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Microstructure evolution of components of ZAlSi8Cu3Fe alloy in processing of thixo-diecasting

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Abstract: The microstructures of components of ZAlSi8Cu3Fe alloy in the process of thixo-diecasting were investigated. The effects of processing conditions on the microstructure of the alloy in the thixo-diecasting procedures of original casting billets, remelting billets and casting components were researched, and the morphological evolution of α-particles in the alloy was analyzed quantitatively. The results show that, the microstructure of the original billets poured at 582 ℃ consists of rosette-like primary α-particles; in the procedure of remelting, when the temperature rises over solidus, arms in the rosette-like α-particles begin to fuse off from dendritic branches and after further heating, α-particles surrounded by liquid phase are refined by the diffusion of atoms and rounded owing to the least interface stress and interface energy principles; and in the procedure of thixo-diecasting, the morphologic characteristics of α-particles and the distribution of phases in the structure change greatly for the high shear rate under the restricted area of the ingate.

Key words: ZAlSi8Cu3Fe alloy; microstructure; thixo-diecasting; semi-solid

1 Introduction

Nowadays, ZAlSi8Cu3Fe alloy is mainly used in the high pressure die-casting(HPDC) form for structural components in the automobile industry, because HPDC is of high efficiency and low cost[1]. However, HPDC components contain a substantial amount of porosity due to gas entrapment during melt filling and hot tearing during the solidification in the die cavity[2]. Since the inception of semi-solid metal(SSM) processing concept in early 1970s[3], because semi-solid die casting is suitable for complicated large parts of near net shape without defect and with excellent mechanical properties in comparison with conventional casting process[4−5], much work including the optimization of original microstructure, the microstructural evolution during remelting the billet and the relationship between the thixotropy and the microstructure of semi-solid aluminum alloy[6−10] has been discussed deeply. However, it is known that different casting processes, especially semi-solid processes, will result in a variation of the as-cast microstructure, and there are many uncertainties to be clarified for the microstructural characterization under various processing conditions.

Based on the above facts, the thixo-diecasting technique is applied to form a component of motorcycle with the semi-solid metal HPDC. In this work, the effects of pouring temperature, remelting processing and thixo-diecasting processing on the morphological evolution of primary α(Al) phase in ZAlSi8Cu3Fe alloy are reported, the primary α(Al) phases pre/post thixo-diecasting are analyzed quantitatively, and the relationship between the microstructure of ZAiSi8Cu3Fe alloy and processing conditions is discussed.

2 Experimental

The chemical compositions of commercially available ZAlSi8Cu3Fe alloy are listed in Table 1. The liquidus and solidus temperatures of the alloy are 594 ℃ and 540 ℃, respectively.

In the present thixo-diecasting process, ZAlSi8Cu3Fe alloy ingot was firstly melted at 750 ℃ in an electric resistance furnace, then degassed for 10 min with bubbled argon through a graphite lance. The original billets for remelting were fabricated by the low super-heat casting process. In this process, the melt was allowed to cool down to a chosen pouring temperature near liquidus in a ladle firstly, and then poured into a

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Table 1 Chemical composition of Al-Si8Cu3Fe alloy (mass fraction, %)

Si	Cu	Fe	Impurities	Al
8.86	3.44	1.29	0.02	Bal.

steel mold (180 mm in length and 60 mm in diameter) that had been preheated to 180 ℃. By this process, original billets for remelting with non-dendritic microstructure were fabricated at 582 ℃.

In the remelting processing, the billets poured at 582 ℃ were reheated to 560, 565, 568, 570 and 571 ℃ using a high-frequency induced heating equipment, respectively, and then quenched in cold water immediately. In all cases, two K-type thermocouples were installed at the center near the exterior location of one end of a billet with their tips inserting into the depth of 80 mm from another side of the billet (shown in Fig.1) to monitor temperature varieties of the bulk billet during reheating.

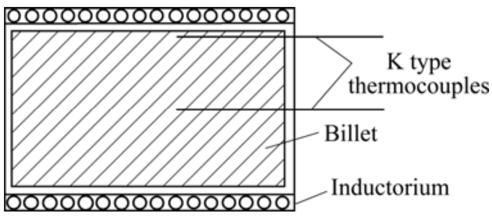

Fig.1 Schematic diagram of experimental set-up for billet temperature testing

The semi-solid billet remelted to 570 ℃, corresponding to a solid volume fraction of about 40% for the ZAlSi8Cu3Fe alloy, was transferred into the shot sleeve of a 2 500 kN commercial cold chamber high pressure die-casting(HPDC) machine for mould filling to form a component of generator bracket in JH70 motorcycle[11]. The as-cast samples poured at 582 ℃, the partially remelted samples reheated to different temperatures mentioned above and the component samples obtained in different locations of a component (shown in Fig.2) were sectioned, polished and etched with 4% H_3PO_4 solution. The microstructure characteristics were observed in an optical microscope.

A quantitative metallography analytic system[12] was used to measure α-phase particle cross-sectional area, A_j, and perimeter, L_j, as well as the percentage of α-particles in samples. The samples used for quantitative metallography analysis came from the original billet remelted at 570 ℃, the locations of punch(A) and ingate(B) in gating system of the component, the location inside a component near ingate(C) and the location far from ingate(D). The particle size was characterized by its

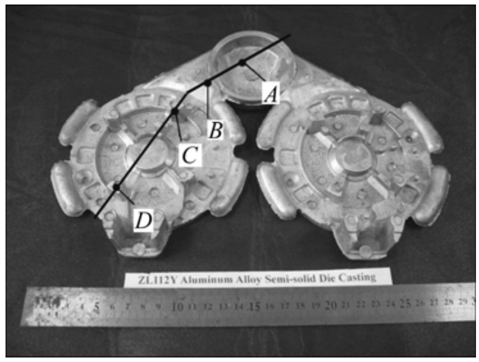

Fig.2 Different locations of samples of component for structure observation

equivalent circle diameter, defined as: $2(A_j/\pi)^{1/2}$, and the particle shape was characterized by roundness, defined as: $(4\pi A_j)/L_j^2$. The roundness varies from 0 to 1, and 1 denotes a microstructure having perfectly spherical particles and 0 highly branched particles of elongated microstructures.

3 Results

3.1 Effect of pouring temperatures on microstructures

Fig.3 shows the microstructure of a billet sample poured at 680 ℃. Fig.4 shows the microstructures of samples poured at 582, 585, 600, 610 and 620 ℃, respectively. In these micrographs, the white microstructure is primary α aluminum phase, while the black one is eutectic phase of aluminum and silicon, $CuAl_2$ and low melting point composites, and most of the eutectic phase is intergranular. From Figs.3 and 4, it can be seen that the morphology of α-solid phase varies with different pouring temperatures from large dendritic microstructure (Fig.3), to coarse dendritic microstructure (Fig.4(e)), to finer dendritic microstructure (Figs.4(c) and (d)) and to rosette-like microstructure (Figs.4(a) and (b)).

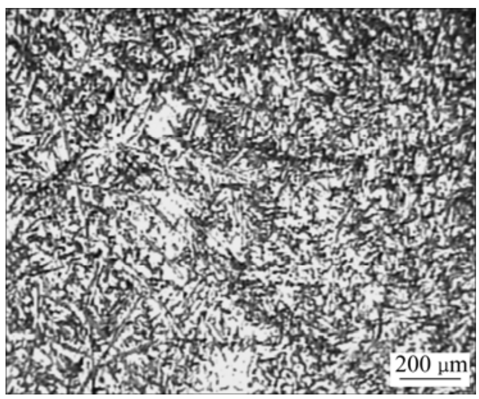

Fig.3 Microstructure of original billet prepared at 680 ℃

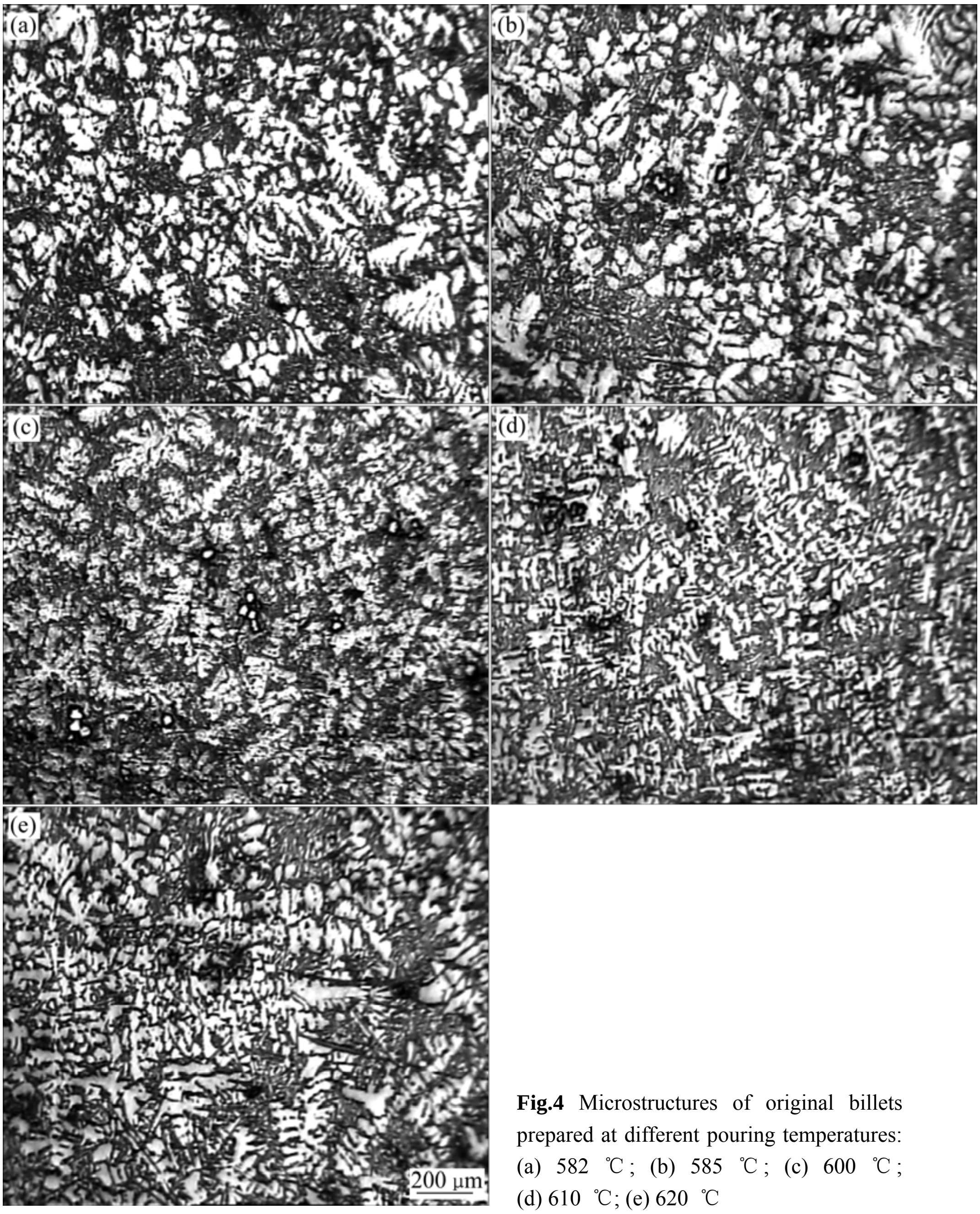

Fig.4 Microstructures of original billets prepared at different pouring temperatures: (a) 582 ℃; (b) 585 ℃; (c) 600 ℃; (d) 610 ℃; (e) 620 ℃

3.2 Microstructural characteristics in process of remelting

The microstructural characteristics during remelting were observed and shown in Fig.5. The eutectic phase at α crystal boundary begins to melt at 540 ℃ (Fig.5(a)), and when the billet is remelted at 560 ℃ (Fig.5(b)), the solute elements start to transfer between the melting eutectic and α solid crystal. At 565 ℃ (Fig.5(c)), the remained branches of rosette-like dendrites start to melt, and some isolated grains appear in the billet. At 568 ℃ (Fig.5(d)), the dendritic microstructures of billet totally disappear and the visible boundaries of isolated crystals almost form. At this time, an erosion effect of liquid to solid crystals continues and the sphericizing stage begins. When the remelting temperature increases to 570 ℃ (Fig.5(e)), the primary solid phase presents to be strip or worm shapes with zigzag surface. As melted at 571 ℃ (Fig.5(f)), the solute concentrations at interface tend to be equilibrium and zigzag surface is replaced with smooth one, and α-particles become larger than those remelted to 570 ℃.

3.3 Microstructural characteristics in component

Fig.6 shows the microstructures of components in different locations, corresponding to *A*, *B*, *C* and *D* denoted in Fig.2, respectively.

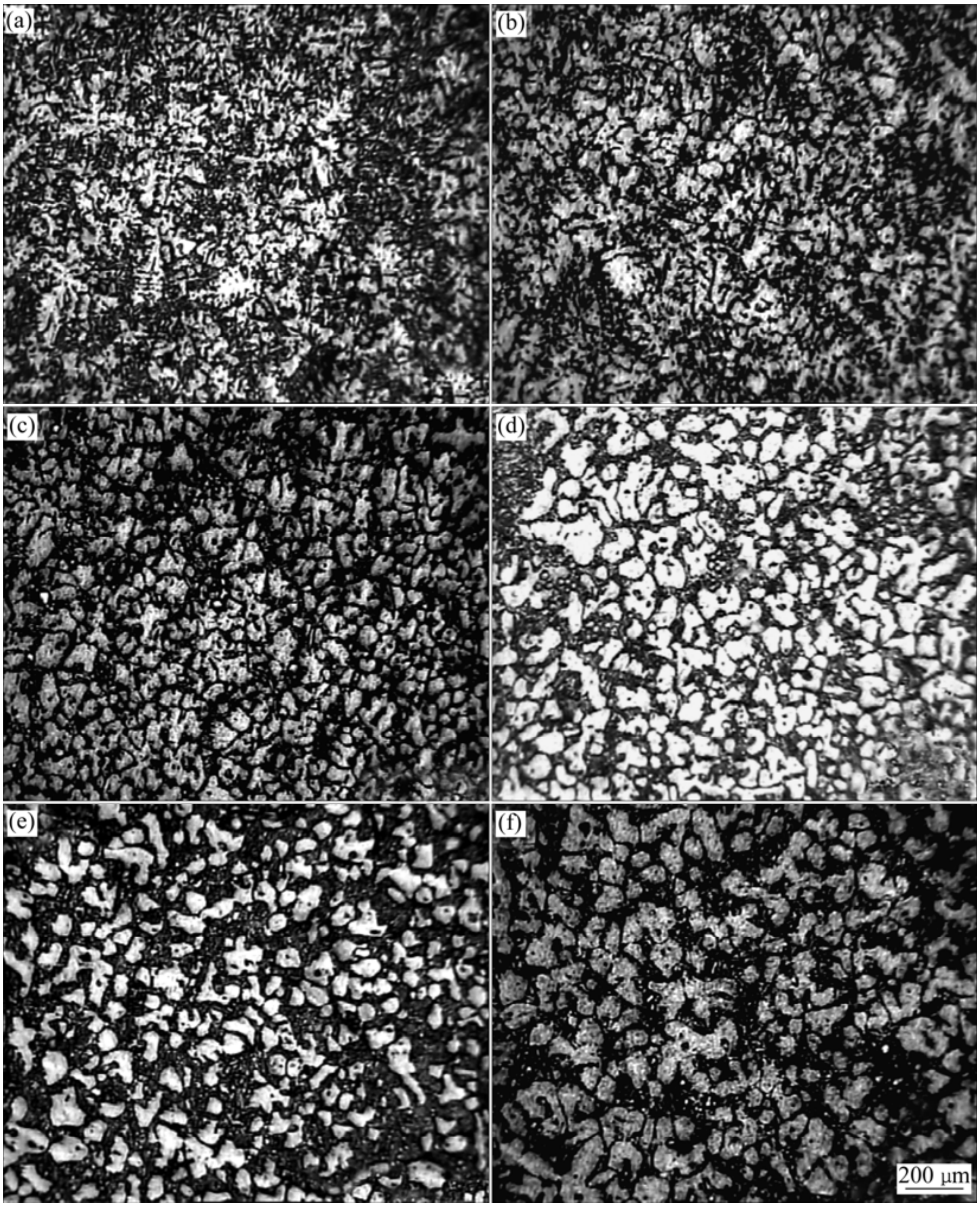

Fig.5 Microstructural characterization of billets during remelting at different temperatures: (a) 540 ℃; (b) 560 ℃; (c) 565 ℃; (d) 568 ℃; (e) 570 ℃; (f) 571 ℃

It can be seen from Fig.6 that, 1) the morphologies of α-particles in all locations present a trace of flowing morphology along flowing direction of liquid metal obviously; 2) there are more liquid phase and less solid phase at the locations far away from the ingate than at the locations close to the ingate in a component; 3) there are staff and strip α-particles everywhere in Figs.6(c) and (d), by comparing the particles in Fig.6 with the particles in Fig.5(e), which shows the distortions of particles obviously as they flow with liquid; and 4) the microstructure in components is compact, and few holes appear.

3.4 Quantitative metallography analysis results of α-particles

Fig.7 shows the quantitative analysis results of α-particles in the samples, in which the original billet represents the sample of the semi-solid billet remelted to 570 ℃, and *A*, *B*, *C* and *D* denote the samples of components corresponding to *A*, *B*, *C* and *D* locations denoted in Fig.2 respectively. It is shown that, 1) α-particles fraction at the punch increases to 0.42 from

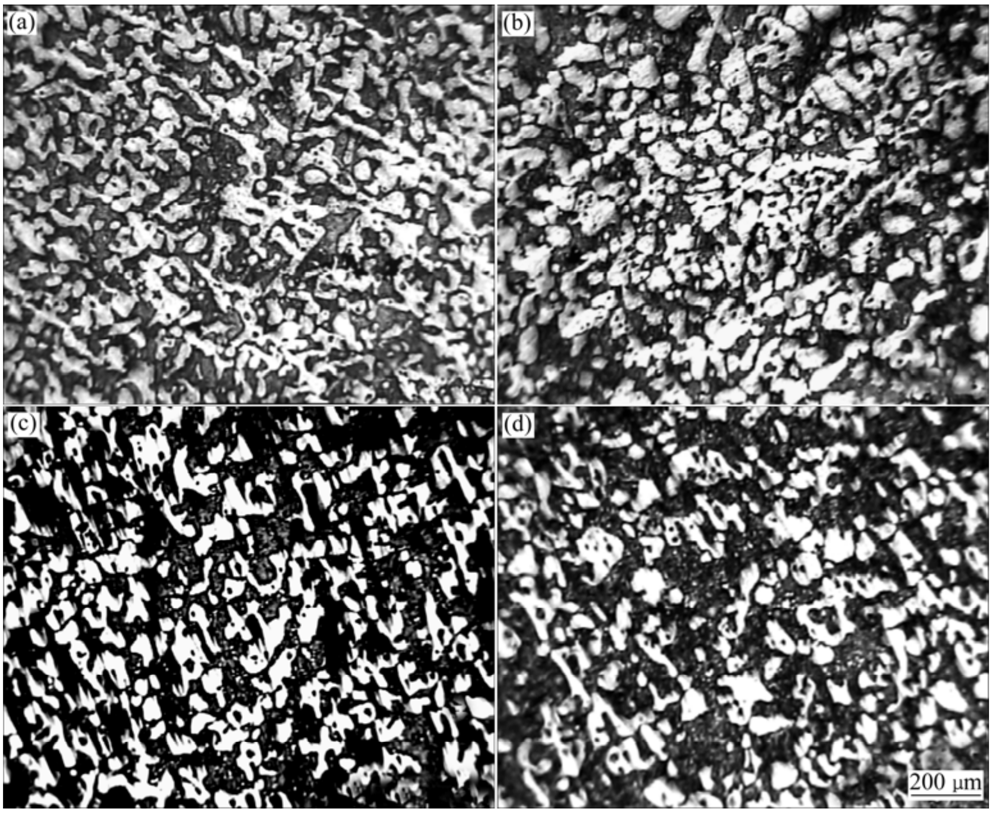

Fig.6 Microstructures of component with (a), (b), (c) and (d) corresponding to *A*, *B*, *C* and *D* in Fig.2, respectively

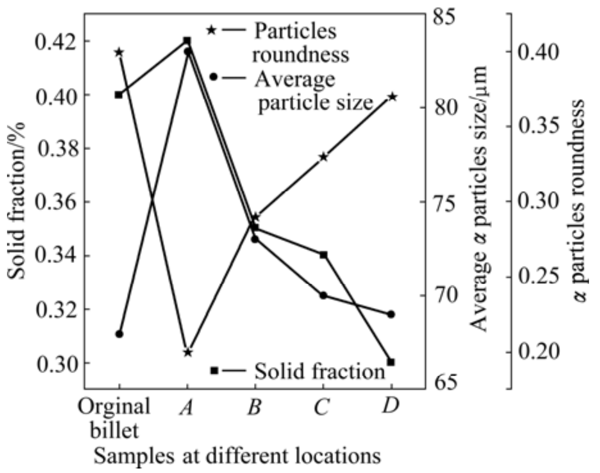

Fig.7 Results of solid phase structures by quantitative analysis

0.40 of the billet remelted at 570 ℃, and the α-particles fraction reduces from 0.29 at ingate to 0.33 at the location near the ingate, and to 0.37 at the location far from the ingate in the component; 2) the average α-particle size in the sample of the original billet remelted at 570 ℃ is 68 μm, which is in the range of 69 μm and 74 μm inside the component, and it becomes the largest in the punch; 3) the roundness of α-particles in original billet is the largest among those samples, and the roundness of α-particles at all locations in a component changes from 0.20 to 0.37.

4 Discussion

4.1 Formation of non-dendritic microstructure

During the fabrication of billet by low super-heat pouring process, when the temperature of the melt in ladle is cooled to the liquidus temperature, a little primary α solid phase appears in the semi-solid melt, and when the semi-solid slurry is poured into the mold, the fine primary α-particles distribute in the melt uniformly. In addition, the highly undercooled melt near the mold wall at low pouring temperature explodes with a large number of nuclei, big bang or copious nucleation, to lift up melt temperature with the released latent heat of fusion. However, the temperature rise near the mold wall is not sufficiently enough to pose any threat to solidification by remelting the nuclei or primary α solid phase even for the lowest pouring temperature. Nor is the total heat content of the melt. The rate of temperature rise near the wall is greater for lower pouring temperature due to higher nucleation frequency and thus shorter time for the metastability period. The central parts however solidify in normal manner, and it is assisted by the floating nuclei and fine primary α-particles, due to fluid flow during pouring and natural convection from the wall region to eventually establish a uniform cooling rate. The probability of such nuclei to survive is much great at lower pouring temperature and the uniform and multi-directional cooling promotes the formation of rosette-like as-cast microstructure, as clearly seen in Fig.4(a).

During remelting, when the temperature of the billet is just up to the solidus temperature (540 ℃), a little of liquid phase appears. With the rise of reheating temperature, the scattered α-particles are obtained because of a branch-fusion of finer dendritic microstructure, as shown in Figs.5(b) and (c). Because the silicon and copper easily concentrate in the concaves at the roots of branches for the segregation of solute during solidification of the alloy, and the melting point of the alloy at the roots of branches is lower than that at other locations of the α-particles, the branch root is firstly fused off and α-particles scatter off each other. When the reheating temperature goes above 565 ℃, the amount of liquid phase becomes more and more, small crystals surrounded by liquid are fused off, and big α-particles grow bigger and their contours become more spherical for the effects of the least interface curvature and the least interface energy. The system energy at liquid/solid interface of α-particles is reduced because the area of solid/liquid interface of the system is reduced by the diffusing of solute atoms on the interface between α-particles and liquid in the procedure of remelting.

In contrast, the primary α-particles in electro-magnetical and mechanical stirred material may have a bi-modal appearance that fine rosette structures coexist with coarse particles up to 300 μm in size[13−14]. However the size of α-particles in billet prepared by low superheating pouring at 582 ℃ and reheated to 570 ℃ in this work is below 100 μm, and the process of fabricating original billet used in this work is very simple, cheap and convenient. As far as the remelting processing in this study, the whole cycle time is shorter and the holding time of temperature is less compared with the other remelting process. WANG et al[14] reported that the roundness and size of α-particles in original billet, which was produced by the controlled-pouring method, were about 15, corresponding to 0.67 in this paper, and 200 μm with zero holding time at some temperature, and with the increase of holding time, the roundness of α-particles became bigger and α-particles size became smaller to some degree. But in this study, the roundness of α-particles and α-particles size are about 0.42 and 80 μm at 570 ℃, respectively. This indicates that the preparing process of original billet, the holding time and the holding temperature during remelting have great effects on the morphology of α-particles. Although the α-particle roundness in this work is lower, and the α-particles size is less, the remelting cycle time is also short. Because the remelted billet for filling has good thixotropy, the dense and good casting can be obtained in the diecasting process[15].

However, the elements of the alloy in solution, especially copper and silicon, would agglomerate in nanometric or micrometric domains during solidification, which leads to the agglomeration of alloy elements in billet. Although the remelting process of billet could decrease the agglomeration of the alloy element to a certain extent owing to the diffusion of solute elements, the agglomeration of alloy elements will still affect the mechanical properties of alloy greatly. Fortunately, the agglomerates of alloy elements could be eliminated by heat-treatment process, and the mechanical properties of the alloy fabricated by semi-solid die casting can be improved[15].

4.2 Evolution mechanism of α-particles in thixo-diecasting

The semi-solid deformation behaviors of solid particles in slurry of an alloy during forging are described with four mechanisms[16]: liquid flow(LF), flow of liquid incorporating solid particles(FLS), sliding between solid particles(SS), and plastic deformation of solid particles(PDS).

During thixo-diecasting, the filling of semi-solid alloy slurry belongs to complicated two-phase flows, in which the flows include not only the absolute flowing of solid particles and liquid together but also the relative flowing of solid particles to the liquid, so the morphologic characteristics of α-particles in the billet also undergo a series of varieties for the separation of liquid from the solid phase under pressure. Firstly, α-particles flow in the mode of flow of liquid incorporating solid particles when pushing a semi-solid billet into ingate, secondly, α-particles slide each other because of the abrupt decreasing of pressure during filling of the semi-solid slurry into cavity from ingate, and at last, in the process of holding pressure, plastic deformation happens to the α-particles in the piercer under elevated pressure. In fact, the deformation mechanisms happened at different locations of the casting are dissimilar and α-particles at every locations undergo more than one kind of deformation mechanisms. So it can be seen from Fig.6 and Fig.7 that the roundness of α-particles at different locations of the cast is lower than that in the remelted billets, and the α-particles size as well as the fraction of solid phase also changes greatly. Therefore, the application of the external force causes liquid and solid phases to move in pressure direction and to increase collisions amongst solid particles. In the case of very high shear rates, the liquid phase tends to run faster than the solid particles to initiate the so-called “liquid segregation”, the inhomogeneous distribution of phases in the structure. Fineness of particles and reduction of shear rate could overcome such problem.

In contrast with forging process, one of the most differences of the thixo-diecasting process is that the ingate of die-casting mould restricts the flowing of semi-solid slurry greatly, a number of α-particles are distorted plastically, and even joined each other greatly so that the morphology of α-particles including the fraction, the average size and the roundness of α-particles also change greatly.

5 Conclusions

1) In the process of preparing original billet, tiny primary α-particles are come into being in a melt under the liquidus temperature, and when this melt is poured into mold, the highly undercooled melt near the wall explodes with a large number of nuclei, big bang or copious nucleation, to lift up melt temperature with the released latent heat of fusion near the mold wall. The floating of these nuclei and α-particles towards the central regions establishes a uniform cooling rate throughout the mold. The uniform cooling rate coupled with multi-directional cooling promotes the formation of fine rosette-like as-cast structure.

2) In the process of remelting billet, the amount of liquid in an alloy is increased along with the increasing of temperature. The isolated α-particles are formed as branches of non-dentritical α-particles are fused off at roots of branches. And at last, α-particles are sphericized increasingly by the atom diffusion at the interface between crystals and liquid.

3) In the process of die-casting, the α-particles in a component distort plastically and joint each other greatly owing to the high shear rate under the restricting of the ingate, and the application of the external force causes liquid and solid phases to move in pressure direction, and to increase the collision amongst solid particles and the inhomogeneous distribution of phases in the structure.

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