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ARTICLE

Centrifugal Forming Mechanism of Al Gradient Composites Reinforced with Complementary Primary Si and Mg_2Si Particles

Zhai Yanbo[1], Ma Xiuteng[1], Mei Zhen[2]

[1] Southwest University, Chongqing 400715, China; [2] Chongqing Machine Tool (Group) Co., Ltd, Chongqing 400055, China

Abstract: To overcome the shortages of Al composites reinforced with a single primary Si or Mg_2Si particles, a new type of gradient composites reinforced with the two particles was investigated through centrifugal casting. The structures and the properties of the composites have the obvious gradient distribution characteristics. The inner zone is the reinforced zone with a high volume fraction of primary Si and Mg_2Si particles, whereas the external zone is the unreinforced zone with few or no primary Si and Mg_2Si particles. Due to the high volume fraction of the complementary particles, the hardness values of the inner zone are much more than that of the external zone. The assembling mechanism analysis reveals that the massive primary Mg_2Si particles are the key factor to form the gradient composites. In the centrifugal field, the relative velocity of the lower density primary Mg_2Si particles is higher than that of primary Si particles. The Mg_2Si particles will collide and impel primary Si particles to move more quickly towards the inner zone of tubular parts during freezing, resulting in a strong concentration of the primary Si and Mg_2Si particles in the inner zone. To obtain the enough primary Mg_2Si particles, the amount of Si should not be lower than 19 wt% and that of Mg not lower than 4 wt% in ternary Al-Si-Mg alloys.

Key words: gradient composites; particle-reinforced composites; primary Si; primary Mg_2Si; centrifugal forming

As the commonest in situ reinforcement of Al composites, Si and Mg_2Si have been widely studied and applied[1]. Si has high melting point, high hardness, low density and good thermal stability, so it is an excellent in situ reinforcement for Al composites[2,3]. Data[2,3] revealed that the hardness HV of Al-15Si alloy can reach 5000~7000 MPa, and that of Al-60Si alloy can even reach about 10 000 MPa. However, when the traditional way is adopted to prepare high Si alloys castings, the primary Si would take on the thick lath form which is harmful to the alloys properties[4]. Moreover, although the high-Si Al alloy bears a large load friction, due to the significant hardness difference between Si and the Al matrix, the Si grains would fall off from the Al matrix and its wear resistance could not be given full play[4,5]. Since the Modulus of Elasticity (MOE) of Si is lower than that of Al, it does not improve the strength of the Al alloy or composites[3].

Mg_2Si is a kind of intermetallic[3], and its thermal, physical and mechanical properties are similar to that of Si, so it is also a common in situ reinforcement for Al composites[6,7]. Compared with Si, Mg_2Si has lower density and higher MOE, so it is able to reduce the density and improve the strength of Al composites. However, because its hardness is lower than that of Si, it can not dramatically improve the hardness and the abrasion resistance of Al composites[8,9]. In addition, similar to the high-Si Al alloy, Mg_2Si would form a thick dendritic structure and reduce the material property when the traditional way of alloy preparation is adopted[6,7].

To overcome the shortcomings of the Al composites reinforced by either Si or Mg_2Si particles, Si and Mg_2Si particles can be simultaneously added into Al matrix and used as complementary reinforcement. In addition, to avoid the Si and Mg_2Si particles becoming bulky with their increasing

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Corresponding author: Zhai Yanbo, Ph. D., Lecturer, College of Engineering and Technology, Southwest University, Chongqing 400715, P. R. China, E-mail: bird513@163.com

volume fraction, an external force field can be introduced to shape a gradient composites[10-12]. Gradient composites was firstly reported in 1980′s by researchers of Japan[13]. Compared with traditional materials, the structure and the performance of gradient composites can be designed to satisfy different application situations. Laser cladding, physical deposition (PCD), thermal spraying and powder metallurgy (PM) etc were often used to prepare the gradient composites in the past [14]. Recent years, the way to use the external force field to form the gradient composites is becoming a new idea with the increasing application and demanding for cost-reduction. For instance, the centrifugal casting Al gradient composite piston and the brake disc reinforced with SiC particles have been used as parts of a car.[15]

For these reasons, the authors have selected ternary Al-Si-Mg alloys as raw material, used primary Si and Mg_2Si particles as complementary reinforcement, and taken the centrifugal force field as the external force field, to explore the formation conditions and mechanism of the Al gradient composites.

1 Experiment

Ternary Al-Si-Mg alloys were prepared using commercial Zl104 alloy, industrial pure Mg and high silicon alloy as starting materials. Through the analysis of the phase diagram of Al-Si-Mg alloys, the following experiments were designed. Group 1. Adjust the amount (mass fraction) of Mg on the basis of 19% Si, i.e. Al-19Si-0Mg, Al-19Si-2Mg，Al-19Si-4Mg; Group 2: Adjust the amount of Si on the basis of 4% Mg, i.e. Al-17Si-4Mg, Al-21Si-4Mg.

5 kg alloys were prepared as described above, incorporating 0.6% scouring agent C2Cl6 and 1.5% phosphorus metamorphic (PM) agent.

A homemade horizontal centrifugal casting machine with the fixed revolving speed 2000 r/min was used. The five different kinds of alloys were handled with an identical technique; that is to say, tubular parts were made with preheating temperature of the mould about 200 °C, centrifugal revolving speed 2000 r/min and pouring temperature 830 °C without cooling water.

The dimensions of the five tubular parts obtained were 109 mm in external diameter, 190 mm long and 15 mm wide. Fig.1 shows its shape and dimensions.

The five tubular parts obtained were each dissected, polished, and then used as the microstructure analytical samples of optical microscopy (DX60). The collection points for structural analysis are shown in Fig.1b, as a, b, c, d, e, and f, which are 1, 3, 5, 8, 11 and 14 mm away from the inner wall of its part, respectively.

A HR150 Rockwell Hardness Tester was adopted, with the diameter of the iron ball head being 1.588 mm and with application of a 100 kg load. The test points were selected from the zones shown in a, b, c, d, e, and f in Fig.1b, and the values reported were the average of at least five readings.

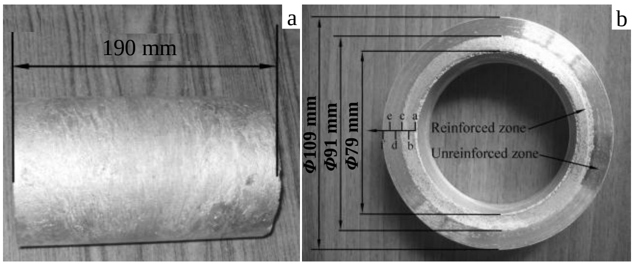

Fig.1 Composite tubular parts fabricated by centrifugal casting: (a) surface of tubular parts and (b) cross section of tubular parts

2 Results and Discussion

2.1 Result of group 1

The cross-section microstructures of Al-19Si-0Mg, Al-19Si-2Mg and Al-19Si-4Mg tubular parts are presented in Fig. 2, 3, and 4, respectively.

As shown in Fig.2, when the mass percentage of Mg is zero, Al-19Si-0Mg is a kind of typical hypereutectic alloy, the microstructure of which is characterized by primary Si, eutectic *α* and eutectic Si. After centrifugal forming, although the distribution of primary Si particles follow the rule of decreasing firstly and then increasing from the inner wall to external wall, there is no significant difference. The eutectic

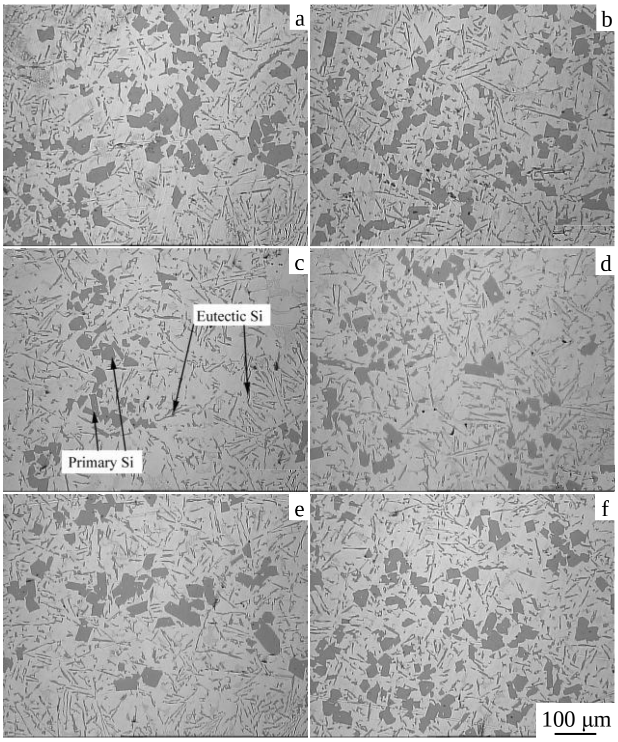

Fig.2 Cross-section microstructures of Al-19Si tubular parts corresponding to the zones a (a), b (b), c (c), d (d), e (e) and f (f) in Fig.1b

Si is evenly distributed on the cross section without being affected by centrifugal force field.

As shown in Fig.3, when the mass percentage of Mg is 2%, a large amount of vermiform Mg_2Si phase appears, and they distribute uniformly over the cross section. The primary Si and eutectic Si take on almost the same distribution characteristics as the Al-19Si-0Mg. In addition to this, the sizes of the primary Si become larger than that of Al-19Si-0Mg. The possible reason for this may be related to the modifications which should be distinguished from the different alloys. While, for the purpose of conducting a contrastive study as in this article, all of the five kinds of alloys used the same modifications as described in the experiment.

When the mass percentage of Mg is 4% (Fig.4), the cross-section structure has changed dramatically as follows:

1) Plenty of black granular Mg_2Si particles appear for the first time, each of which is 30~60 μm in diameter. Almost all of them are distributed in the inner zone and the middle zone (as shown in Fig.4a, 4b, 4c and 4d), and only a few are distributed in the external zone (as shown in Fig.4e and 4f).

2) Contrasted with Al-19Si-0Mg and Al-19Si-2Mg, the primary Si particles of Al-19Si-4Mg are only distributed in the inner zone and the middle zone, just like the Mg_2Si particles.

3) In addition, the matrix of Al-19Si-4Mg is composed of eutectic α, eutectic Si and eutectic Mg_2Si, which are distributed uniformly from the inner layer to the external layer.

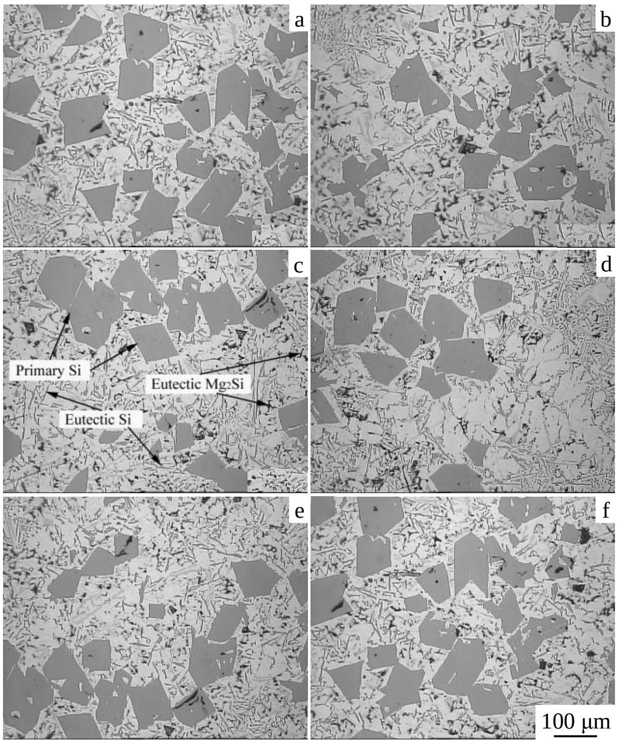

Fig.3 Cross-section microstructures of Al-19Si-2Mg tubular parts corresponding to the zones of a (a), b (b), c (c), d (d), e (e) and f (f) in Fig.1b

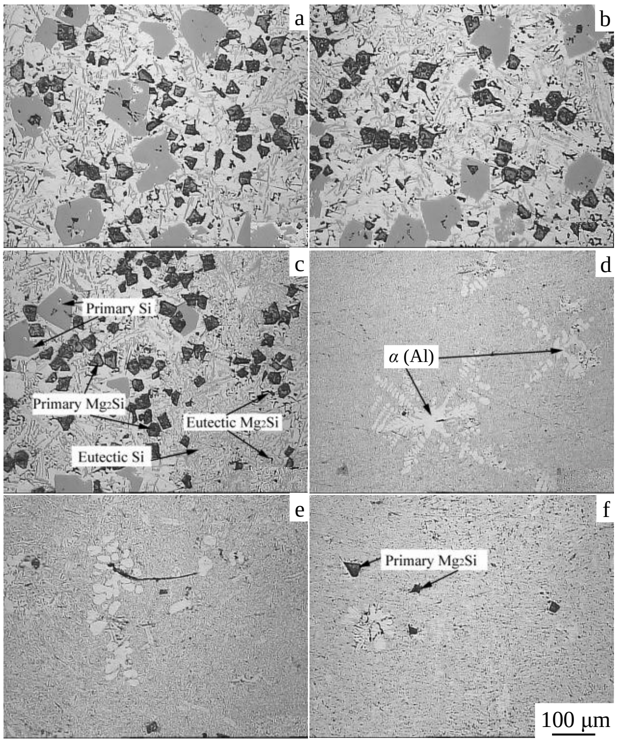

Fig.4 Cross-section microstructures of Al-19Si-4Mg tubular parts corresponding to the zones of a (a), b (b), c (c), d (d), e (e) and f (f) in Fig.1b

4) A clear boundary appears in the macro cross section of the tubular parts between the reinforced zone and the unreinforced zone, as shown in Fig.1b.

Due to the obvious gradient distribution, the reinforced zone which is rich in the primary Si and Mg_2Si particles with a high volume fraction ought to be characterized by high hardness, high abrasion resistance, and better thermal stability. On the contrary, the unreinforced zone consisting of eutectic α, eutectic Si and eutectic Mg_2Si ought to be characterized by excellent machinability. In addition, the transitional zone with a micro metallurgical combination may improve the bond strength between the reinforced zone and unreinforced zone. In engineering practice, this kind of the composite materials can be used to make those parts that need local enhancement, such as ICE cylinder liners and pistons, which need a local enhancement in the inner wall and the piston head, respectively.[16]

2.2 Result of group 2

The cross-section microstructures of Al-17Si-4Mg and Al-21Si-4Mg tubular parts prepared are presented in Fig.5 and 6, respectively.

As shown in Fig.5, the cross-section microstructure of the tubular part of Al-17Si-4Mg is similar to that of Al-19Si-2Mg (Fig.3) in group 1. However, the eutectic Mg_2Si phase of the former one is bulkier and more abundant, whereas the

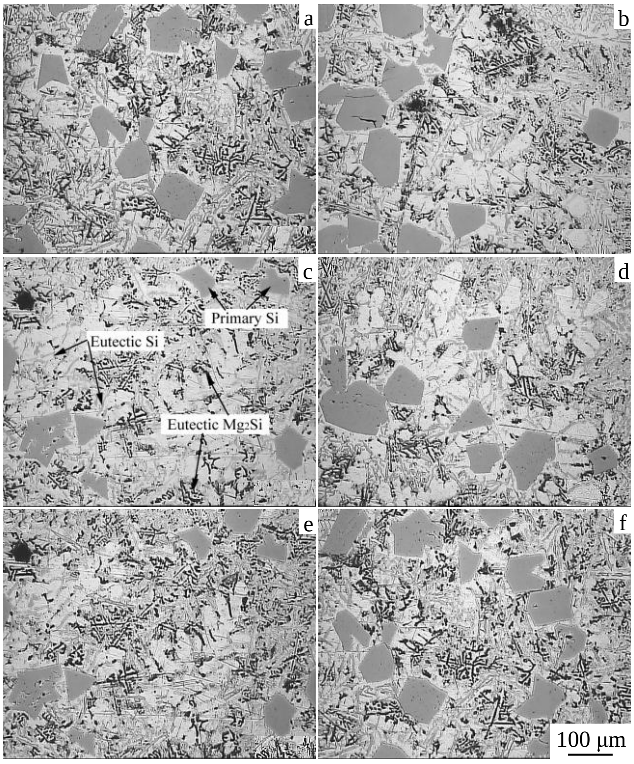

Fig.5 Cross-section microstructures of Al-17Si-4Mg tubular parts corresponding to the zones of a (a), b (b), c (c), d (d), e (e) and f (f) in Fig.1b

volume fraction of the primary Si particles declines.

When the mass percentage of Si is 21%, the cross-section microstructure of the tubular parts (Fig.6) are almost identical to those of Al-19Si-4Mg (Fig.4) in group 1.

Through microstructure analysis of the five tubular parts, it is found that the appearance of the primary Mg_2Si particles is the key factor to form the new type of Al gradient composites. To obtain enough primary Mg_2Si particles, the amount of Si should not be lower than 19% and that of Mg not lower than 4%.

2.3 Result of hardness tests

Fig.7 shows the Rockwell hardness values of the five tubular parts. Corresponding to the microstructures of the five tubular parts, their hardness values show gradient variations with the distribution of the primary particles from the inner wall to the outer wall. Due to the high volume the primary Si and Mg_2Si particles were assembled in the inner zones, the two tubular parts with the composition of Al-19Si-4Mg and Al-21Si-4Mg have the higher hardness, and their values are 70~76 HRB. On the contrary, the values of the outer zones are only 30~35 HRB. For the tubular parts with the compositions of Al-19Si, Al-19Si-4Mg and Al-17-4Mg, their hardness values of the inner zones are 45~50 HRB, those of the intermediate zones hardness are 40~45 HRB, and those of the outer zones hardness are 45~52 HRB.

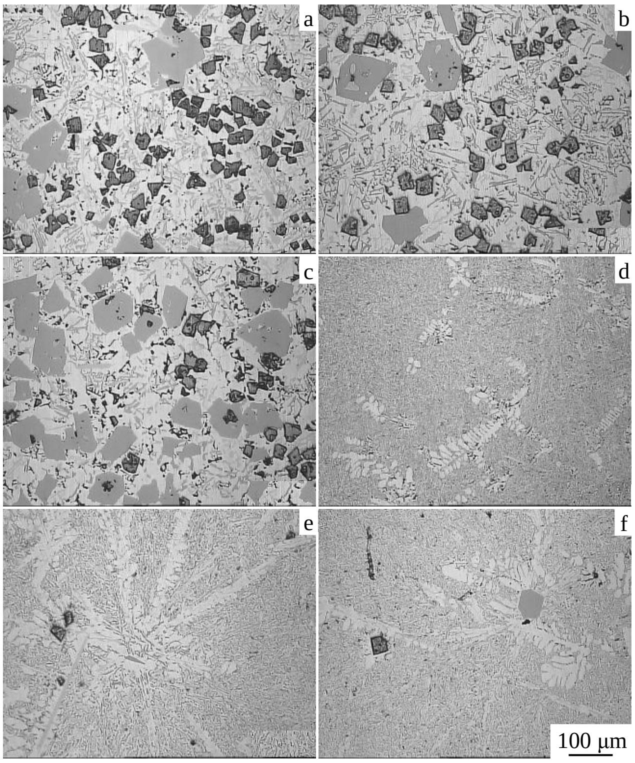

Fig.6 Cross-section microstructures of Al-21Si-4Mg tubular parts corresponding to the zones of a (a), b (b), c (c), d (d), e (e) and f (f) in Fig.1b

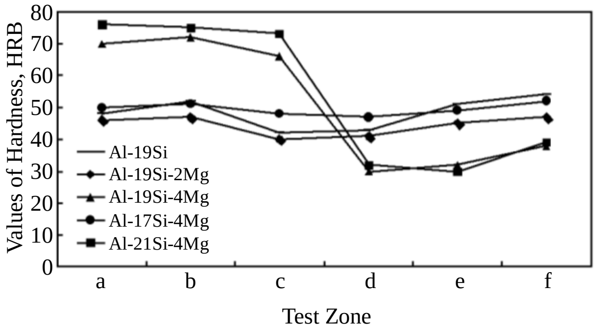

Fig.7 Rockwell hardness test results of the five tubular parts

3 Discussion

3.1 Motion and stress analysis of particles in the centrifugal force field

The load-carrying model of particles in the horizontal centrifugal force field is diagrammed in Fig.8. When the gravity is ignored, particles would bear three forces as shown in Fig.8. The viscous force $F_{r,c}$ is related to melt viscosity, particle diameter and the centripetal velocity. So it is a function of multivariates that are related to the state of the melt. In the early stage, the viscous force $F_{r,c}$ is ignored for simplified calculation.

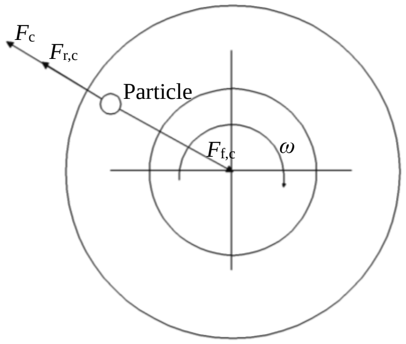

Fig.8 Stress diagram of particles in the horizontal centrifugal force field

Thus, the resultant force borne by particles along the radial direction of the mould would be expressed in the following formula (1) [17]:

$$F=F_{f,c}-F_c=r\omega^2V(\rho_{Al}-\rho_p) \tag{1}$$

where ρ_p is density of particles (g/cm^3), with Si 2.33 and Mg_2Si 1.83; $F_{f,c}$ is centrifugal buoyancy; F_c is centrifugal force; $F_{r,c}$ is centrifugal viscous force; ρ_{Al} is density of Al liquid, which is 2.37 g/cm^3 under the condition of 700 °C; V is unit volume of particles and Al liquid (cm^3); r is centrifugal radius of a particle (cm); ω is rotational angular velocity (r/m).

The resultant force borne by Mg_2Si and Si is:

$$F_{Mg_2Si}=r\omega^2V(2.37-1.83)=0.54r\omega^2V \tag{2}$$

$$F_{Si}=r\omega^2V(2.37-2.33)=0.04r\omega^2V \tag{3}$$

So the resultant force borne by Mg_2Si particles is about 13 times larger than that borne by Si particles at the same centrifugal radius. Therefore, the centripetal velocity of the former is much larger than that of the latter in the same conditions.

3.2 Assembling mechanism of primary Si and Mg_2Si particles in a centrifugal force field

Through analyzing the relationship of the stress and the velocity of primary Si and Mg_2Si particles, it is found that Mg_2Si particles tend to move faster toward the inner layer than primary Si. In view of the microstructure characteristics of group 1 and group 2 shown in Fig.2~6, the assembling model of the two kinds of particles can be described as the following four stages:

In the first stage, the external zone is formed. When the melt is poured into the centrifugal casting mould, the outermost melt that first contacts the mould freezes quickly, and the supersaturated Si and Mg_2Si would gradually precipitate and grow in size, forming the microstructures shown as (f) in Fig. 2, 3, 4, 5 and 6.

The second stage is the forming and moving stage of the primary particles. When the melt in the outermost layer freezes, it releases a massive crystallization latent heat that reduces the solidification rate. While the solidification front heads towards the axis, primary Si particles are precipitated first and move slowly towards the axis; then primary Mg_2Si particles begin to precipitate gradually with dropping of the melt temperature. Once primary Mg_2Si particles are precipitated, they would migrate with much higher velocity than Si particles. During the migration, the relatively small Mg_2Si particles would collide with primary Si particles in the front and impel the primary Si particles to move together at a faster speed. In this process, the primary Si particles without the impelling of the Mg_2Si particles move with a slower velocity and are retained in the intermediate layer, resulting in the formation of the microstructures of (c) and (d) in Fig.2, 3 and 5.

The third stage is the formation of the reinforcement zone. When primary Si and Mg_2Si particles move towards the inner layer, because the centrifugal radius is getting smaller and smaller, the centrifugal force that they bear becomes smaller and smaller; at the same time, the solidoid fraction is getting larger, and the motion resistance of particles is increasing, so the particles motion becomes more difficult. This can be proved by (a) and (b) in Fig. 4 and 6. The two sets of pictures shown in these figures present the microstructures of the reinforcement zone, where the volume fraction of particles does not increase because of the decrease of the centrifugal radius.

The fourth stage is the freezing completion stage. After massive primary Si and Mg_2Si crystals assemble in the inner layer of the reinforcement zone, they start to grow. At this moment, because of the presence of less liquid and more solidoid, reinforcement particles tend to be adhered and wrapped up during the process of growing and form the microstructure of (a) and (b) in Fig. 4 and 6. After the centrifugal force causes primary Si and Mg_2Si particles to migrate into the inner layer, the remaining melt forms the eutectic Al-Si-Mg alloys. When the temperature of the melt drops to E_1 (559 °C)[18], the four-phase balance reaction of $L\rightarrow \text{Al+Si+}Mg_2Si$ occurs, and an eutectic Al-Si-Mg phase begins to form until the liquid completely disappears. This is the last stage of freezing, which is similar to that of Al-19Si-2Mg and Al-17-4Mg alloys.

4 Conclusions

1) The new type of Al-based composites reinforced by primary Si and Mg_2Si particles have the obvious gradient characteristics. The inner zone is the reinforced zone with the high volume fraction of primary Si and Mg_2Si particles, whereas the external zone is the unreinforced zone with a little or no primary Si and Mg_2Si particles, and the matrix zone is composed of α(Al), thin strip eutectic Si and network Mg_2Si.

2) The high volume fraction of primary Si and Mg_2Si particles can effectively increase the Rockwell hardness values of the composites.

3) The appearance of the primary Mg_2Si particles is the key factor to form the discontinuous functional gradient composites in the centrifugal force field. In the centrifugal

force field, the resultant force borne by Mg_2Si is much bigger than that borne by primary Si particles, so the Mg_2Si particles, though relatively small, will collide and impel primary Si particles to move more quickly towards the inner zone of tubular parts during freezing, resulting in the primary Si and Mg_2Si particles becoming massively assembled in the inner zone.

4) To obtain the enough primary Mg_2Si particles, the amount of Si should not be lower than 19% and that of Mg not lower than 4%.

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初晶 Si 与 Mg_2Si 颗粒互补增强 Al 基梯度复合材料的离心成形机制

翟彦博[1]，马秀腾[1]，梅　镇[2]

(1. 西南大学，重庆 400715)

(2. 重庆机床（集团）有限责任公司，重庆 400055)

摘　要：为了克服单一初晶Si或Mg_2Si颗粒增强的铝基复合材料的不足，采用离心铸造的方法制备了一种由初晶Si与Mg_2Si两种颗粒互补增强的铝基梯度复合材料。这种复合材料的组织与性能具有明显的梯度分布特征：内层含有高体积分数的初晶Si与Mg_2Si颗粒，形成互补增强区域，具有高硬度的特点；外层没有或含有极少量初晶颗粒，形成非增强区域，具有硬度低的特点。对该复合材料的离心成形机制探讨发现，大量细小的初晶Mg_2Si颗粒是形成这种梯度复合材料的关键因素。在离心力场中，密度更小的初晶Mg_2Si颗粒具有比初晶Si颗粒大得多的向心运动速度，在运动过程中它与初晶Si发生碰撞并推动后者一起快速运动，最终导致二者在内层的剧烈偏聚。此外，为了获得足够的初晶Mg_2Si颗粒，在三元Al-Si-Mg合金中，Si的质量分数应不低于19%，Mg的质量分数应不低于4%。

关键词：梯度复合材料；颗粒增强复合材料；初晶 Si；初晶 Mg_2Si；离心铸造

作者简介：翟彦博，男，1979 年生，博士，讲师，西南大学工程技术学院，重庆 400715，E-mail: bird513@163.com