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Microstructure and Mechanical Behavior of in Situ Primary Si/Mg_2Si Locally Reinforced Aluminum Matrix Composites Piston by Centrifugal Casting

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Abstract: Al-Si pistons are frequently damaged by burning piston top surface due to elevated combustion temperature, and by rubbing the first ring groove against the engine cylinder liner. To prevent piston from these damages, some technologies were invented, such as mounting high Ni cast iron ring around the first ring groove in Al alloy piston body and thermal resistant steel on piston top surface, and fabricating Al composite pistons by squeeze casting for enhancing the whole or local piston performance. In this paper, composite pistons locally reinforced with in situ primary Si and primary Mg_2Si particles are fabricated by centrifugal casting. The microstructure characteristics, hardness and wear resistance of the composite piston are investigated and the motion characteristic of the in situ particles in centrifugal field is analyzed. The results of the experiments show that primary Si and Mg_2Si particles mix up with each other in melt and segregate at the regions of piston top and piston ring grooves under the effect of centrifugal force. Particulate reinforced regions have a higher hardness and better wear resistance compared with the unreinforced regions and this performance increases after heat treatment. The analysis result of particle movement shows that, primary Si and primary Mg_2Si particles move at approximately the same velocity in the centrifugal field, because of the growth of primary Si and fusion after colliding between primary Si particles, which compromised the velocity difference of primary Si and primary Mg_2Si particles caused by the difference of their densities. Research results have some theory significance and applicative value of project in development of new aluminum matrix composites piston products.

Key words: piston, centrifugal casting, in situ composite, primary Si, Mg_2Si

1 Introduction

Aluminum matrix composites as an advanced engineering material are being increasingly used in diesel engine pistons because of their high specific tensile strength and modulus, as well as their high wear resistance, in particular, low thermal-expansion, and improved mechanical properties at a wide range of temperatures[1]. During the last three decades, to meet the requirements for high-power, high-speed and low energy consumption, short fibers and SiC particulates reinforced aluminum matrix composites are fabricated by squeeze casting for enhancing the whole or local piston performance[2–4]. But the ceramic reinforcement phase is directly added into its matrix, and a series of problems, such as interface reaction between matrix and reinforcement, intricacy fabrication processes, high costs, etc., are existed in these technology and greatly limited its application[5–6].

The concept of in situ composites was firstly proposed by former Soviet researchers in 1979[7]. In situ composites involve the production of reinforcements within the matrix during the fabrication process, and they posse well matrix-reinforcement interface, thermodynamically stable systems and low processing costs[8]. Several in situ technologies have emerged in the past two decades including: self-propagation high-temperature synthesis (SHS), exothermic dispersion (XD), mixing salt reaction, and centrifugal casting etc.. Compared with other technologies, centrifugal casting method, proposed by Fukui et al. , has several important advantages such as excellent properties, simple fabrication technology, easiness to control technology parameters, small investment and good adaptability to large-scale industry production. Thus, in situ composites fabricated by centrifugal casting have attracted considerable attention recently.

Hypereutectic Al-Si alloy containing a certain amount of magnesium can separate out primary Si and primary Mg_2Si particles during the solidification process[9]. These primary phases are very suitable as reinforced phase in aluminum matrix composites due to its low density, high melting point, high hardness, low coefficient of thermal expansion (CTE) and a reasonably high elastic modulus[10-11]. In this study, the Al-20Si-4Mg aluminum matrix composites piston was fabricated by centrifugal casting which made primary Si and Mg_2Si particles locally enriched in the regions of

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piston top and piston ring grooves. The microstructures, hardness and wear resistance of the piston were examined and the movement process of the in situ particles of the composites during centrifugal casting was analyzed.

2 Experimental procedures

2.1 Materials

Commercial ZL104 alloy, Al-29%Si alloy ingots, Al-Sr alloy ingots, Al-Ti alloy ingots and AZ91 alloys were used to prepare the Al-20Si-4Mg alloy. The chemical compositions of this alloy are listed in Table 1.

Table 1. Chemical compositions of Al-20Si-4Mg alloy in experiment

Composition	Si	Cu	Mg	Ni	Ti	Sr	Al
Mass fraction *w*/%	20.25	1.24	4.29	0.69	0.184	0.011	Bal.

2.2 Methods

The pistons were produced in a vertical centrifugal casting apparatus, and its rotation speed was set at 800 r/min. The material was melted at 770℃ and poured into the mould which was preheated at 400 ℃. A schematic representation of the casting process is presented in Fig. 1. According to Al-Si-Mg ternary phase diagram, the melt of this Al-20Si-4Mg alloy can separate out primary Si and primary Mg_2Si particles during the solidification process. Because the densities of these in situ particles are less than that of the liquid alloy, on the effect of centrifugal force, the particles move towards the direction of the centrifugal axis of the mould and the liquid move opposite to the axis. Finally, the particles were congregated in the regions of piston top and piston ring grooves by controlling the casting processes. The dimensions of the piston obtained were 70 mm in length and 46 mm in diameter.

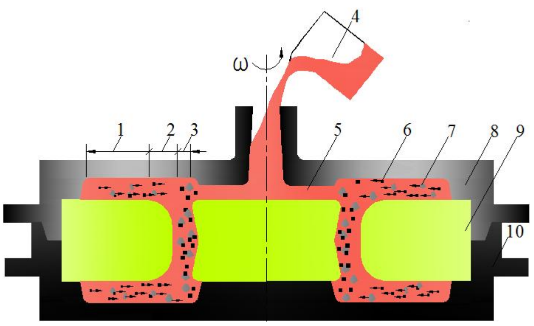

Fig. 1. Schematic of centrifugal casting process

1.Piston skirt; 2.Piston ring grooves; 3.Piston top; 4.Ladle; 5.Ingate; 6.Primary Mg_2Si ;7.Primary Si; 8.Upper mould; 9.Core; 10.Down mould

2.3 Samples preparations for structure observation and mechanical test

The schematic of the composite piston is given in Fig. 2. The samples for microstructure observations and mechanical test were cut along the piston axial and test locations were shown in Fig. 3. Metallographic specimens for microstructure observation were polished through standard routines and microstructures were examined with an optical microscope. The Rockwell hardness apparatus was adopted to test *HRB* hardness under the load of 98 N with a steel ball of 1.588 mm in diameter.

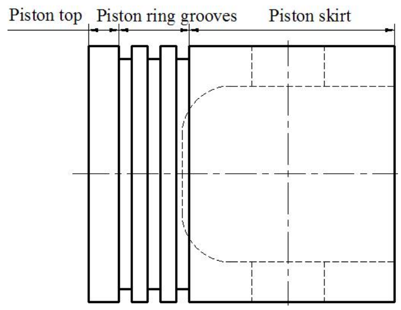

Fig. 2. Schematic of composite piston

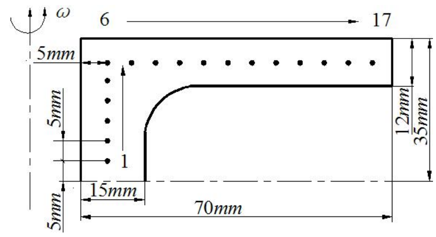

Fig. 3. Schematic of locations for microstructure and performance testing

Wear resistant test was carried out on a friction testing machine with loads of 200 N at a rotation speed of 280 r/min and the test period was 10 min. The mass *m* of the specimen before and after the test was weighed by a 1/10 000 g precision analytical balance, and then the mass loss Δ*m* of each specimen was calculated.

3 Results and discussions

3.1 Macrostructure on the axial section of the piston

Fig. 4 shows the macrostructure of the piston on the axial section. The grey particles, representing in situ reinforced particles (primary Si and primary Mg_2Si), were segregated to the regions of piston top and piston ring grooves by centrifugal force and formed the reinforced zoon. Rare reinforced particles are there in outer wall of the piston and none of this kind of particles can be seen in the other region in the piston. It should be noticed that there is a clear boundary between these two regions.

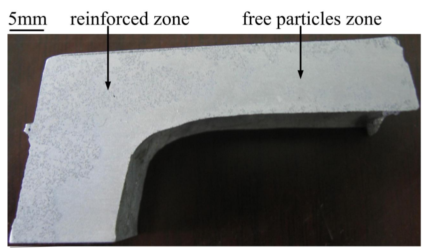

Fig. 4. Macrostructure on axial section of piston

3.2 Microstructures of the piston

Microstructures of the piston in different positions are shown in Fig. 5. Figs. 5 (a)–(h) are the microstructures of the areas marked 1, 3, 5, 6, 8, 11, 14 and 17, respectively, in Fig. 3. Figs. 5 (a)–(d) correspond to the microstructures of the top reinforced zone which has been shown in Fig. 3, and Figs. 5 (e)–(h) correspond to the microstructures of the piston ring grooves to the skirt, respectively. It can be observed from Fig. 5 that primary Mg_2Si particles, blocky phases with dark grayness, with the average diameters from 30 to 40 μm, and primary Si particles, blocky phases with light grayness, with the average diameter from 80 to 120 μm, segregate and enrich in piston top and piston ring grooves; in the meantime, microstructures of piston skirt are eutectic structure, and the contents of primary Si and primary Mg_2Si particles are extremely low.

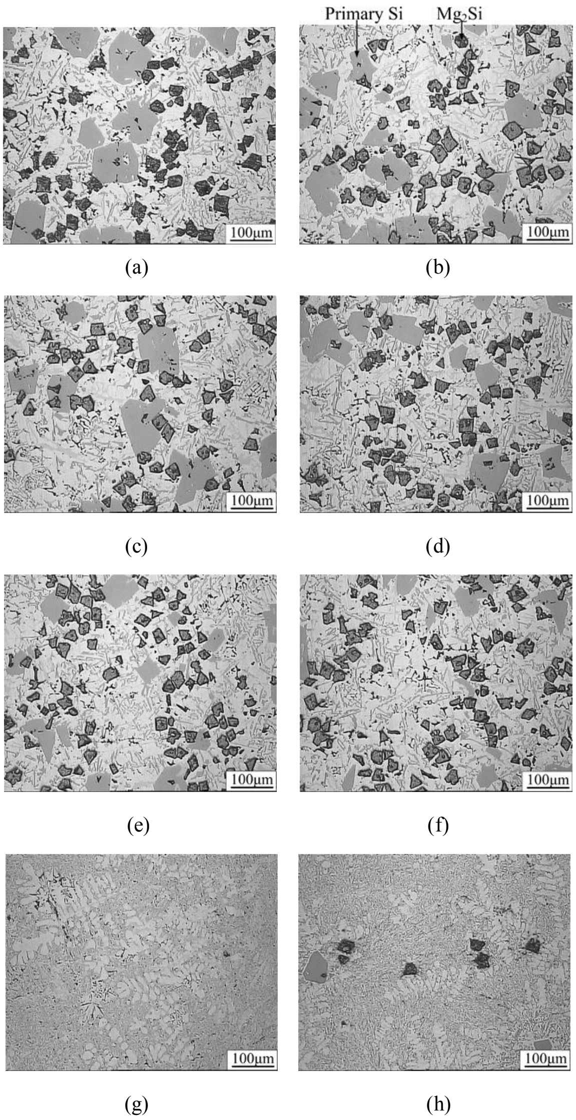

Fig. 5. Microstructures of the piston in different positions

Fig. 6 shows the particle volume fractions in different positions of the piston. As it can be seen from Fig. 6, the contents of primary Si and primary Mg_2Si particles in piston top and piston ring grooves are greater than that in piston skirt, and, the total amount of primary Si and primary Mg_2Si particles is about 26% to 28%.

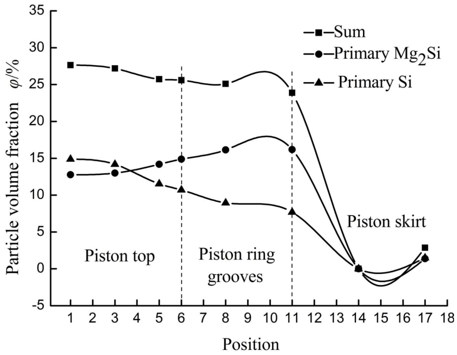

Fig. 6. Particle volume fraction curves of the piston in different positions

3.3 Hardness distribution of the piston

Fig. 7 shows the results of the hardness measurement before and after heat treatment. The distribution characteristics of hardness indicates that, in both as-cast and heat treated conditions, the hardness on the reinforced zone of the piston is higher than that on the unreinforced zone, and, the hardness after aging is the highest and the hardness of as casting is the lowest. As seen in the figure, heat treatment improves the hardness of the piston.

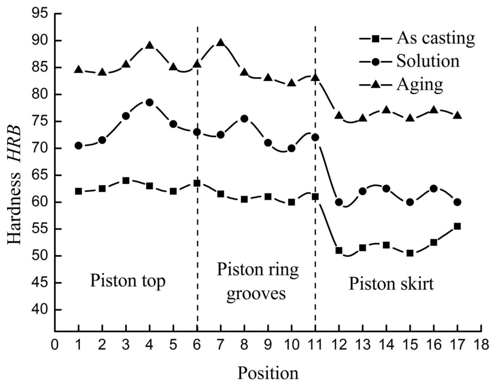

Fig. 7. Hardness distribution of the piston in different positions

Compared with the microstructure shown in Fig. 5 and particles volume fraction shown in Fig. 6, it can be seen that the varying regularity of the hardness distribution is basically agreeable to the particles volume fraction distribution. It is inferred that primary Si and primary Mg_2Si particles, whose hardness are much higher than that of the matrix, segregated in piston top and piston ring grooves, result in the higher hardness in piston top and piston ring grooves. The hardness in piston skirt without primary Si and primary Mg_2Si is relatively low and the variation of hardness is also little. In the as-cast condition, the hardness at the bottom of the piston skirt is a little higher than that in the piston skirt due to containing a small amount of primary Si and primary Mg_2Si particles. Because the solidification velocity in the bottom of the piston skirt is higher than the moving velocity of primary Si and primary Mg_2Si particles there, primary Si and primary Mg_2Si particles will be captured and stay in the bottom of piston skirt. Therefore, it is deduced that the hardness of the in situ composite piston increases with the increase of the amount of primary Si and primary Mg_2Si particles.

3.4 Wear resistance distributions of the piston

Fig. 8 shows the results of wear resistance distributions before and after heat treatment. The results demonstrate that wear resistance in different states in piston skirt, without primary Si and primary Mg_2Si particles, is less than that in piston top and piston ring grooves containing lots of blocky primary Si and primary Mg_2Si particles, and the wear resistance in aging state is higher than that in the as casting state. Corresponding to the microstructure and particles volume fraction of the piston, it is obvious that the wear resistance of the composites is determined by the quantity, shape and distribution of primary Si and primary Mg_2Si [12].

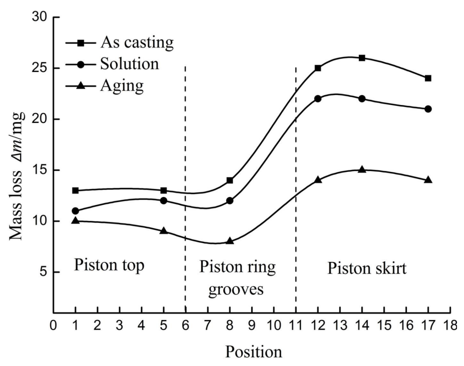

Fig. 8. Results of wear resistance before and after heat treatment

3.5 Analysis of particles motion in a centrifugal force field

It is known that the motion of particles in a viscous liquid under a centrifugal force obeys the Stokes' law[13].On each particle there are six forces, the radial centrifugal force, the viscous drag force and the virtual mass force in horizontal direction, and, the gravity, buoyant and virtual mass forces in vertical direction [14].Particle motions are determined by the composition of the forces in horizontal direction and the motions in vertical direction can be ignored, because the motion forces in the horizontal are much greater than that in vertical direction. Therefore, the moving velocity of particles under the action of centrifugal force can be expressed as follows: [15–16]

$$v = \frac{|\rho_p - \rho_l| G g D_p^{\ 2}}{18\eta}. \tag{1}$$

Where *v, ρ, G, D, g, and η* are velocity, density, *G* number, particle diameter, gravitational acceleration and viscosity of the molten metal (matrix-particle mixture), respectively. The subscripts "*p*" and "*l*" denote particle and matrix, respectively. The *G* number is represented as

$$G = \frac{4\pi^2 N^2}{g} r. \tag{2}$$

Where *r* is the distance of the particle to the rotation axis , and *N* is the velocity of rotation of the mould.

From Eq. (1), it is obvious that, in the centrifugal force field, the difference in density between particles and the molten metal results in particle movement; the velocity of particles with different densities is also different. In this study, the densities of primary Si, Mg_2Si and molten metal are 2.33, 1.99 and 2.37 g/cm^3, respectively. Based on Eq. (1), the ratio of moving velocity of primary Mg_2Si to primary Si particles is

$$\frac{v_{Mg_2Si}}{v_{Si}} = 9.5 \frac{D_{Mg_2Si}^{\ 2}}{D_{Si}^{\ 2}}. \tag{3}$$

Eq. (3) shows that the movement ratio of primary Mg_2Si and primary Si in molten alloy mainly depends on particle diameter. During the solidification process, primary Si precipitated earlier than primary Mg_2Si and priority grew up, as well as some primary Si particles integrated to each other during moving ,which caused the average particle size of primary Si particles was larger than primary Mg_2Si particles. In microstructure, these two particles appeared simultaneously and the ratio of the final diameters between primary Si and primary Mg_2Si was about 2.7 to 3. According to Eq. (3), the final ratio of moving velocity of primary Mg_2Si to primary Si particles was 1.1 to 1.3. It could be concluded that primary Si and primary Mg_2Si particles moved at approximately the same velocity in the mixed particles reinforced composites. Because the larger average diameter of primary Si particles had compromised the velocity difference of primary Si and primary Mg_2Si particles caused by the difference of their densities, two particles finally coexisted in the regions of piston top and piston ring grooves to get the effect of mixed strengthening.

4 Conclusions

(1) A new in situ particles reinforced composite piston was manufactured successfully by centrifugal casting. In situ primary Si and primary Mg_2Si particles, precipitated during solidification, were segregated at the regions of piston top and piston ring grooves to get an effect of strengthening.

(2) Test results showed that mixed primary Si and

primary Mg_2Si particles had obviously improved the hardness and wear resistance of the composite piston. The degree of the hardness and wear resistance improved is proportional to the volume fraction of particles. After solution and aging heat treatment, the hardness and wear resistance were improved further.

(3) In composites solidification process, primary Si particles precipitated foremost and grew up faster than primary Mg_2Si particles. As moving forward, primary Si particles collided with each other and integrated, which could cause the average particle size of primary Si particles were larger than that of primary Mg_2Si particles. Finally, due to these two characteristic above, these two particles moved at approximately the same velocity and obtained the effect of mixed strengthening.

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