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Mechanical properties of hypereutectic Al-Si alloy by semisolid processing①

LI Shu-suo(李树索)[1,2], ZHAO Ai-min(赵爱民)[1], MAO Wei-min(毛卫民)[1], ZHONG Xue-you(钟雪友)[1]
(1. Foundry Institute, University of Science and Technology Beijing, Beijing 100083, P.R.China;
2. Beijing Institute of Aeronautical Materials, Beijing 100095, P.R.China)

[Abstract] Semisolid hypereutectic Al-Si alloy billets were obtained by electromagnetic stirring, in which microstructure of primary silicon gets rounder and there are a large number of rosette α phases appearing. Compared with conventional gravity die casting alloys, the tensile strength and elongation of semisolid forming hypereutectic Al-Si get obviously improved. Change of primary silicon morphology of semisolid hypereutectic Al-Si alloy made by electromagnetic stirring is the main reason of better tensile strength, and a large number of rosette α phases precipitation is the main reason of better elongation.

[Key words] semisolid processing; hypereutectic Al-Si alloy; tensile strength; elongation
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1 INTRODUCTION

Hypereutectic Al-Si alloys own excellent wear resistance. However, the size and microstructure of primary silicon have great effect on its properties, then the present studies mainly focus on the improvement of the primary silicon size and microstructure by means of modification[1~3] and the rapid solidification[4~6]. Semisolid processing is an advance metal forming technology which has been successfully applied on hypereutectic Al-Si alloys[7,8], but only little investigations concern about semisolid forming of hypereutectic Al-Si alloys. Recent years, some researchers used mechanical stirring to produce semisolid billet of hypereutectic Al-Si alloys, and got promising results whose size and microstructure of the primary silicon can be improved[9,10]. In this study, electromagnetic stirring was used to manufacture semisolid billets of hypereutectic Al-Si alloys. The results of experiments indicated that not only the microstructure of primary silicon gets rounder and the size of primary silicon becomes finer like mechanical stirred, and also a large number of rosette α phases appear[11,12]. These changes of microstructure will make a great effect on its mechanical properties. The mechanical properties of semisolid alloy with different silicon contents are systematically investigated in this paper.

2 EXPERIMENTAL

The hypereutectic Al-Si alloys with silicon content 18 %, 21 %, 24 %, 27 %, 30 % and 33 % (mass fraction) were investigated, respectively. These alloys were melted together with industrial pure aluminum and crystalloid silicon in the electric resistance furnace. After modified by 0.1 % phosphorus, the liquid alloys were poured into electromagnetic stirring equipment to be continually stirred until muddy alloys formed or cannot be stirred, then be quenched into water to obtain the semisolid billets which remain characteristics of semisolid microstructures (the liquid became solid with fine microstructure). These billets of semisolid state were reheated and thixoformed to tensile samples whose gauge is $d10$ mm × 160 mm (GB6397-86). For comparison, the conventional tensile samples were formed by gravity die casting after 0.1 % phosphorus modified with same silicon contents. The mechanical properties were tested on universal testing machine. Microstructures of semisolid hypereutectic Al-Si alloys and microstructure fracture surfaces of tensile samples were observed with optical microscope and SEM.

3 RESULTS

3.1 Microstructure of electromagnetic stirring hypereutetic Al-Si alloy billets

The metallographic observation indicated that the microstructures of semisolid hypereutectic Al-Si alloy billets produced by electromagnetic stirring are more different from the conventional ones. Fig.1(a) and (b) are microstructures of the gravity die casting sample and the electromagnetic stirring semisolid sample of Al-21 %Si alloy, respectively. The grain of primary silicon is a little rounder and the size of primary silicon is a little finer than those of conventional

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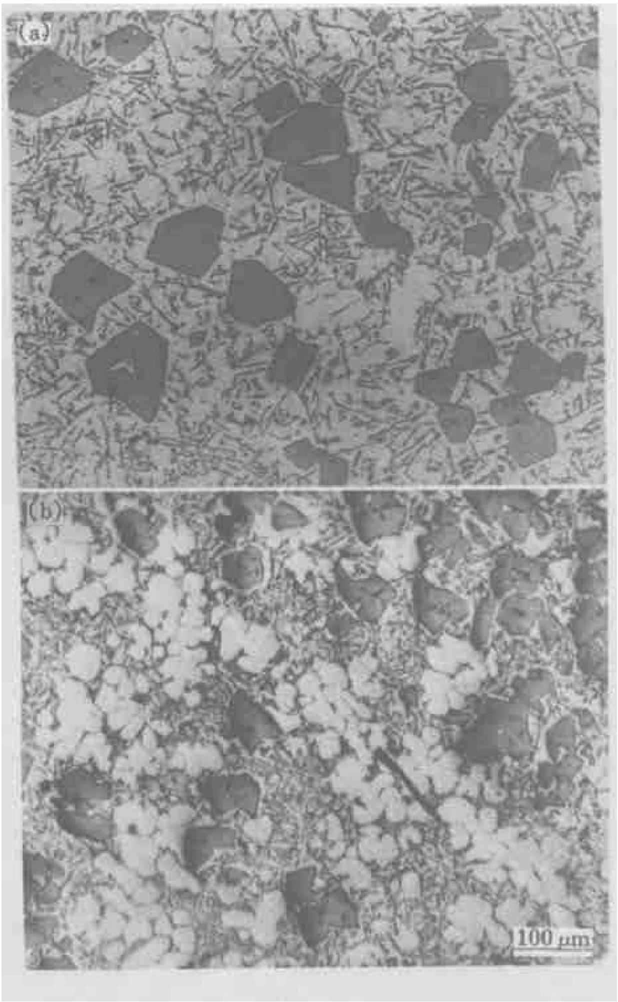

Fig.1 Microstructures of Al-21 %Si alloy
(a) —Conventional gravity die casting;
(b) —Electromagnetic stirring semisolid billet

casting samples as shown in Fig.1. The similar results were discovered in mechanical stirring semisolid billet[9,10]. Another important characteristic is that a large number of rosette α(Al) phases appeared in microstructure of electromagnetic stirring billets.

3.2 Results of mechanical property tests

The results of mechanical property tests are listed in Table 1 and shown in Figs.2 and 3. The results in Table 1 and Fig.2 indicate that the tensile strengths of conventional samples and semisolid forming samples are gradually decreased when silicon content increases except a special point. But the decrease rate of the tensile strength of semisolid forming sample is smaller than that of conventional gravity die casting sample. The tensile strength σ_b of semisolid forming Al-33 %Si is 145 MPa, while that of gravity die casting sample is only 68 MPa. The results also indicate that the tensile strength of semisolid forming samples are obviously higher than that of gravity die casting samples.

Table 1 Test results of tensile strength and elongation of hypereutectic Al-Si alloys

Alloy No.*	σ_b/ MPa	δ/ %	Alloy No.*	σ_b/ MPa	δ/ %
B18	195	2.90	Z18	162	0.72
B21	185	2.50	Z21	140	0.61
B24	167	3.20	Z24	118	0.40
B27	154	2.10	Z27	90	0.50
B30	168	1.40	Z30	82	0.40
B33	145	0.60	Z33	68	0.20

"B" shows semisolid forming sample, "Z" indicates gravity die casting sample, and the numbers followed by B/ Z express silicon content.

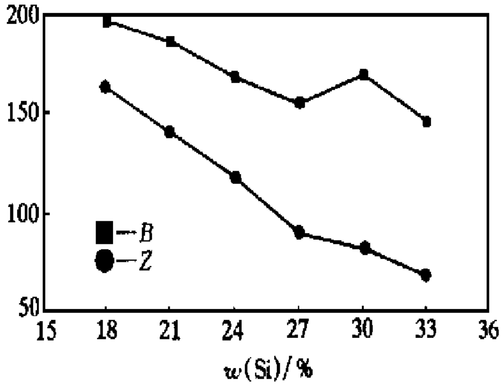

Fig.2 Relationship of tensile strength with silicon content

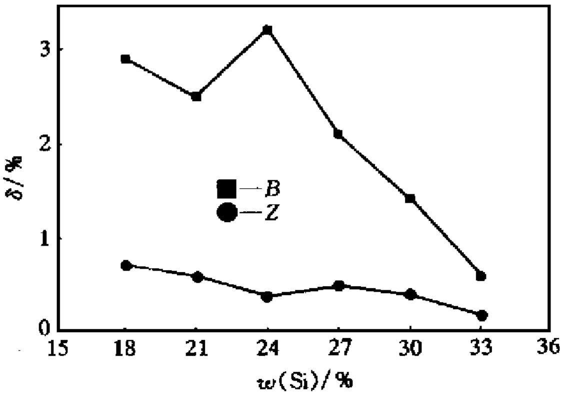

Fig.3 Relationship of elongation with silicon content

Fig.3 indicates that the elongation of semisolid forming samples increase greatly compared with gravity die casting samples. When the silicon content was less than 30 %, the elongation of semisolid forming sample is 1.40 % ~ 3.20 %, but the elongation of gravity die casting sample is only 0.4 % ~ 0.7 %. The stress—strain curves of tensile experiments of two kinds of sample have an obviously yielding strain before rupture, but the gravity die casting samples fractured at once and almost has no yielding process when tensile stress reached the maximum value.

According to the above experiment, the mechanical properties of semisolid forming hypereutectic Al-Si alloys are obviously improved. Even though the silicon content reaches 30 %, the semisolid forming samples still have good mechanical properties.

Fig.4 shows the morphologies of the fracture surfaces of the two kinds of samples observed by SEM. There were only very a little part of ductile fracture countenance in the gravity die casting samples, but there were a quite number of ductile fracture countenance in the semisolid samples. This concluded that the semisolid forming hypereutectic Al-Si alloy has a better ductile than the conventional gravity die casting alloy. These results are related to the microstructure and fracture behavior of semisolid forming hypereutectic Al-Si alloy.

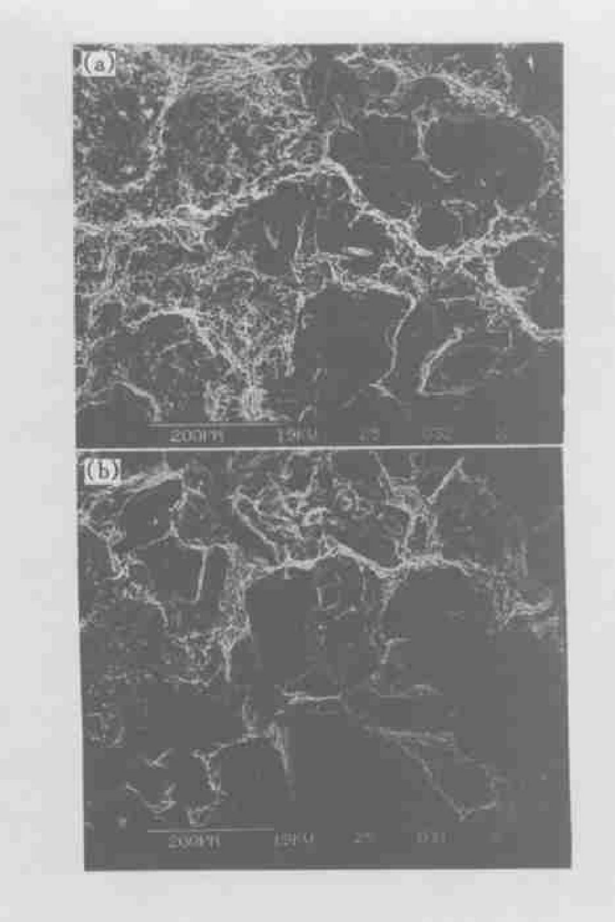

Fig.4 Morphologies of fracture surface of semisolid forming sample (a) and gravity die casting sample (b)

4 DISCUSSION

In the hypereutectic Al-Si alloy there exists two phase, α(Al) and silicon(include primary silicon and eutectic silicon); the α(Al) phase is soft and flexible to deformation, and the silicon phase is very hard and difficult to deformation. When tensile stress applied on the alloy, it deforms, but the deformation ability of these two phases is different. If the stress are high enough, the crack may be formed. Generally, the crack always initiates in silicon phase or interface of α(Al) and silicon, then the crack would propagate in the adjacent α(Al) phase, the condition of the crack propagating is[13]

$$\sigma_F \geqslant \left[\frac{\pi E(\gamma_{Si} + \gamma_\alpha)}{4(1 - \nu^2) C_o}\right]^{1/2} \quad (1)$$

where σ_F is fracture stress, E is tensile elastic modulus, ν is Poisson ratio, C_o is the thickness of silicon particles, γ_α and γ_{Si} are the surface energy of α(Al) phase and silicon phase, respectively.

If the silicon particles are ideal sphere, Eqn.(1) will be

$$\sigma_F \geqslant \left[\frac{\pi E(\gamma_{Si} + \gamma_\alpha)}{2 C_o}\right]^{1/2} \quad (2)$$

The value of metal materials is about 0.25 ~ 0.35. Compared Eqn.(1) with Eqn.(2), it is easy to discover that the rounder and smaller the silicon particle is, the higher the fracture strength of alloy is. Compared with conventional gravity die casting, electromagnetic stirring decrease the size of primary silicon and make the shape of primary silicon rounder, so fracture strength rises.

The maximum strain value ε of alloy before fracture is controlled by the size and microstructure of α phase in the Al-Si alloy. According to McClintock's crack gap linking model[14], the total fracture stain is

$$\varepsilon = \frac{(1 - n)\ln(L_o/l_o)}{\sinh[(1 - n)(\sigma_{11}^{\infty} + \sigma_{22}^{\infty})/(2\sigma/3)]} \quad (3)$$

where n is material constant, σ_{11}^{∞} and σ_{22}^{∞} are the long distance positive stresses, σ is equivalent stress, l_o is the size of microcrack, L_o is the distance between microcracks.

In conventional cast hypereutectic Al-Si alloy, α phase exists as eutectic state. In semisolid forming hypereutectic Al-Si alloy produced by electromagnetic stirring, except eutectic α phase there are a large number of similar spheres appeared. It makes the distance between silicon particles increase obviously. The micro crack always increases in silicon particles or interface between silicon and α phase, so the distance between micro cracks in semisolid forming hypereutectic alloy, L_o, is longer than that of conventional cast alloy. According to Eqn.(3), the maximum strain ε is increased in a great extent. This is the reason why the elongation of semisolid hypereutectic Al-Si alloy rises considerably.

Overall, semisolid processing makes hypereutectic Al-Si alloy has fine mechanical properties, and reveals a promise industry application.

5 CONCLUSIONS

1) The tensile strength and elongation of semisolid forming hypereutectic Al-Si alloys are obviously improved compared with conventional casting alloys. As silicon content increases, the tensile strength and elongation of hypereutectic Al-Si alloys decrease gradually, but the decrease extent of semisolid forming hypereutectic Al-Si alloys is obvi-

ously smaller than that of conventional casting alloys.

2) Through electromagnetic stirring semisolid process, the primary silicon becomes a little rounder and smaller, and a large number of similar sphere α particles appear in hypereutectic Al-Si alloy. The change of the size and the microstructure of primary silicon is the reason why the tensile strength of semisolid forming alloys rises, and a large number of similar sphere α particles existing in the alloy is the reason why its elongation increases.

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