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Microstructural characteristics and properties in centrifugal casting of SiC_p/Zl104 composite

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Abstract: The microstructural characteristics and Brinell hardness of a cylinder produced by centrifugal casting were investigated using 20% (volume fraction) SiC_p/Zl104 composites. Macrostructure and XRD analysis show that most of SiC particles segregate to the external circumference of the cylinder, the other SiC particles maintain in the inner circumference of the cylinder, and a free particle zone is left in the middle circumference of the cylinder. Microstructural characteristics and quantitative assessment of SiC particles show that most of congregated SiC particles in 20%SiC_p/Zl104 composites are dispersed by centrifugal force, and the other congregated SiC particles and most of alumina oxide are segregated to the inner circumference of the cylinder. The SiC particles in aluminum melt can promote the refinement of primary α(Al) during solidification, and fine primary α(Al) grains can also promote the uniform distribution of SiC particles. Brinell hardness of SiC_p/Zl104 composites is connected with not only the volume fraction of SiC particles, but also the distribution of SiC particles in matrix alloy.

Key words: metal-matrix composites; particle reinforcement; centrifugal casting; microstructure; hardness

1 Introduction

Nowadays, metal matrix composites(MMCs) can be used in wide applications ranging from civil structures, to aerospace and recreational products[1−2]. This is due to the capability of MMCs to be designed to provide a vast varieties of mechanical, thermal and dimensional accuracy properties. It is shown that uniform distribution of particulates in metal matrix has great effect on properties of composites, and homogeneously reinforced MMC components are well corresponding to homogeneous properties[1]. Among various preparation methods, compocasting[3] is a relatively simple process of mechanical agitation for the production of MMCs which can be easily scaled as required. But the volume fraction of SiC particles in the composites is below 35%; and pores of composites cannot be avoided completely [4]. Therefore, it is necessary to form further by pressure forming processes, such as extrusion[5] and centrifugal casting[1].

Centrifugal casting is one of the most effective methods for processing functionally graded materials (FGMs) made of aluminum matrix composites (AMCs) [6−7], and it has been demonstrated that a compositional gradient can be obtained by using centrifugal casting to segregate phases with different densities[8−9]. In general, microstructural characteristics of these centrifugally cast composites were performed as a function of position along the radial direction of centrifugal caster owning to the difference of centrifugal force along the radial direction [10−11]. Previous researches have also demonstrated that the distribution of heavier ceramic particles in melt are influenced by various centrifugal casting processing parameters, such as rotation velocity of mold, crucible furnace temperature, and mold heating temperature [8, 12−13]. So, controlling processing parameters of centrifugal casting can achieve homogeneous MMCs with higher volume fraction of ceramic particles during centrifugal casting. Also centrifugal casting contributes to lower costs by reducing the number of production steps compared with surface modification and coating methods which have to be performed separately[14]. For SiC_p/Al composites fabricated by compocasting, congregated SiC particles and voids in SiC_p/Al composites cannot be avoided completely, and very few

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reports were found concerning the microstructural characterization of this kind of SiC_p/Al alloys under centrifugal force.

Based on those considerations, this work aims to segregate SiC particles in liquid aluminum alloy to local region using 20%(volume fraction) SiC_p/Zl104 composites fabricated by compocasting to achieve uniformly-distributed SiC_p/Zl104 composites. Microstructural characteristics, and Brinell hardness of the cylinder sample along radial direction were presented in detail.

2 Experimental

2.1 Material

The raw material used in this study was a SiC_p/Al composites (Zl104 aluminum alloy matrix reinforced with 20% (volume fraction) silicon carbide particles), which were synthesized by compocasting. The matrix alloy was an Al-Si alloy whose composition is listed in Table 1. The advantage of using this alloy is mainly the optimum level of Si content. The amount of Si present in this alloy helps to reduce chemical reactivity with SiC[15]. The reinforcement particles were chosen as commercial SiC with 99.5% purity, and a mean particle size of (15.8±5.2) μm, whose size distribution is shown in Fig.1.

Table 1 Chemical composition of aluminum alloy (mass fraction, %)

Si	Mg	Fe	Ti	Zn	Mn	Al
9.24	0.54	0.22	0.09	0.01	0.007	89.8

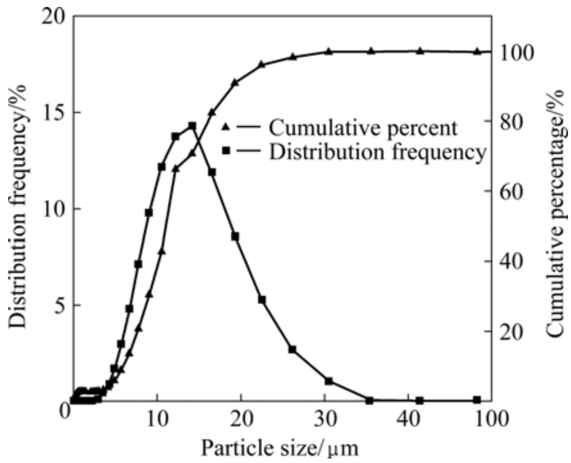

Fig.1 Particle size distribution of SiC as reinforcement of composites

2.2 Experimental processing

A centrifugal machine was designed and built, and its details are given in Fig.2, which contains a power rotation system and a mould fixed on the centrifugal casting equipment for forming cylinder samples. The mould is made of $45^{\#}$ steel, and unidirectional solidification is enforced directly by the unidirectional heat transfer of outer circumference of the mould.

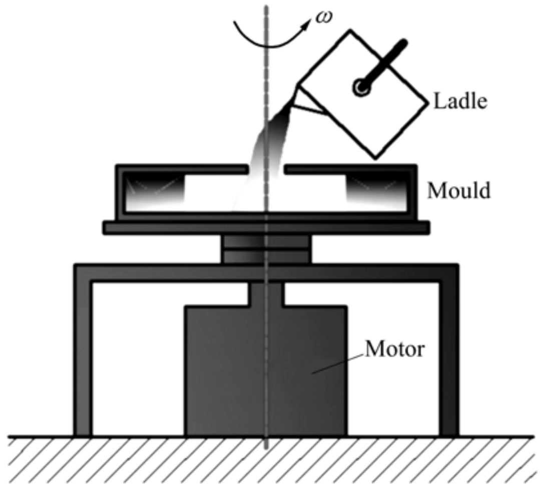

Fig.2 Schematic drawing of equipment for centrifugal casting

In this experiment, the mould was pre-heated to 500 ℃, and the pouring temperature of SiC_p/Zl104 composite slurry was 750 ℃. A centrifugal casting was performed at 800 r/min, which corresponded to the maximum centrifugal acceleration of 54*g* (the values of the centrifugal accelerations are given in terms of *g*, the acceleration of gravity). The dimensions of the cylinder are 128 mm(outer diameter)×72 mm(inner diameter)×110 mm(length), weighing 2 300 g each approximately.

2.3 Microstructural observation and properties test

Samples were sectioned from the cylinder along the radial direction, and samples for microstructural observation and properties test were taken at different positions (*x*) from the external circumference of the cast cylinder. Microstructure was observed using optical microscope after these specimens were machined, polished and eroded by solution of 2 mL HF+3 mL HCl+5 mL HNO_3+190 mL H_2O. Quantitative assessment of SiC particles in the centrifugally cast samples was carried out using the chemical dissolution method. The Brinell hardness of the cylinder sample was tested along the radial direction on HB−3000B type Brinell hardness tester.

3 Results and discussion

3.1 Cross-section macroscopic photograph of cylinder

The cross-section macroscopic photograph of the centrifugally casting cylinder is shown in Fig.3. This cross-section of the sample contains external reinforced

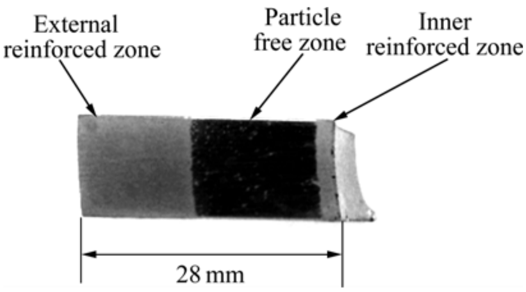

Fig.3 Macroscopic photograph showing cross-section of block cast

zone, particle free zone and inner reinforced zone. Most of SiC particles in Zl104 slurry are segregated towards the external circumference of the cylinder by centrifugal casting, and SiC_p/Zl104 composite with high SiC particle volume fraction is obtained. And the other SiC particles remain in the inner circumference of the cylinder.

3.2 Microstructural characteristics

Fig.4 shows the optical microstructures of compocasting 20%SiC_p/Zl104 composites. The SiC particles are dispersed uniformly in the aluminum matrix except some congregated SiC particles, and only a few voids can be observed.

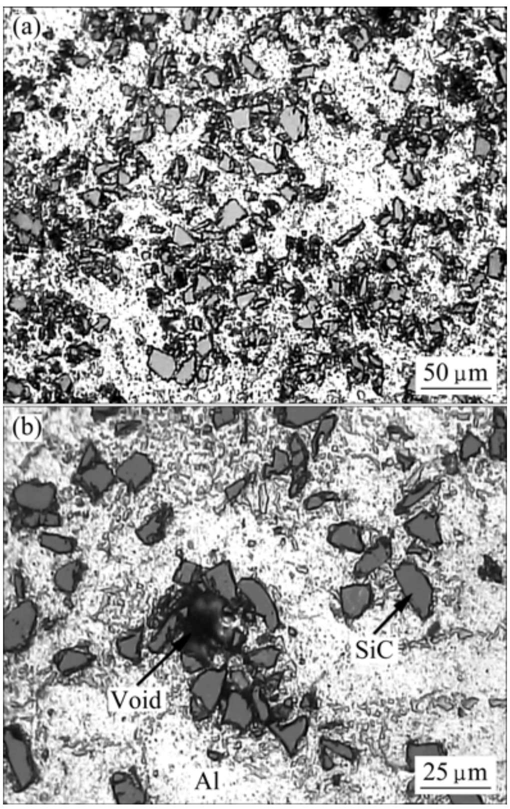

Fig.4 Microstructures of SiC_p/ZL104 composite fabricated by compocasting: (a) In lower magnification; (b) In higher magnification

Fig.5 shows optical microstructures of cylinder sample taken at different positions from the external circumference (x). As seen from Figs.5(a)−(h), the cross-section of the sample along the radial direction of the cylinder is divided into external reinforced zone, middle free particle zone and inner reinforced zone, and the distribution of SiC particles and microstructure of the matrix alloy are different in these three zones. Figs.5(a)−(c) show that SiC particles in Zl104 melt segregate to the external circumference of cylinder after centrifugal casting, and the SiC particles in samples taken at 1 mm or 5 mm from circumference have more uniform distribution compared with those in the sample taken at 9 mm. In addition, few congregated SiC particles and voids can be observed in sample located at 9 mm. As seen in Fig.5(d), there is a distinct interface between external reinforced zone and free particle zone. Figs.5(f)−(h) show that there are no SiC particles in visible, and thin granular eutectic Si phase presents among coarse dendritic primary α(Al) phases at those positions (shown in Fig.5(e), (f) and (g)). As seen in Fig.5(h), there are many voids, congregated SiC particles and a little alumina oxides.

For the samples located in the external reinforced zone, because some congregated SiC particles are scattered into isolated particles under centrifugal force, the distribution of SiC particles of samples becomes more uniform compared with raw SiC_p/Al composites after centrifugal casting, and more uniform distribution of SiC particles with the larger centrifugal radium is found in this study. Because alloy solidification takes place in very restricted zone at the interfaces between particles, the quick transport process of solution elements in liquid aluminum alloy promotes the homogeneous nucleation of matrix alloy during solidification. The fine equiaxed primary α(Al) can be achieved in this zone, and the solidification front of primary α(Al) pulls SiC particles to the interface between thin primary α(Al) phases. The larger the number of primary α(Al) grains is, the more uniform the distribution of SiC particles is.

For the samples located in the free particle zone, the centrifugal agitation prevents the growth of eutectic silicon and dendritic primary α(Al), and low undercooling leads to a coarse primary α(Al). Therefore, the thin granular eutectic Si phase and coarse non-dendritic or dendritic primary α(Al) in this zone are observed.

3.3 Segregation of SiC particles

The phase analysis results shown in Fig.6 identify that the SiC particles in external reinforced zone leave a free particle zone in the middle zone of the cylinder. This confirms that the SiC particles in SiC_p/Zl104 composites segregate to external circumference completely in this study.

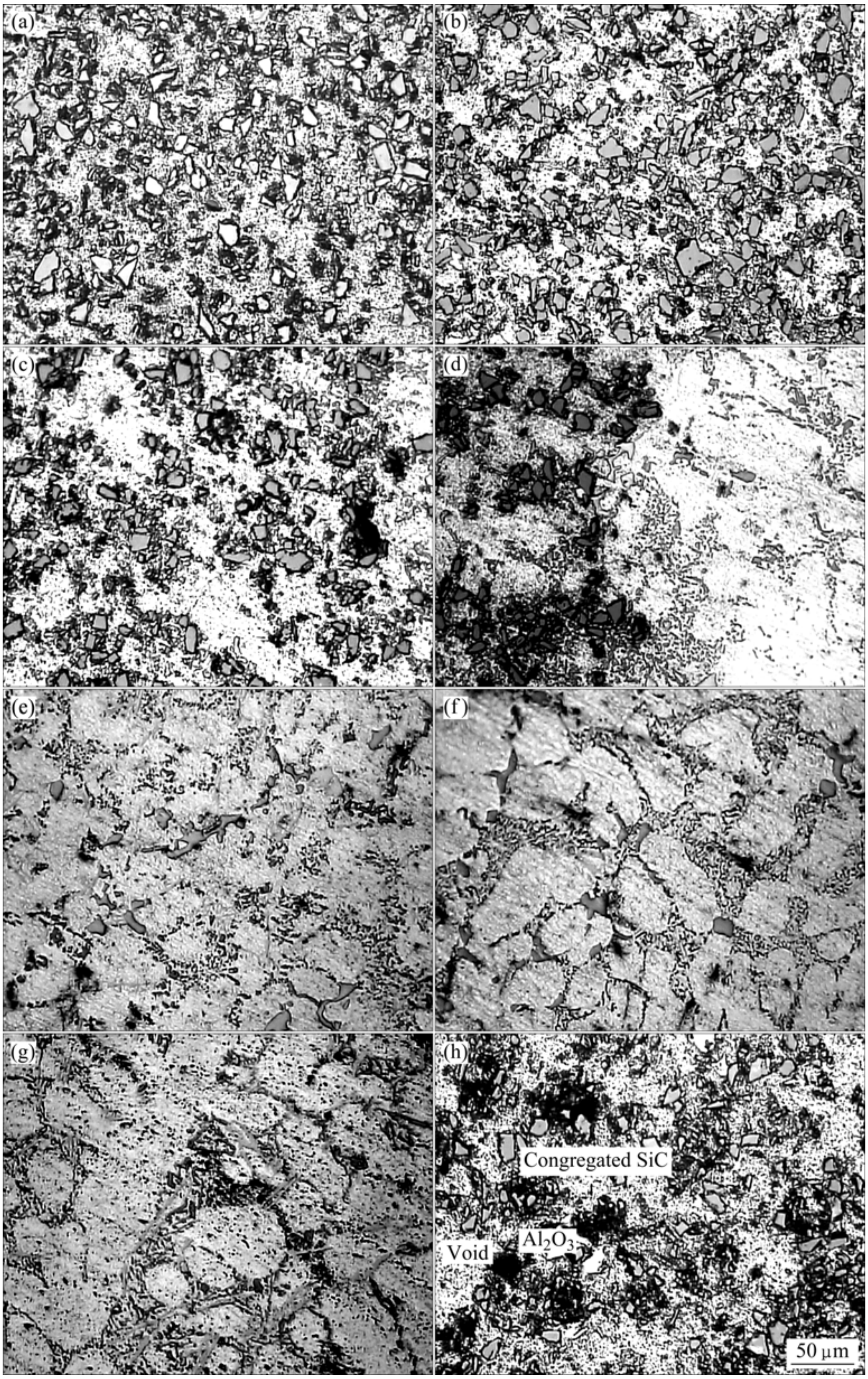

Fig.5 Optical micrographs of sample located at different positions from external circumference of cylinder: (a) x=1 mm; (b) x=5 mm; (c) x=9 mm; (d) x=12 mm; (e) x=16 mm; (f) x=20 mm; (g) x=24 mm; (h) x=27 mm

Fig.7 demonstrates the SiC particle volume fraction of samples at different positions from external zone to inner zone of the cylinder. The volume fraction of SiC particles in samples decreases gradually with the increase of distance. The higher volume fraction for larger diameter specimens is found, and the difference of volume fraction at different positions in external zone is very small.

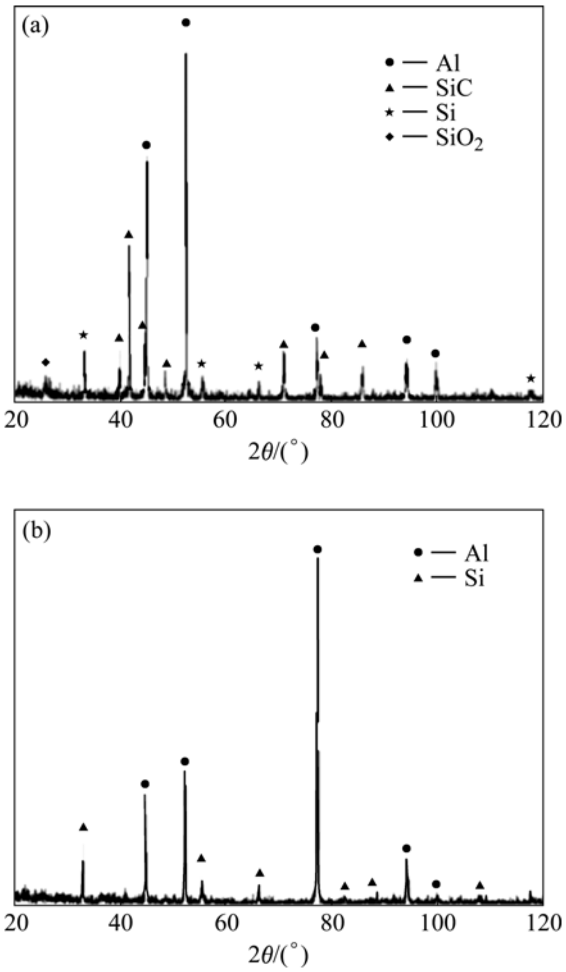

Fig.6 XRD patterns of samples located in reinforced zone (a) and free particle zone (b)

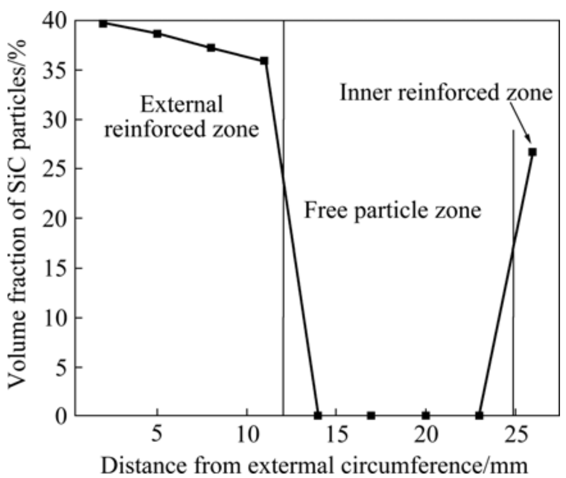

Fig.7 Volume fraction of SiC particles with distance from external circumference of cylinder

The volume fraction of SiC particles along the radial direction of cylinder changes under centrifugal force. It is known that the motion of ceramic particles in a viscous liquid under a centrifugal force can be determined by the Stokes' law[10]. The velocity of the particles is proportional to the square of the particle diameter and the density difference between ceramic and viscous liquid. In general, heavier ceramic particles in a viscous liquid alloy can segregate to external circumference during centrifugal casting. But for 20%SiC_p/Zl104 composites in this study, the uniformly-scattered SiC particles, pores, voids and congregated SiC particles in SiC_p/Zl104 composites have different bulk density, so different motion directions during centrifugal casting can be found. Uniformly-scattered SiC particles segregate to the external circumference of the cylinder, while alumina oxidize, pores and voids migrate to the inner circumference of the cylinder during centrifugal casting. But for congregated SiC particles, some of them can be scattered and segregate to the external circumference, and others with low bulk density migrate to the inner circumference under centrifugal force. On the other hand, quick cooling of inner circumference of cylinder prevents the movement of the SiC particles in this two-direction fluidity so that some SiC particles remain at the inner circumference. The volume fraction of SiC particles located in inner particle zone, therefore, increases a little compared with that in raw 20%SiC_p/Zl104 composites.

Hence, the distribution conditions of ceramic particles in a viscous liquid influence the microstructural characteristics in centrifugal casting of composites reinforced with ceramic particles. Meanwhile, the morphology of primary α(Al) in turn affects the distribution of SiC particles. It is helpful for the uniform distribution of SiC particles in composites by refining microstructure of the matrix alloy during solidification.

3.4 Brinell hardness

Fig.8 shows the Brinell hardness of samples at different positions from the external circumference of the

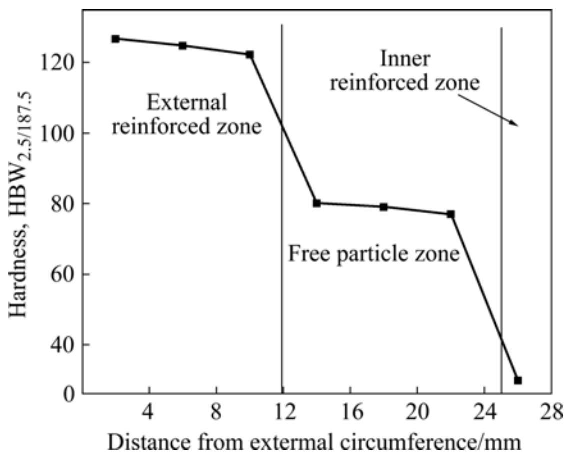

Fig.8 Brinell hardness of samples at different positions from external circumference of cylinder

cylinder. There is a corresponding increase in Brinell hardness with the increase of volume fraction of SiC particles gradually, a big gap in hardness from external reinforced zone to free particle zone, and a huge decrease at inner reinforced zone because of appearance of amounts of voids and congregated SiC particles. These defects can destroy the microstructural continuity of composite material so that the mechanical properties decrease greatly. So, the Brinell hardness of SiC_p/Zl04 composites is related with the number and the distribution of SiC particles in the matrix alloy. For SiC_p/Zl104 composites with uniformly-distributed SiC particles, adding SiC particles can improve the Brinell hardness of the matrix alloy obviously, and the larger number of SiC particles for higher Brinell hardness are found in external reinforced zone. The Brinell hardness of the sample located in free particle zone can be affected by the thin granular eutectic silicon phase, and this requires more in-depth investigation.

4 Conclusions

1) Most of SiC particles in 20%SiC_p/Al composites are enriched in the external zone of the cylinder under centrifugal force, and some congregated SiC particles with low bulk density segregate to the inner reinforced zone of the cylinder. A cylinder with external reinforced zone, middle free particle zone and inner reinforced zone is fabricated by centrifugal casting.

2) The agitation of centrifugal force promotes the dispersion of congregated SiC particles and the nucleation of amounts of primary α(Al) phases in external reinforced zone. The larger the number of primary α(Al) grains is, the more uniform the distribution of SiC particles in matrix alloy is, and vice versa.

3) The agitation of centrifugal force prevents the growth of dendritic primary α(Al) and flaked eutectic silicon, so the thin granular eutectic Si phase and some coarse non-dendritic primary α(Al) phases are achieved in free particle zone.

4) Uniform distribution and the high volume fraction of SiC particles in matrix alloy can improve Brinell hardness obviously.

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