Study on the preparation technology of centrifugal Al-18Si-X composite reinforced with in situ particles

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Abstract: Al-18Si-X (X=Mg, Ti, Ni) composite tubular castings were prepared by centrifugal casting. The microstructure of cylindrical casting of Al-18Si-X composite was observed along the radial direction, and the segregation behavior and distribution characteristics of primary particles formed in different alloys under the action of centrifugal field were studied. The results show that the in situ particles in Al-18Si-7Mg, Al-18Si-7Ti, and Al-18Si-7Ni tubular castings have different segregation behaviors under the action of centrifugal field, which results in the formation of particle reinforcing layers in different regions of the castings. It is found that the volume fraction, size and particle morphology of primary particles in particle reinforcement layer of different castings are different.

1. Introduction
In recent years, lightweight has become the trend of modern industrial development. More and more light alloys are used to produce various mechanical parts, such as mower cylinder and piston. Among them, Al-Si alloy has attracted much attention due to its excellent comprehensive mechanical properties\cite{1-5}. By adding other metals into the hypereutectic Al-Si alloy, aluminum matrix functional composites reinforced with in situ particles can be prepared to meet different performance requirements. Zhai Yanbo et al. prepared Al-19Si-4Mg by centrifugal casting method, and found that the primary particles were concentrated in the inner layer of the casting, and proposed the concept of rapidly changing functional gradient composite\cite{6}. LV Xunjia et al. prepared Al-Si-Ni composite material with bilateral segregation of in situ particles by centrifugal casting method\cite{7}, and discussed preliminarily the microstructure and performance characteristics of the composite material. In this experiment, Al-18Si was used as the matrix, and the same mass fraction of Mg, Ti and Ni were added respectively. Three types of composite tubular castings of Al-18Si-7Mg, Al-18Si-7Ti and Al-18Si-7Ni were prepared by centrifugal casting. The distribution characteristics and segregation behavior of in situ particles in centrifugal field were compared and analyzed.

2. Experimental method
The industrial pure Al, Si, Mg and Al-10Ni, Al-10Ti and other intermediate alloys were used as raw materials, and the slurry of Al-18Si-7Mg, Al-18Si-7Ni and Al-18Si-7Ti alloys were prepared by heating and melting in the well-resistance furnace. The centrifugal casting speed is 3800r/min, and mold temperature is 200–250°C. Cylindrical castings with a height of 159mm, an outer circle diameter

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of 85mm and a thickness of 15mm were obtained by centrifugal casting.

A block sample of appropriate size was taken from the middle part of the casting, and the microstructure of each composite material was observed from one side to the other side, and the distribution characteristics of particles were calculated and analyzed.

3. Results and Discussion

3.1 Macroscopic morphology of Al-18Si-X casting

Figure 1 shows the macroscopic morphology of Al-18Si-X sample, which is Al-18Si-7Mg, Al-18Si-7Ni and Al-18Si-7Ti from left to right. It can be seen that a certain thickness of particle reinforcement layer is formed in the inner side of the centrifugal casting Al-18Si-7Mg castings; a particle reinforcement layer of Al-18Si-7Ti casting is formed on the outside of the casting with a certain thickness; and two particle reinforcement layers of Al-18Si-7Ni casting are formed both on the inner and the outer sides of the casting. The reinforcement layer formed by reinforcing particles in different parts of casting is related to the behavior of particles migration and segregation in centrifugal field.

![Fig.1 Macro-graph of samples obtained from Al-18Si-X castings](image)

3.2 Microstructure of Centrifugal Al-Si-X castings

3.2.1 Microstructures of Centrifugal Al-Si-Mg castings

According to XRD and SEM analysis[6], primary Si, Mg2Si particles, α and eutectic structures are formed in Al-18Si-7Mg alloy. Among them, the larger size and lighter color particles are primary Si phase, while the smaller size and darker color particles (black microscopic image) are primary Mg2Si phase.

Fig.2 (a) ~ (f) shows the microstructure of Al-18Si-7Mg casting at different positions along the radius direction. It can be seen that the inner layer of the Al-18Si-7Mg casting sample has a large amount of black primary Mg2Si and a very small amount of light gray massive primary Si particles, as shown in Fig. 2 (a), (b) and (c); Fig. 2 (d) shows the microstructure at the interface between outer layer and inner layer of casting. The outer layer of the casting is matrix structure without primary particles, as shown in Fig. 2 (e) and (f). It can be seen from the figure that primary Mg2Si particles are in the majority in the inner particle reinforcement layer of the casting, which is related to more Mg content and less Si content in the alloy composition. The volume fraction of primary particles decreased gradually from inside to outside.

![Fig.2 Micrographs of Al-18Si-Mg casting](image)
3.2.2 Microstructures of Centrifugal Al-Si-Ni castings

According to the literature[7], primary NiAl$_3$ and Si particles are mainly formed in Al-18Si-7Ni alloy. Fig. 3 shows the microstructure of Al-18Si-7Ni casting at different distances from the outer wall of the casting along the radius direction. It can be seen that a large number of black primary NiAl$_3$ and light gray massive primary Si particles are concentrated in the outer layer of Al-18Si-7Ni sample, as shown in Fig. 3 (a) and (b); Fig. 3 (c) shows the microstructure at the interface between outer layer and middle layer of casting. The middle layer is the matrix without primary particles, as shown in Figure 3 (d); The coexistence of primary NiAl$_3$ and Si particles can be seen on the interface between the middle and inner layers, as shown in Fig. 3 (e); While primary Si particles are mainly located near the inner wall of the casting, as shown in Fig. 3 (f). It can be found that primary Si particles are distributed in the outer, middle and inner layers of the casting. In addition, from the outer layer to the middle layer, the volume fraction of primary particles gradually decreases, while the particle size gradually increases.

3.2.3 Microstructures of Centrifugal Al-Si-Ti castings

According to the literature[5], more primary TiAlSi particles and a very small number of primary Si particles are formed in Al-18Si-7Ti alloy. Fig. 4 shows the microstructure of Al-18Si-7Ti casting at different distances from the outer wall of the casting along the radius direction. It can be seen from the figure that the outer layer of the Al-18Si-7Ti sample contains more massive primary TiAlSi particles.
with a diameter of about 20-50μm, as shown in Figure 4 (a) and (b); Fig. 4 (c) shows the microstructure at the interface between the outer and inner layers of the alloy sample, where a small number of primary TiAlSi and Si particles are scattered; The inner layer is the matrix without primary particles, as shown in Fig. 4 (d) and (e). In addition, an extremely thin layer of primary Si particles is distributed on the inner wall of the casting, as shown in Fig. 4 (f), which can be neglected. Therefore, it is considered that Al-18Si-7Ti alloy castings have formed two layers of microstructure with reinforcing particles in the outer layer. It can be found that the particle volume fraction of the casting decreases gradually from the outside to the inside, and the particle size also decreases gradually. A small number of primary Si particles were found in the inner wall of the alloy, indicating that the content of Si in the alloy is sufficient. The primary TiAlSi is mainly concentrated in the outer layer of the casting, while a small amount of primary Si is observed in the inner wall of the casting, indicating that the centrifugal TiAlSi particles have a relatively small effect on the primary Si phase with centralization deviation in the centrifugal field, which is mainly because the primary TiAlSi particles form at an earlier time and complete the clustering behavior in advance.

Fig. 4 Microstructures at different positions from outer wall to inner wall along radial direction of Al-18Si-7Ti casting

3.3 Particle volume fraction of centrifugal Al-Si-X castings

The particle aggregation regions are formed in different regions of the three Al-Si-X alloy castings. In order to facilitate the formation of contrast effect, the particle volume fraction of Al-Si-Mg alloy is counted from the inner wall to the outer wall of the casting, while that of Al-Si-Ti and Al-Si-Ni alloys is counted from the outer wall to the inner wall.

3.3.1 Particle volume fraction of centrifugal Al-18Si-7Mg castings

Figure 5 (a) shows the particle volume fractions at different positions in the Al-18Si-7Mg alloy casting. As can be seen from the figure, the volume fraction of both primary Si and primary Mg2Si in the inner layer of the casting presents a decreasing gradient trend from the inner wall outward. The sum of the volume fraction of the two particles is up to 24.16%. However, no primary particles are found in the outer layer of the casting, which indicates that under the action of centrifugal force, the primary particles formed in the alloy are migrated to the inner side of the casting, and the segregation effect is good.
3.3.2 Particle volume fraction of centrifugal Al-18Si-7Ni castings
Figure 5 (b) shows the volume fractions of particles at different positions in the Al-18Si-7Ni alloy casting. It can be seen that a certain volume of primary Si particles are formed in the outer layer of the casting, and the volume fraction of primary Si decreases gradually from the outside to the inside. In this region, the volume fraction of primary NiAl3 particles also shows a similar trend, which indicates that the primary NiAl3 has a driving effect on the primary Si in the centrifugal field, and more primary NiAl3 drives more primary Si to migrate closer to the outer wall of the casting. In the outer layer of the casting, the maximum volume fraction of primary NiAl3 and primary Si reaches 18.95% and 11.08% respectively, that is, the maximum particle volume fraction of outer layer is 30.03%; In the inner layer of the casting, more primary Si particles are concentrated, and the volume fraction of primary Si gradually increases from the outside to the inside, which is consistent with the centripetal migration behavior of primary Si particles. There is less primary NiAl3 concentration in the inner layer of the casting near the middle layer, and the volume fraction decreases gradually from the outside to the inside. In this region, the change trend of the volume fraction of primary Si and primary NiAl3 is opposite, which indicates that primary Si also drives primary NiAl3 in the centrifugal field. However, compared with the driving effect of primary NiAl3 on primary Si, its effect is limited, so that the primary NiAl3 is not sufficiently concentrated towards the inner wall of the casting. Therefore, there is only primary Si instead of primary NiAl3 in the inner wall of the casting. The maximum volume fraction of primary Si and NiAl3 particles in the inner layer of the casting is 18.67% and 7.44%. When the maximum particle volume fraction in the inner layer is 20.52%, the volume fraction of primary Si and NiAl3 particles is 13.08% and 7.44%, respectively. There are no primary particles in the middle layer of the casting. Compared with the change of particle volume fraction in Al-18Si-7Mg casting, the decrease trend of particle volume fraction in Al-18Si-7Ni casting is more obvious.

3.3.3 Particle volume fraction of centrifugal Al-18Si-7Ti castings
Figure 5 (c) shows the particle volume fractions at different positions in the Al-18Si-7Ti alloy casting. Theoretically, the primary TiAlSi formed in the alloy has a high density, while the primary Si has a low density. Under the action of centrifugal force, the two particles will move centrifugally and centripetally respectively, and migrate towards the outer and inner sides of the casting. However, it can be seen from Fig. 4 that no primary particles of a certain volume are formed in the inner layer of the casting. Only a small number of primary Si particles were found in the inner wall of the casting, and primary TiAlSi was not found. The primary particles formed in the casting are mainly concentrated in the outer layer of the casting, and the primary TiAlSi is mainly formed in the outer layer of the casting. The volume fraction of the primary particles reaches 22.7%, and gradually decreases from the outer wall to the inside. A small number of primary Si particles (Fig. 4d) were found near the inner layer, and the volume fraction was only 1.65%, indicating that the primary TiAlSi particles had a certain pushing effect on the primary Si particles, which caused the primary Si particles to migrate toward the outer part of the casting, but the pushing effect was quite limited. Compared with the changing rule of
the particle volume fraction in Al-18Si-7Mg casting, the decrease of the particle volume fraction in Al-18Si-7Ti casting is quite obvious as well.

3.4 Formation process of particle reinforced layer in Al-Si-X composites

According to the force analysis of primary particles in the centrifugal field, the migration behavior of particles in the casting is related to the density difference between particles and melts\(^[8]\). When \(\rho_s > \rho_m\), the particles move along the direction of centrifugal force, when \(\rho_s < \rho_m\), the particles move in the opposite direction of centrifugal force. In this experiment, both the density of primary Si and Mg\(_2\)Si in Al-Si-Mg alloy are less than the melt density \((\rho_{\text{Si}}=2.33\text{kg/m}^3, \rho_{\text{Mg}_2\text{Si}}=1.99\text{kg/m}^3, \rho_m=2.4\text{kg/m}^3)\), so both of these two particles move towards the inner side of the casting in the centrifugal field, for which the primary Si and Mg\(_2\)Si inner layer reinforced aluminum matrix composites were formed. The primary NiAl\(_3\) and TiAlSi in Al-Si-Ni and Al-Si-Ti alloys have high density \((\rho_{\text{NiAl}_3}=4.0\text{kg/m}^3, \rho_{\text{TiAlSi}}=3.1\text{kg/m}^3)\), and the two particles will migrate to the outside of the casting in the centrifugal field. At the same time, the primary Si with low density in the two alloys will move towards the inner side of the casting, which results in different types of primary particles deviating from each other, and finally forms the aluminum matrix composite with inner and outer particle reinforcement layers, and the existence forms of particles in the two reinforcing layers are different.

4. Conclusions

(1) Al-18Si-7Mg, Al-18Si-7Ti and Al-18Si-7Ni alloy castings were successfully prepared by centrifugal casting. The microstructure observation shows that Al-18Si-7Mg alloy has formed particle reinforcement layer in the inner layer of casting, the particle reinforcement layer of Al-18Si-7Ti alloy is formed in the outer layer of the casting, and Al-18Si-7Ni alloy formed particle reinforcement layer in both inner and outer casting respectively.

(2) Under the action of centrifugal force, the volume fraction of inner reinforcement particles of Al-18Si-7Mg casting decreases gradually from inside to outside, and the maximum particle volume fraction reaches 24.16%. The volume fraction of particles in Al-18Si-7Ni castings decreases first and then increases from the outer wall to the inner wall. In the outer layer, the maximum volume fraction reaches 30.03%, while in the inner layer, the maximum volume fraction reaches 20.52%. The particle volume fraction of Al-18Si-7Ti casting decreases gradually from outer layer to inner layer, and the maximum particle volume fraction of outer layer reaches 22.7%.

(3) The segregation behavior of primary particles in centrifugal field is related to the density difference between particles and melts. The primary Si and Mg\(_2\)Si particles with low density migrate and aggregate to the inner layer of the casting to form Al-18Si-7Mg casting with inner reinforcing layer, while the primary TiAlSi particles with high density converge to the outer layer of the casting to form Al-18Si-7Ti casting with outer reinforcing layer. Similarly, for Al-18Si-7Ni, primary NiAl\(_3\) and Primary Si with higher density are formed in the melt. Therefore, both the inner reinforcing layer and outer reinforcing layer are formed simultaneously, and both of them contain two different primary particles.

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