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Effect of pouring temperature on fractal dimension of primary phase morphology in semi-solid A356 alloy

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Abstract: The fractal dimensions of primary phase morphology in semi-solid A356 alloy prepared by low superheat pouring and slightly electromagnetic stirring were calculated, and the effect of pouring temperature on fractal dimension of primary phase morphology in semi-solid A356 alloy was researched. The results indicate that it is feasible to prepare semisolid A356 alloy slurry by low superheat pouring and slightly electromagnetic stirring, and there is an important effect of pouring temperature on the morphology and the grain size of the primary phase in semi-solid A356 alloy, in which the reduction of pouring temperature can obviously improve grain size and shape factor of primary phase in semi-solid A356 alloy under the condition of a certain stirring power. The primary phase morphology of semi-solid A356 alloy prepared by low superheat pouring and slightly electromagnetic stirring can be characterized by fractal dimension, and the primary phase morphology obtained by the different processing parameters has the different fractal dimensions. Solidification of semi-solid alloy is a course of change in fractal dimension.

Key words: semi-solid; fractal dimension; morphology; pouring temperature; A356 alloy

1 Introduction

The morphology and the evolution of primary phase in semi-solid alloy are key issues for semi-solid alloy processing all along[1−2], because they directly determine the final processing properties as well as service properties. Many scholars have researched the growth of primary phase in semi-solid Al alloy by experiment, and described the morphology of primary phase in semi-solid Al alloy under the different preparing conditions[3−12]. However, the description does not provide a specific index to quantitatively distinguish the different morphologies. The reason is that the morphology of primary phase in semi-solid Al alloy is irregular or non-smooth.

The fractal theory is a powerful tool that can be used to probe the law and the physical mechanism implied in unlawful appearance, and fractal dimension is a parameter to quantitatively describe the structure of irregular geometric graph. At present, the fractal theory has been applied to researching metal solidification [13−14]. QIN et al[15−16] introduced fractal dimension, D, into the quantization of semi-solid structures and estimated the value of D by the experimental results of continuous cooling of Sn-15%Pb. Later, JIANG et al[17], GUO et al [18] and CUI and YANG[19] researched fractal dimensions of microstructure morphology in Al alloy and Mg alloy. However, these researches do not involve the evolution of fractal dimension of primary phase in semi-solid alloy. The new inspiration is derived from the characterizing ability of the fractal theory on the irregular graph, namely the morphology characteristics of semi-solid primary phase can be researched from the view of fractal, then the forming mechanism of semi-solid non-dendritic microstructure is probed. Therefore, there is a certain practical value to research the primary phase morphology of semi-solid alloy by the

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fractal theory, to optimize the preparing technology and to improve the morphology and properties of primary phase in semi-solid alloy. Semi-solid Al alloy slurry is prepared by low superheat pouring and slightly electromagnetic stirring in this work, and the corresponding calculating program written by Matlab is used to compute fractal dimension of morphology of primary phase in semi-solid hypoeutectic Al-Si alloy[20] to study the effect of pouring temperature on fractal dimension of primary phase morphology in semi-solid Al alloy.

2 Experimental

A356 alloy, as a kind of hypoeutectic Al-Si alloy, is extensively used to semisolid processing because of its wider solid-liquid range and good fluidity. A356 alloy was used in this work. The composition of A356 was 7.46 Si, 0.49Mg and balance Al (mass fraction, %).

The liquidus temperature of A356 alloy was determined to be 615.3 ℃ by DTA. A356 alloy was melted in an electric resistance furnace. The melting point was 700 ℃. The mould, a cylinder made of strainless steel with 102 mm in diameter and 220 mm in depth, was inserted into an electromagnetic stirrer. In this work, the stirring power was 136 W[10].

The pouring temperature was determined to be 650, 630 and 615 ℃. When liquid A356 alloy was poured into the mould at the set temperature, the stirrer was started at the same stirring power for a short time. Then, the mould was quenched in order to maintain the structure.

Some wafers with thickness of 10 mm were cut from the same position of the ingots. The sector samples were fetched from the wafer (through the circle center of the wafer). The samples were polished using standard metallographic practice, and etched with 0.5% aqueous solution of hydroflouric acid. The microstructure of the sample was observed on an optical microscope, and MIAPS (Micro-image Analysis & Process) image analyzing soft was used to determine average equal-area-circle grain diameter and shape factor of primary phase.

3 Results

3.1 Effect of pouring temperature on semi-solid microstructure

Fig.1 shows the semi-solid microstructures of A356 alloy obtained at the different pouring temperatures. The microstructure of semi-solid A356 alloy poured at 650 ℃ is shown in Fig.1(a). It is seen that the morphology of primary phase is mainly rosette-like, and a few globular-like and particle-like coarse grains are observed.

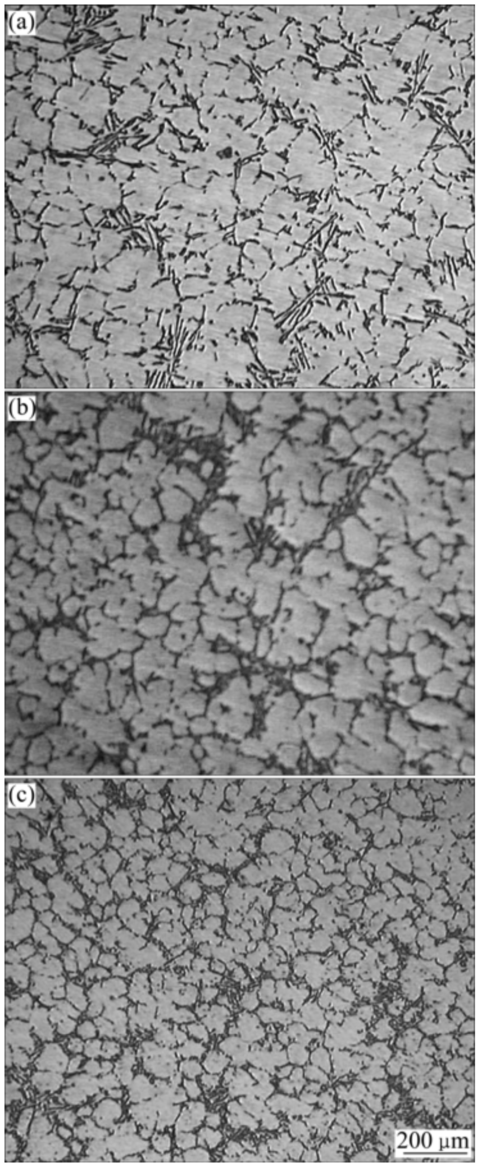

Fig.1 Morphologies of primary phase in A356 alloy obtained at different pouring temperatures: (a) 650 ℃; (b) 630 ℃; (c) 615 ℃

The microstructure of semi-solid A356 alloy poured at 630 ℃ is shown in Fig.1(b), which consists of globular-like and particle-like primary phase and a few rosette-like fine grains. The microstructure of semi-solid A356 alloy poured at 615 ℃ is shown in Fig.1(c), and it basically consists of globular-like and particle-like primary phase with small grain size. It is seen from Fig.1 that under the condition of slightly electromagnetic stirring (i.e. 136 W), the morphology of primary phase obtained from semi-solid A356 alloy is changed from rosette-like to particle-like, and the grain size is gradually decreased as pouring temperature of liquid alloy decreases. It is still seen from Fig.1 that under the condition of slightly electromagnetic stirring, satisfied morphology of primary phase is attained in semi-solid

A356 alloy poured at 615 ℃ and 630 ℃, and 136 W stirring power looks too weak to form primary phase with particle-like in semi-solid A356 alloy poured at 650 ℃. In addition, from the view point of convenient operation, selecting 630 ℃ as pouring temperature can obtain semi-solid A356 alloy slurry.

Fig.2 shows the effect of pouring temperature on average equal-area-circle grain diameter and shape factor of primary phase in semi-solid A356. It is seen from Fig.2(a) that the reduction of pouring temperature can obviously refine grain size of primary phase in semi-solid A356 alloy during low superheat pouring and slightly electromagnetic stirring, from 120.6 μm poured at 650 ℃ to 81.6 μm poured at 615 ℃. In addition, the reduction of pouring temperature can obviously improve shape factor of primary phase in semi-solid A356 alloy as shown in Fig.2(b), from 0.63 poured at 650 ℃ to 0.84 poured at 615 ℃. The results confirm that it is feasible to refine grain size and improve grain morphology through controlling pouring temperature or making use of low superheat pouring[1, 10], which are identical with the experimental results from EASTON et al[21].

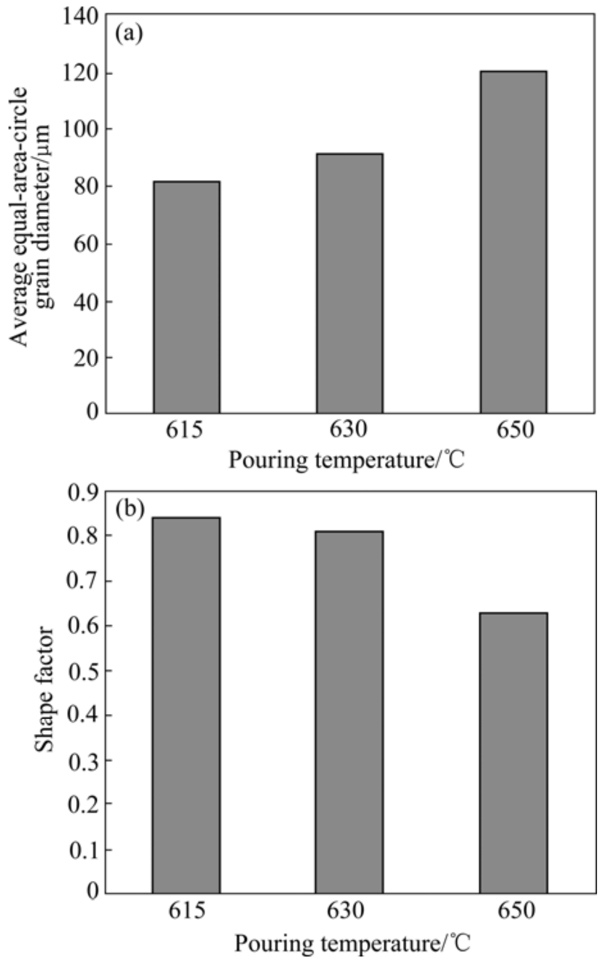

Fig.2 Effect of pouring temperature on average equal-area-circle grain diameter (a) and shape factor (b) of primary phase in semi-solid A356 alloy

3.2 Fractal dimension of primary phase morphology in semi-solid A356 alloy under different pouring temperatures

Figs.3−5 show the morphology and fractal dimension of primary phase in semi-solid A356 alloy poured at 650, 630 and 615 ℃, respectively. Calculation of fractal dimension confirms that the values of fractal dimension obtained from the different pouring temperatures are 1.610 8, 1.618 4 and 1.647 7, respectively.

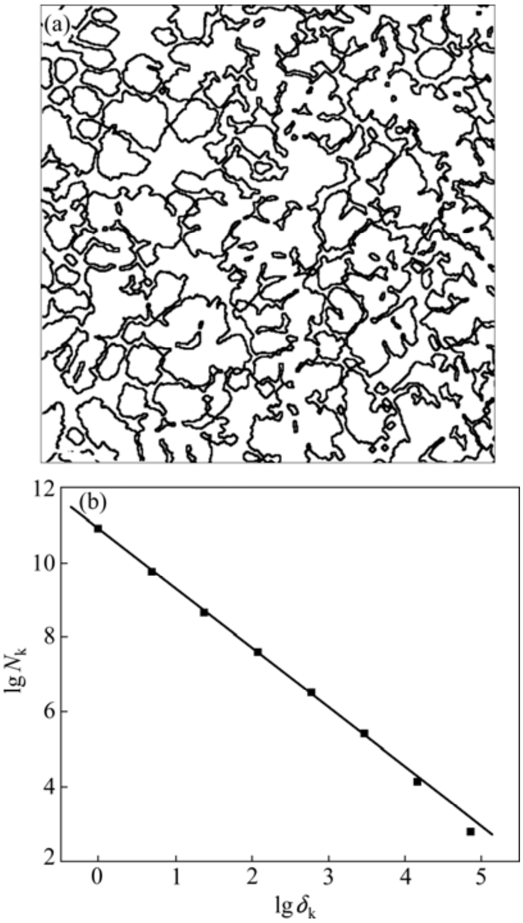

Fig.3 Fractal dimension of primary phase morphology in semi-solid A356 alloy poured at 650 ℃: (a) Boundary graph processed; (b) Bi-logarithm graph

It is seen from Figs.3−5 that during the preparation of semi-solid A356 alloy slurry by low superheat pouring and slightly electromagnetic stirring, fractal dimensions of primary phase morphology obtained at the different pouring temperatures are different, in which the values of fractal dimensions are all greater than one. The law of change expresses that the fractal dimension gradually increases with decreasing the pouring temperature, as shown in Fig.6.

In general, the grain of semi-solid primary phase gradually becomes fine with pouring temperature decreasing when the semi-solid A356 alloy slurry is

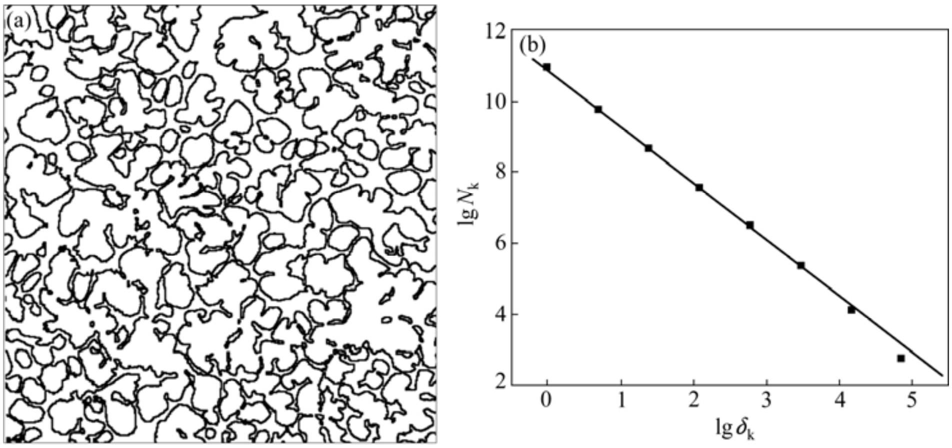

Fig.4 Fractal dimension of primary phase morphology in semi-solid A356 alloy poured at 630 ℃: (a) Boundary graph processed; (b) Bi-logarithm graph

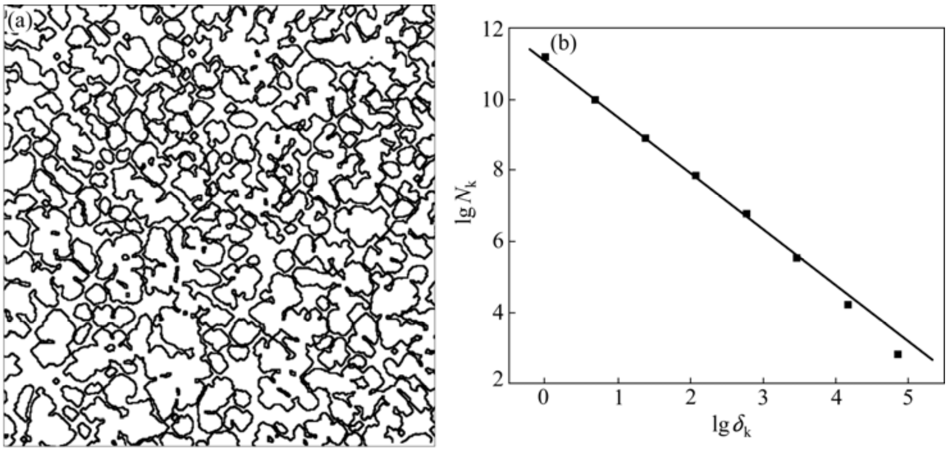

Fig.5 Fractal dimension of primary phase morphology in semi-solid A356 alloy poured at 615 ℃: (a) Boundary graph processed; (b) Bi-logarithm graph

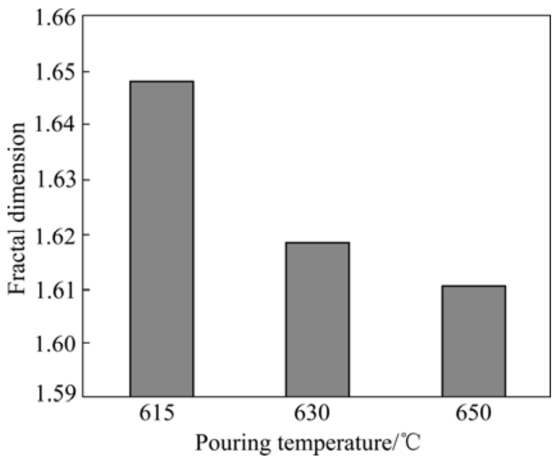

Fig.6 Change of fractal dimension of primary phase morphology in semi-solid A356 alloy with pouring temperature

prepared by low superheat pouring and slightly electromagnetic stirring. The grain size (average equal-area-circle grain diameter) reduces from 120.6 μm to 81.6 μm; the shape factor of primary phase raises from 0.63 to 0.84, and the morphology of semi-solid primary phase obtained gradually changes from dendritic to rosette-like and globular-like[7, 22]. In other words, the primary phase morphology gradually transforms from the complicated shape to the simple shape with the pouring temperature decreasing. The computing results of fractal dimension of the primary phase morphology indicate that the value of fractal dimension relates not only to the complicated extent of the object shape but also to the size of the object measured. The effect of grain size of semi-solid primary phase on the fractal dimension should be considered when fractal dimensions of semi-solid primary phase morphology are researched because it is reported that fractal dimension increases with grain size decreasing[14].

4 Discussion

It is seen from Fig.6 that the values of the fractal dimension (D) of primary phase morphology in semi-solid A356 alloy obtained at the different pouring temperatures in this work are all greater than its topological dimension D_T (D_T=1). This indicates that the primary phase morphology of semi-solid A356 alloy prepared by low superheat pouring and slightly electromagnetic stirring belongs to a kind of fractal structure according to the fractal definition presented by MANDELBROT[23]. It is known from the calculation of fractal dimension of primary phase morphology in semi-solid A356 alloy obtained under the different preparing conditions that all data accord with power law relationship of the fractal theory. The linear relationship between lg N_k and lg δ_k in Figs.3(b)−5(b) further shows that primary phase morphology of semi-solid A356 alloy has the fractal characteristic. This indicates that primary phase morphology of semi-solid A356 alloy prepared by low superheat pouring and slightly electromagnetic stirring has fractal characteristic, in which fractal dimension as a characteristic parameter can be used to describe its primary phase morphology.

Through analyzing the fractal dimension obtained at different pouring temperatures, it is found that fractal dimension of primary phase morphology in semi-solid A356 alloy obviously changes with the change of preparing conditions, such as pouring temperature. This means that solidification of semi-solid alloy is a course of change in fractal dimension.

The physical mechanism of the fractal structure produced lies in the dissipation of system[24]. During solidification of semi-solid A356 alloy, the region with several atomic layer widths at the front of growing interface and the growth environment around constitute a kind of dissipative system, which satisfies the ample and essential condition to form the dissipative structure[25], once nuclei of primary phase are formed. First, it is an opening system, in which primary phase during solidification will continuously exchange energy and matter with outside (liquid phase). Second, the growing course of primary phase is far from the equilibrium state because solidification of semi-solid A356 alloy goes on under the forced convection condition[11, 26], especially strongly forced convection[6, 9]. Third, there is non-equilibrium fluctuation in the system, for example, the change of temperature gradient and concentration at the growing interfacial front of primary phase is caused by the change of solidifying condition. Fourth, there is the nonlinear relationship between the essential factors in the system, for example, the changes of temperature and concentration under non-equilibrium solidification conditions are very complicated, in which the relationship between the effecting factors is nonlinear.

The dissipative structure has the self-organized characteristic[27], namely, when the controlling parameters outside change, the system will spontaneously adjust the exchange form and exchange rate of matter and energy with outside environment to change its growing morphology. In this work, decreasing pouring temperature means increasing cooling rate, and rate and intensity for heat and mass transmission of primary phase with environment around are accelerated, resulting in the morphology evolution of 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 semi-solid primary phase is a dynamically self-organized process, and the fractal morphology in microstructure is the geometrical expression of dissipation in the system.

The change of fractal dimension is the expression of interior characteristic in material, and the change of microstructure in material also closely relates to the manufacture condition. Therefore, the relationship between manufacture condition and microstructure may be understood through the research on the fractal dimension of microstructure.

5 Conclusions

1) The semi-solid A356 alloy slurry with primary phase of globular-like fine grains can be prepared by low superheat pouring and slightly electromagnetic stirring. Pouring temperature has great influence on the morphology and the grain size of the primary phase in semi-solid A356 alloy. In the range of temperature researched, the reduction of pouring temperature can obviously reduce grain size and improve shape factor of primary phase in semi-solid A356 alloy.

2) The primary phase morphology of semi-solid A356 alloy prepared by low superheat pouring and slightly electromagnetic stirring can be characterized by fractal dimension, and the primary phase morphology obtained by the different processing parameters has different fractal dimensions.

3) When the semi-solid A356 alloy slurry is prepared by low superheat pouring and slightly electromagnetic stirring, the fractal dimension of primary phase morphology in semi-solid A356 alloy obtained will obviously change with preparing parameters (such as pouring temperature) changing. It is shown that the solidification of semi-solid alloy is a course of change in fractal dimension.

4) The calculating results of fractal dimension can be used to research the morphology and properties of primary phase in semi-solid A356 alloy.

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