morphology in material, which is extensively applied to analyze the metallic material phases[4−6]. But the deficiency of this method is that the extent of the phase morphology tending towards circle is given and extent of undulating in outline of the morphology is not reflected. The primary phase morphology in semisolid alloy is globular-like, rosette-like and dendritic with different preparing conditions[7−11]. The morphology of semisolid micro-structure is the geometrically complicated, usually irregular or non-smooth, so that it is unable or difficult to be described with Euclidean geometry.

Fractal theory is a powerful tool which probes some law and the physical mechanism implied in unlawful appearance, and fractal dimension is a parameter quantitatively describing the irregular geometric figure. So far, the fractal theory has been applied to the research of solidification of metallic material[12−15]. The fractal theory is applied to study the fractal dimensions of primary phase morphology in semisolid hypoeutectic Al-Si alloy prepared by low superheat pouring and the results indicate that the primary phase morphology of the semisolid alloy can be characterized by fractal dimension, which changes with the processing parameters[16−17]. The new inspiration can be drawn from the characterizing ability of the fractal theory on the irregular morphology, namely the morphology characteristics is studied from the view of fractal, then probed the forming mechanism of semisolid nondendritic microstructure. The microstructure in semi-solid A356 prepared by low superheat pouring and slight electromagnetic stirring[18] (LSPSES) are researched, and some characteristic parameters characterized the morphology of primary phase in semisolid A356 are calculated and investigated in this paper.

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2 Experimental

A356 alloy is selected in this test, which is hypoeutectic Al-Si alloy and extensively used to semisolid processing because of the wider solid-liquid range and good fluidity. The composition of A356 is 7.46%Si, 0.49%Mg and balance Al.

The liquidus temperature of A356 is determined as 615.3 ˚C by DTA. The alloy is melted in an electric resistance furnace. The melting temperature is 700 ˚C and the pouring temperature is 630 ˚C. The mould, a cylinder made of stainless steel with 102 mm in diameter and 220 mm in depth, is inserted an electromagnetic stirrer made by ourselves. As A356 melt is poured into the mould at the set temperature, the stirrer is started at stirring powers of 60, 136, and 352 W for 8 s, respectively.

After pouring and stirring, the mould is quenched in order to maintain the microstructures stirred. Finally, some billets of the semisolid A356 are obtained.

To check the effect of slight electromagnetic stirring on low superheat pouring A356 alloy, some samples without stirring are poured at 630 ˚C.

Some wafers with thickness in 10 mm are cut from the same position of the billets. The sector samples are fetched from the wafer. The samples are polished using standard metallographic practice, etched with 0.5% aqueous solution of hydroflouric acid. The micro-structure of the sample is observed on an optical micro-scope, and MIAPS (Micro-image Analysis & Process) image analyzing soft is used to determine average equal-area-circle grain diameter (GD) and shape factor (SF) of the primary phase.

3 Results

3.1 Observation of solidified microstructure

Fig.1 shows the microstructure of the semisolid A356 prepared at different stirring powers. There is stronger “stirring effect” in the melt at larger stirring power (e.g. 352 W)[19], and the forced convection caused by stirring the melt makes the second arms of primary primary fuse and break, to have a lot of dendritic fragments as nuclei[20]. At the same time, the shrewd convection can greatly quicken up heat transferring from the center of the melt so that the superheat in the melt rapidly dissipates, and the solid-liquid phase range is enlarged. The convection can promote the mass transfer in the melt to make the layer of diffusion boundary at the front of solidified interface become thin and the concentration gradient become large, and the composition undercooling in the solid- liquid phase range increases. All this is favorable to the evolution of equiaxed grains and the grain-refinedment, so that the primary phase morphology nearly presents the globular-likeform, as shown in Fig.1(a). The “stirring effect” gradually reduces as the stirring power decreases to 136 W. The size is still fine, and only the morphology slightly changes, a little rosette-like and most globular-like or particle-like, as shown in Fig.1(b). The “stirring effect” becomes weak as the stirring power further reduces to 60 W. The morphology mainly presents the rosette-likeform and the primary phase becomes coarse, but there is no the primary phase with dendritic-likefrom in the solidified microstructure, as shown in Fig.1(c).

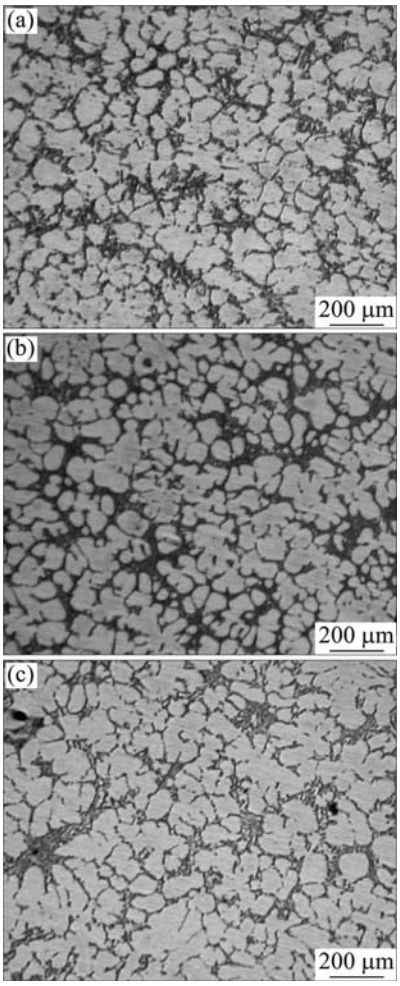

Fig.1 Microstructures of semisolid A356 prepared at different stirring powers: (a) 352 W; (b) 136 W; (c) 60 W

Fig.2 shows the microstructure of the semisolid A356 poured at 630 ˚C without stirring. It can be seen from Fig.2 that the morphology of the primary phase changes from the developed dendritic crystals poured at the general temperature to rosette-like, and there are a spot of the coarse dendritic-like primary phase. Compared with the microstructure poured at the same temperature stirring, there is no dendritic crystals in the microstructure of the semisolid A356 no matter how the stirring power is strong or not, which consists of the rosette-like or more particle-like primary phase and the size of the primary phase is smaller than that of the primary phase in the alloy without stirring, as shown in Fig.1. Moreover, the morphology of the primary phase obtained by LSPSES gradually changes from rosette-like to particle-like as the stirring power increases. The shape of the primary phase becomes more round as the stirring power increases further. These indicate that the stirring applied to the melt during the low superheat pouring can increase the number of crystal nuclei in the melt to reduce the grain size, and can make the primary phase morphology to become more round.

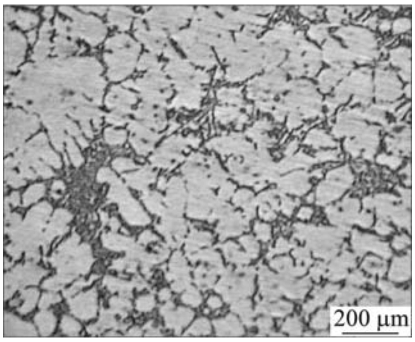

Fig.2 Microstructure of semisolid A356 without stirring

Thus it can be seen that suitable slight electromagnetic stirring applied to the melt is favorable to increasing the number of crystal nuclei and to refining the grain size, which promotes the formation of non-dendtritic grain so that the semisolid A356 satisfying rheo-forming can be obtained.

Table 1 Effect of stirring power on GD and SF of primary phase in semisolid A356 alloy

Stirring power/W	GD/μm	SF
0	144.6	0.55
60	127.1	0.71
136	91.2	0.81
352	82.7	0.83

Table 1 shows the GD and SF of primary phase in the semisolid A356 prepared at different stirring powers.

Fig.3 gives the effect of stirring power on GD and SF of the primary phase in the semisolid A356 according to the results in Table 1. It can be seen that the size of primary phase decreases with the increase of stirring power, namely GD of the primary phase decreases with the increase of the stirring power, as shown in Fig.3(a). There is greater effect of stirring power on the morphology of the primary phase too, in which SF of the primary phase increases with the increase of the stirring power, as shown in Fig.3(b).

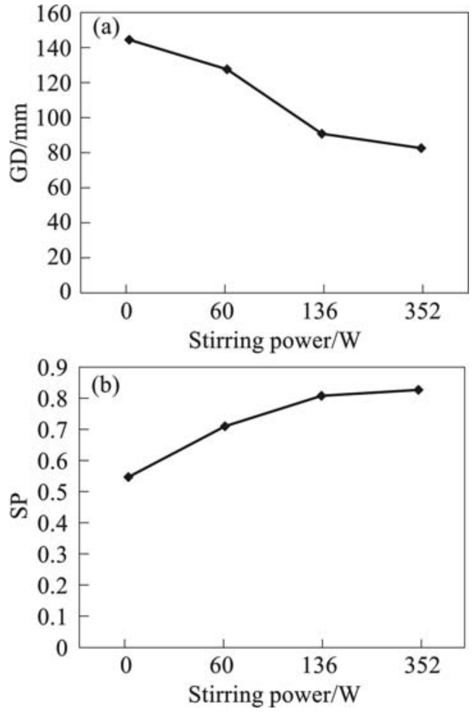

Fig.3 Effect of stirring power on (a) average equal-area- circle grain diameter and (b) shape factor of primary phase in semi-solid A356

3.2 Fractal dimension (*F*) of primary phase morphology in semisolid A356 alloy

The calculating soft written by Matlab and computing method of fractal dimension in image box-counting[16] is used to research the fractal characteristics of morphology of the primary phase. Fig.4 shows the morphology and fractal dimension (*F*) of the primary phase in the semisolid A356 prepared by LSPSES. The value of *F* of the primary phase obtained from different stirring powers is listed in Table 2 after calculation of *F*.

Table 2 Effect of stirring power on fractal dimensions of primary phase morphology in semisolid A356 alloy

Stirring power/W	Fractal dimension
352	1.606 7
136	1.598 6
60	1.589 8
0	1.579 5

It can be seen from Table 2 that *F* of the primary phase morphologies obtained at different stirring powers are different, and *F* changes with stirring power. The changing law expresses that *F* gradually decreases with the decrease of stirring power. In other words, when poured at a certain temperature during the semisolid A356 slurry preparation by LSPSES, it is a course of increase in *F* for the morphology with the increase of stirring power, as shown in Fig.5.

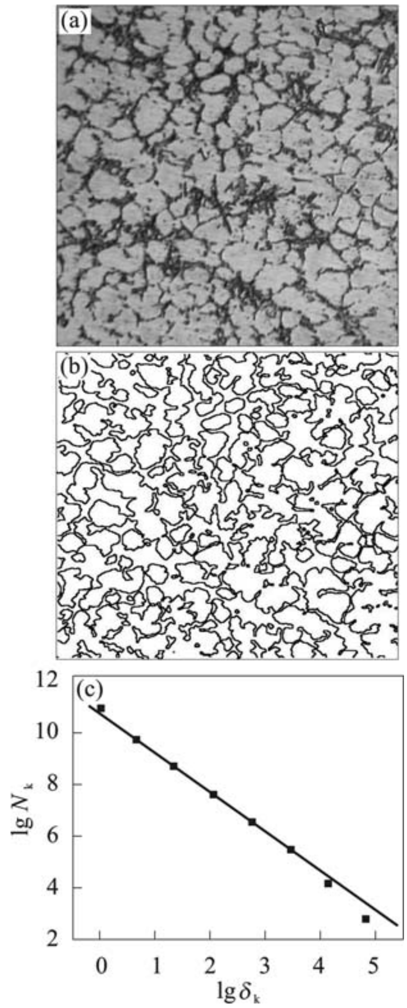

Fig. 4 Fractal dimensions of primary phase in semisolid A356 prepared by stirred with 352 W and poured at 630 ˚C: (a) Semisolid microstructure; (b) Boundary graph processed; (c) Bi-logarithm grap

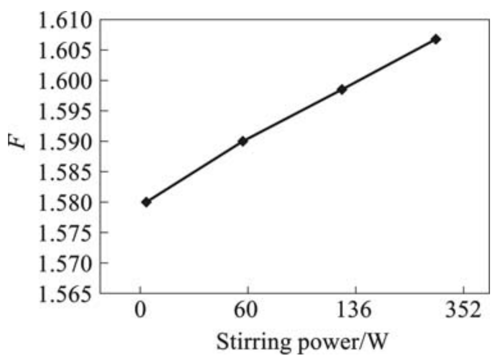

Fig.5 Change of F of primary phase morphology in semisolid A356 with stirring power

In general, the size and morphology of the primary phase gradually changes with stirring power increasing during the semisolid A356 preparation by LSPSES, in which GD reduces from 144.6 μm to 82.7 μm and SF of primary phase rises from 0.55 to 0.83, as shown in Table 1. The morphology gradually changes from dendritic to rosette-like and particle-like[19]. In other words, the morphology gradually transforms from the complicated shape to the simple shape with the stirring power increasing.

It can be seen from Table 2 and Fig.5 that the morphology of the primary phase in the semisolid A356 prepared by LSPSES posseses the fractal characteristics. In addition, F of the primary phase presents the increasing tendency with the increase of stirring power, which means that the primary phase gradually posseses more space in the alloy and its structure also becomes fine. It can be seen from the microstructure that there is more particle-like primary phase with fine size in the semisolid A356 prepared by larger stirring power, and the F calculated is larger. The mentioned analysis shows that F can be used as a kind of structure parameter to describe the primary phase morphology in the semisolid A356 prepared by LSPSES.

4 Discussion

During formation and growth of the semisolid primary phase, because of the preparation condition change(such as stirring power, pouring temperature, stirring time, isothermal holding, ultrasonic or mechanical disturbance, addition of modifier), there will be change on the morphology and size of the primary phase. At the same time, there is other change, including the growth and migration of the primary phase, even melting and separation of the primary phase. As seen by the morphology formation of the primary phase, the morphology of each primary phase experiences the same change process during the evolution, to present better self-similarity. F also correspondingly changes during the growth and evolution of the primary phase, and the F also gradually changes with the growth of the primary phase.

It can be seen from Fig.5 that F of primary phase morphology in the semisolid A356 obtained at different stirring powers in this test is greater than its topological dimension D_T(D_T = 1). This indicates that the primary phase morphology of semisolid A356 prepared by LSPSES belongs to a kind of fractal structure according to F presented by MANDELBROT[21]. It is known from the calculation of F in the primary phase morphology of the semisolid A356 obtained under different preparation conditions in this test that all data results are in accord with power law relationship in fractal theory, in which most data points distribute about straight line with better linear pertinency. The linear relationship between $\lg N_k$ and $\lg \delta_k$ in Fig.4(c) also further shows that the primary phase morphology of the semisolid A356 has the fractal characteristic. This indicates that primary phase morphology in semisolid A356 prepared by LSPSES has fractal characteristic in faith, in which F as a characteristic parameter can be used to describe its primary phase morphology.

In fact, the parameters which can characterize the the semisolid primary phase, such as average equal-area-circle grain diameter and shape factor, will change with stirring power increasing during the semisolid A356 preparation by LSPSES[18]. Since the fractal dimension can reflect the complication extent of curve or plane graph to some extent, the fractal dimension of the microstructure would reflect the complication extent of the morphology and the roundness of the primary phase. The smaller the fractal dimension is, the more simple, regular and round the morphology is. Therefore, F of the morphology has a direct bearing on its SF. But, the computing results of F of the morphology indicate that F relates not only to the complication extent of the object shape measured but also to the object size measured. The effect of size of the primary phase on F should be thought when F of the morphology are researched because HISATSUNE et al[13] reported that F increased with the grain size decreasing. Thus, there is the effect of the morphology and size of primary phase on its fractal dimension, only the size is mainly effective on F during preparation of semisolid A356 by LSPSES.

Through analyzing F obtained at different stirring powers, it is found that F of the primary phase morphology in semisolid A356 alloy will obviously change with the change of preparation conditions, such as stirring power. This means that solidification of semisolid alloy is a course of change in F.

The fractal structure is the result of the complicated system after the evolution, in which randomicity, dissipativity and nonlinearity are the physical mechanism produced fractal structure. There are numerous complicated factors affecting the evolution of the primary phase morphology in the semisolid A356, in which they are nonlinear in essence. The physical essence of nonlinearity is the dissipativity, but the dissipativity is the consequence of randomicity, therefore, evolution of the primary phase morphology in the semisolid A356 has fractal character.

The dissipative structure has the self-organized characteristic[22], namely when the controlling parameters in the outside change, the system will spontaneously adjust the exchange form and rate of matter and energy with outside environment to change its growing morphology. In this test, increasing stirring power means increasing cooling rate, and the rate and intensity for heat and mass transmission of the primary phase with around environment are quickened, resulting in the morphology evolution of the primary phase from dendritic to rosette-like or globular-like, and its fractal dimension changes finally. It is thus clear that the growing course of the primary phase is a dynamic self-organized process, and all the fractal morphology in the primary phase is the geometrical expression of dissipativity in the system.

5 Conclusions

1) The semisolid A356 containing fine particle- like primary phase can be prepared by LSPSES. There is an important effect of stirring power on the morphology and size of the primary phase, in which increase of stirring power can obviously improve the size and shape factor of the primary phase.

2) The primary phase morphology of semisolid A356 prepared by LSPSES can be characterized by fractal dimension, and the morphologies obtained by different processing parameters has different fractal dimensions.

3) During semisolid A356 preparation by LSPSES, the fractal dimension of the morphology will obviously change with the change of the preparing parameter (such as stirring power), in which it shows that solidification of the semisolid alloy is a course of change in the fractal dimension.

4) The morphology and size of the primary phase have effect on its fractal dimension, only the size of the primary phase is mainly effective on the fractal dimension during preparation of semisolid A356 by LSPSES.

5) The calculated results of the fractal dimension can be used to research the morphology of the primary phase, and to improve the preparation technology according to the calculated results of the fractal dimension so that the microstructure and characteristic of the primary phase are researched further.

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