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Rapidly solidified hypereutectic Al-Si alloys prepared by powder hot extrusion①

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[Abstract] Rapidly solidified hypereutectic Al-Si alloys were prepared by powder hot extrusion. By eliminating vacuum degassing procedure, the fabrication routine was simplified. The tensile fracture mechanisms at room temperature and elevated temperature were investigated by SEM fractography. Compared with KS282 casting material, the tensile strength of rapidly solidified Al-Si alloy is greatly improved due to silicon particles refining while its density and coefficient of thermal expansion are lower than those of KS282. The wear resistance of RS AlSi is better than that of KS282.

[Key words] hypereutectic Al-Si alloys; rapid solidification; powder hot extrusion; properties
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1 INTRODUCTION

Hypereutectic aluminum silicon alloys are used extensively as piston materials due to its low coefficient of thermal expansion (CTE) and high wear-resistance. The most common industrial fabrication method for this alloy is casting. However, casting technology cannot solve the problems of primary silicon coarsening and the mechanical properties of cast alloys, especially its high temperature properties are not good enough, thus its applications are limited. It is well known that rapid solidification (RS) technology can refine the alloy microstructure and enlarge solubility of alloy elements, so it has been used to fabricate hypereutectic Al-Si alloys recently[1~3]. These kinds of materials are drawing more and more attention worldwide now.

Although RS hypereutectic Al-Si alloys have good properties, the high cost of the complicated fabrication process limits its industrial use. In fact, this problem also exists in other RS aluminum alloy application[4]. The most popular fabrication technology of RS hypereutectic Al-Si alloys is atomization+ powder metallurgy (RS/PM). Since alloy powders have oxide film which hinder powder densification, vacuum degassing and hot extrusion are used to densify powder billets. Vacuum degassing process includes canning, degassing with heating and vacuum sealing[5], thus makes the whole fabrication process more complicated and its cost turns high. In this paper, a simplified method which eliminates vaccum degassing is used to prepare RS hypereutectic Al-Si alloys.

It seems that the RS advantage of enlarging solubility is still not fully used since the silicon content of most research works in this field is below 25%, and 20% Si is studied widely among these researches[1~3, 6~8]. In this paper, a high silicon content of 28%~32% is used.

2 EXPERIMENTAL

The composition of the experimental alloy named RS Al-Si is Al-28%~32%Si-1%~3%Cu-0%~1%Mg-0%~2%Fe. Alloy powders were made by air atomization. Cold pressing was used to prepare green billets. After canning by aluminum, the billets were hot extruded. Extrusion temperature of 500 ℃ and extrusion ratio of 6:1 was used. Diameter of the extruded rods is 20 mm. After hot extrusion, the extruded rod was T6 heat-treated. The heat-treatment parameters were as follows: heated at 500 ℃ for 1 h, quenched in hot water, 160 ℃ artificial aged for 6 h.

Tensile properties of the materials were tested at room temperature and at 300 ℃ using a SANS CMT5000 Universal Testing Machine. Round tensile test samples were machined from extruded rods. For the test at 300 ℃, samples were heated to the testing temperature and held for 1 h. Coefficient of thermal expansion was measured from 25 ℃ to 300 ℃ with a heating speed of 2 ℃/min on a V1.7FTMA thermal mechanical tester. Pin-on-ring wear tests were performed on an MM200 wear test machine with and without oil lubrication. Pin samples were made of RS hypereutectic Al-Si materials and the ring samples were made of GCr15 bearing steel. The sliding speed and sliding distance for wear test without oil lubrication is 0.47 m/s and 850 m, respectively, while under oil lubrication condition, the sliding speed and sliding distance is 0.94 m/s and 3 390 m, respectively. Experimental load used was 294 N in both tests.

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After wear test, the width of wear surface was measured to calculate wear volume. A German piston material KS282 (Al-25Si-1Mg-1Cu-1Fe) made by casting method was used for comparison in both mechanical and wear tests. Heat-treatment of KS282 is the same as those used in RS AlSi.

Microstructures of experimental materials were examined on an MeF3 Optical Microscope. Tensile fracture surface and wear surface were examined on a PHILIPS XL30 Scanning Electron Microscope (SEM) equipped with energy dispersive spectrometer (EDS).

3 RESULTS AND DISCUSSION

3.1 Microstructures and properties

Table 1 shows the physical and mechanical properties of the alloys. It could be seen that the density and CTE of RS AlSi (i.e. RS Al-Si alloy) are lower than those of KS282, while the mechanical properties of RS AlSi both at 25 ℃ and at 300 ℃ are much higher than those of KS282. Since silicon content of RS AlSi is higher than that of KS282, it is easy to understand that its density and CTE decrease.

Fig. 1 shows the optical micrograph of the alloys. Microstructures of both RS AlSi and KS282 are mainly composed of α(Al) and silicon, with a few intermetallic compounds. The size of primary silicon in RS AlSi is 5~15 μm, a few of them are about 20 μm. As to KS282, the size of primary silicon grains is 50~100 μm. Silicon particles refinement is the most important factor for the improvement of mechanical properties, including strength and plasticity.

3.2 Wear behavior of alloys

Table 2 shows the wear test results of the alloys. It could be found that under both test conditions, the wear resistance of RS AlSi is better than that of KS282. The pin samples surface turned dark and relatively high contents of Fe and O were found on the worn surface. Fig. 2(a) and (b) show the worn surface morphologies for test without oil lubrication. Grooves can be found on both pictures. Compared with KS282, grooves on RS AlSi are more narrow. Under dry sliding condition, the wear mechanism includes adhesion wear, oxidation wear and abrasion wear, while the wear of KS282 is more serious than that of RS AlSi. Fig. 2(c) and (d) show the worn surface morphologies of RS AlSi and KS282, respectively, under oil lubrication condition. Plough wear is the main mechanism on both samples. On the worn surface of KS282, some pits appeared and implied that silicon particles fall off during wear test. Few pits were found on the worn surface of RS AlSi.

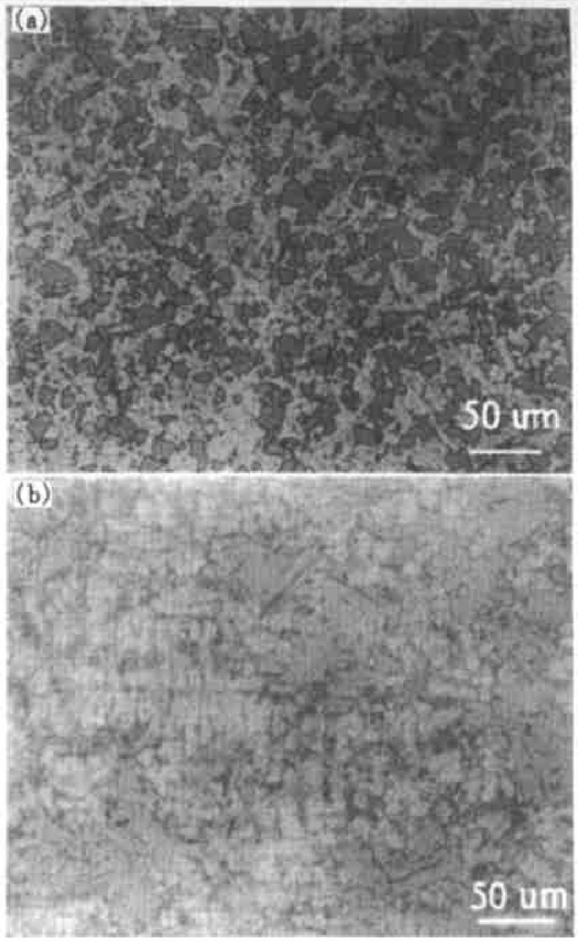

Fig. 1 Microstructures of experimental materials (a) —RS AlSi; (b) —KS282

Table 1 Properties of experimental materials

Material	Density / (g·cm^{-3})	CTE$_{25\sim300\ ℃}$ / 10^{-6}K^{-1}	$\sigma_{b(25\ ℃)}$ / MPa	$\delta_{(25\ ℃)}$ / %	$\sigma_{b(300\ ℃)}$ / MPa	$\delta_{(300\ ℃)}$ / %
RS AlSi	2.60	16.7	380	0.9	140	3.5
KS282	2.70	17.5	200	0.2	75*	~

* —data from Ref. [9].

Table 2 Wear behaviors of experimental materials

Material	Without oil lubrication		Oil lubrication	
	Wear volume / mm^3	Wear rate / (10^{-5}·mm^3·m^{-1}·N^{-1})	Wear volume / mm^3	Wear rate / (10^{-6}·mm^3·m^{-1}·N^{-1})
RS AlSi	6.16	2.47	0.42	0.042
KS282	7.22	2.89	0.54	0.055

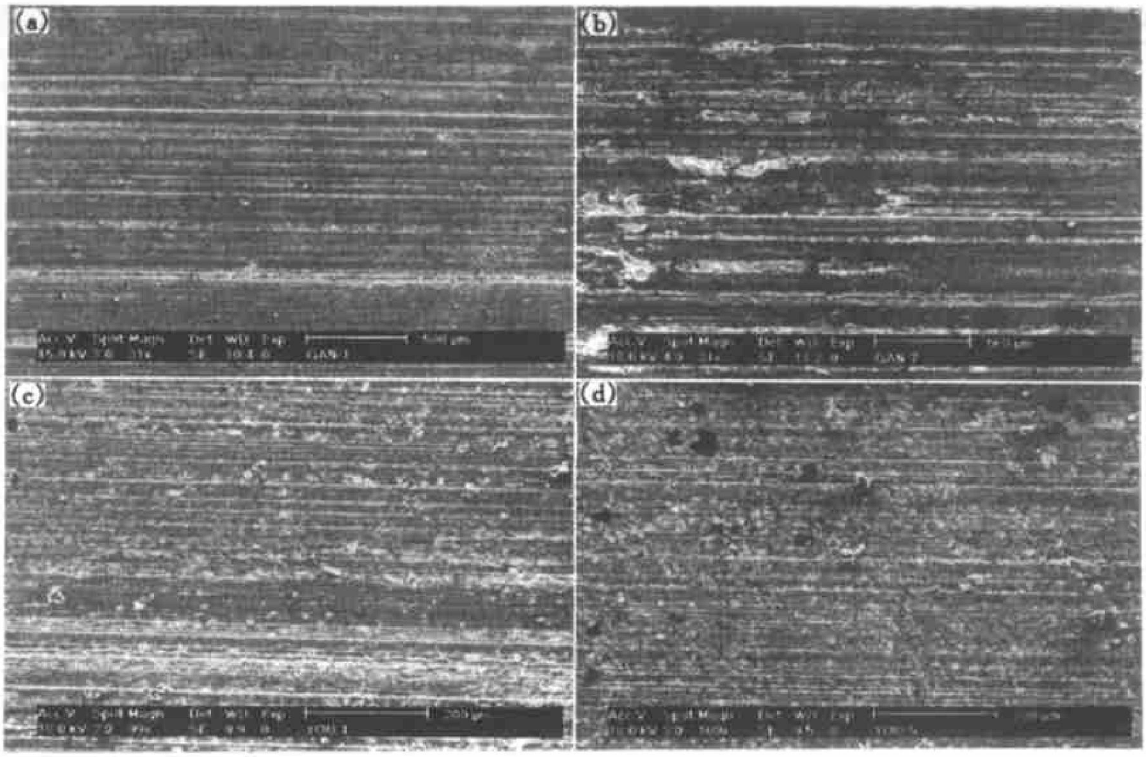

Fig. 2 Wear fractographs of experimental materials
(a) —RS AlSi without lubrication; (b) —KS282 without lubrication;
(c) —RS AlSi with oil lubrication; (d) —KS282 with oil lubrication

3.3 Discussion

By eliminating vacuum degassing, the fabrication routine of RS AlSi is simplified compared with other works[1, 2, 6, 7]. The oxide film of aluminum alloy powders is mainly composed of Al_2O_3 and $Al_2O_3 \cdot xH_2O$. The purpose of degassing is to remove the crystalline water from $Al_2O_3 \cdot xH_2O$ by heating the powders, thus the total oxygen content of powders is reduced[4]. It is well known that hydrogen is very harmful for aluminum alloys because it will cause hydrogen brittleness. With the water molecules removed, the hydrogen content also decreases. Since the water in $Al_2O_3 \cdot xH_2O$ is bonded by hydrogen bonding, it is not strong enough to withstand heating. As to the Al_2O_3 film on powder surface, it is compacted so that further oxidation reaction is hindered if the temperature and holding time of heating is chosen properly. On the other hand, billet need to be pre-heated to afford enough plasticity for deformation before extrusion. Since vacuum degassing need special equipment, degassing and preheating before extrusion are mostly two separated steps. However, in order to keep the RS microstructure as much as possible, less exposure to heat is preferred. Based on the analyses, we chose heating the billet in dry air before extrusion. The two steps, degassing and preheating, are combined into one in our experiment and the results show that this simplification is feasible. Heating the billets at 500 ℃ for 1 h then extruding, the properties of extruded rods is quite good.

Fig. 3 shows the longitudinal section of RS AlSi tensile fracture surface. From Fig. 3(a), it could be found that some large silicon particles are cracked but the micro-cracks are still not linked together. Thus silicon particles are the crack source while samples are

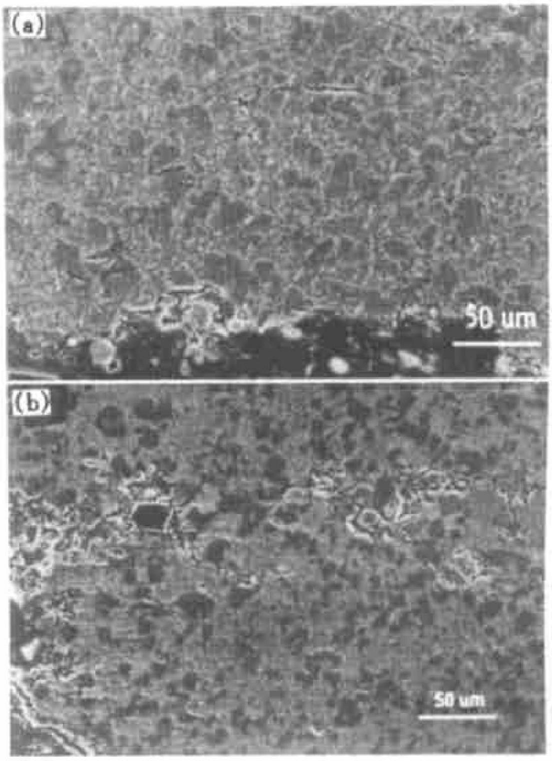

Fig. 3 SEM photographs showing longitudinal section of fracture surface of RS AlSi
(a) —25 ℃; (b) —300 ℃

tensioned at room temperature. By theoretical calculation, Mocellin pointed out that the larger the silicon particle is, the more easily the crack originates[10]. In other words, there must be many defects in Si particles since Si particles in experimental material are not ideal crystals. Large Si particles contain more defects and are easier to crack. This is also an explanation that tensile strength of RS AlSi is much higher than that of KS282. From Fig. 3(b), cracked Si particles are hard to be found, which implies that fracture mainly takes place on Al matrix at high temperature. Silicon particles turn to be impediments for crack propagating. That is to say, silicon particles play different roles in fracture at different temperatures.

Besides mechanical properties improvement, silicon particle refining is also beneficial to wear resistance improvement of hypereutectic Al-Si alloys. According to the above fracture analysis, large silicon particles are easy to crack, thus compared with RS AlSi, more pits appear on the worn surface of KS282 under oil lubrication condition. For dry sliding wearing, the temperature of wear couples turns high because much heat is produced. Wear-resistance of RS AlSi is better than that of KS282 since its high temperature strength is higher.

The strengthening mechanism of rapidly solidified hypereutectic Al-Si alloys is a mixing mechanism of grain refining, solution strengthening, dislocation strengthening and precipitation hardening[3, 6, 11]. When hot extrusion is employed during fabrication, texture structure also has some contribution to strengthening[12]. Among all of the strengthening mechanisms, silicon particle refining is the most important factor, especially at room temperature.

4 CONCLUSIONS

1) A RS hypereutectic Al-Si alloy (RS AlSi) with high silicon content (28% ~ 32%) is prepared by means of powder hot extrusion. The processing routine is simplified by eliminating vacuum degassing compared with common fabrication process.

2) The tensile strength of RS AlSi is much higher than that of KS282 casting material both at room temperature and at 300 ℃ due to silicon particles refining by rapid solidification. The density and CTE of RS AlSi are lower than those of KS282, and its wear resistance is better than that of KS282.

3) Silicon particles play different roles in fracture at different temperatures. At room temperatures, silicon particles are the crack source. The larger the silicon particle is, the more easily the crack originates. While at 300 ℃, silicon particles seldom crack in tensile test.

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