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Microstructure and performance of Al-Si alloy with high Si content by high temperature diffusion treatment

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Abstract: The Al-Si alloy with high Si content was prepared by pressure infiltration. Microstructure observation shows that three-dimensional structure (3D-structure) is obtained from irregular sharp Si particles via high temperature diffusion treatment (HTDT). Flat Si-Al interfaces transform to smooth curves, and Si phases precipitate in Al and Si-Al interface. The bonding of Si-Al interface is improved by HTDT, which improves the mechanical performance of Al-Si alloy. The bending strength of 3D-Al-Si alloy increases by 6% compared with that of Al-Si alloy, but the elastic modulus changes a little. The coefficient of thermal expansion (CTE) of the 3D-Al-Si alloy is 7.7×10^{-6}/°C from 20 °C to 100 °C, which decreases by 7% compared with that of Al-Si alloy. However, HTDT has little effect on the thermal conductivity of Al-Si alloy.

Key words: Al-Si alloy; 3D-structure; interface; diffusion

1 Introduction

Al alloys have been widely used in aerospace, automotive, electronics, and machinery manufacture industries due to low density, high thermal conductivity and excellent machinability[1−2]. However, with the development of science and technology, green industry and green materials are being paid appreciate attentions[3−5]. Therefore, more and more research activities focus on the recycling of Al alloys[6−8]. Fortunately, the special solution ability between Si and Al makes the recycling of Al-Si alloys come true[9−10].

BRESLIN et al and LU et al reported that the Al alloys with three- dimensional structure (3D-structure) show higher mechanical properties than common Al alloys[11−12]. Hot isostatic pressing[13], in-situ reactive synthesis method[14] and infiltration technique[15] have been used to fabricate 3D-structure. However, the reinforcement content reported is very low. It is difficult to form a stable 3D-structure. High volume content SiC_p/Al-12Si composite could be produced by pressure infiltration method[16].

Therefore, in the present work, high pure Si particles are introduced into 4032 aluminum by pressure infiltration method, and then Si particles are transformed to smooth 3D-structure via high temperature diffusion treatment (HTDT). The effects of high temperature diffusion treatment on the microstructure, mechanical properties, thermal extension and conduction are discussed.

2 Experimental

High pure Si particles were introduced into 4032 aluminum by pressure infiltration method. Si particles (65% in volume fraction) were filled and pressed into a mold, and subsequently molten Al was infiltrated into the mold under pressure and cooled rapidly. Then, the Al-Si alloy was treated in sealed mold at 700 °C for 2 h under 0.2 MPa.

The morphology and distribution of Si in Al-Si alloy was observed by OLYMPUS PMG3 optical microscope (OM). Further microstructure analysis was conducted by using Philips CM−12 and JEOL 200CX transmission electron microscope (TEM) with accelerated voltage of 100−120 kV and 200 kV, respectively.

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The CTEs of Al-Si alloys were measured on DIL 402C (NETZSCH Corp.) with a heating rate of 5 °C/min. The thermal conductivity measurement was performed on JK2 laser conductivity tests (Germany) at a heating rate of 5 °C/min. The diameter of the samples for thermal conductivity testing was 12.7 mm and the length was 3 mm. The mechanical properties were measured by three point bending testing on the Instron5569 machine with sample sizes of 3 mm×4 mm×36 mm, while the span was 30 mm and the ram speed was 0.5 mm/min.

3 Results and discussion

3.1 Effects of HTDT on microstructure of Al-Si alloy

Figs.1(a) and (b) give the microstructures of Al-Si alloy before and after HTDT. Fig.1(c) shows the morphology of 3D-Si after HTDT, in which Al was etched by NaOH solution. Fig.1(d) presents the EDS results of 3D-Si.

It can be seen that irregular Si particles with edges are distributed uniformly in the Al-Si alloy before HTDT. After HTDT, Si particles contact with each other and transform to 3D-structure. Thus the Al-Si alloy transforms into 3D-Al-Si alloy.

After HTDT, the clean and clear Si-Al interfaces have changed to smooth curves, as shown in Fig.2. Fine Si precipitates are dispersed at Si-Al interface and in Al alloy. These Si precipitates have improved the Si-Al interfacial bonding strength.

TEM observations show that defects, such as high densities stacking faults and twins, exist in Si particle, as shown in Figs.3(a) and (c), respectively. Stacking faults and twins are common defects in Si particles[17]. These defects would be the crack source and paths for cracks propagation, eventually affect the fracture behavior of Al-Si alloy.

Moreover, the above defects could also affect the thermal conduction properties. Generally, heat conduction is via phonon in alloy. The longer the average free path of phonons move, the higher the thermal conduction ability of alloy is. However, phonons will be scattered by crystal defects as stacking faults and twins, which would decrease the average free path, and eventually perform negative effect to thermal conduction. In the present research, the crystal defects decreased the thermal conduction ability of the Al-Si alloy.

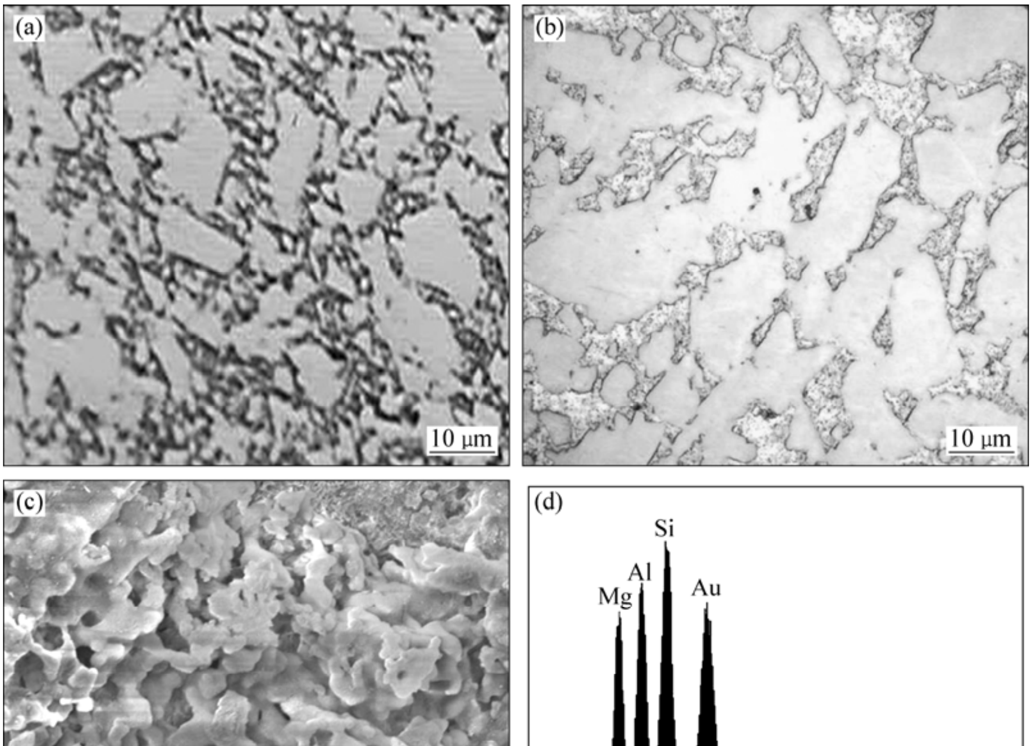

Fig.1 Micrographs of Al-Si alloy and 3D-Si: (a) Al-Si alloy before HTDT; (b) 3D-Al-Si alloy after HTDT; (c) 3D-Si; (d) EDS analysis of 3D-Si

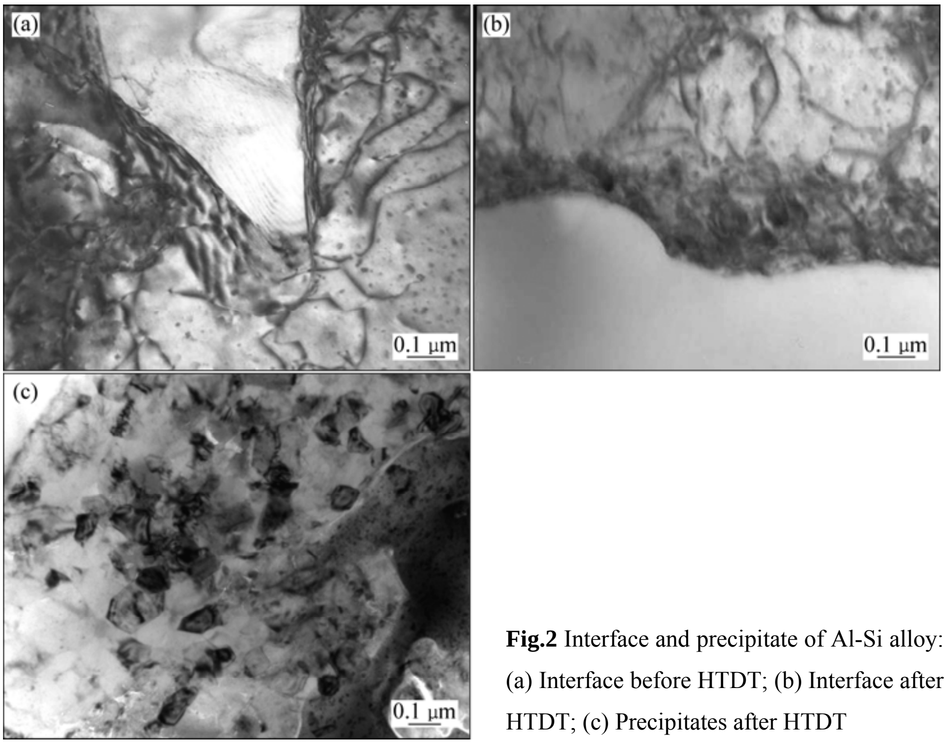

Fig.2 Interface and precipitate of Al-Si alloy: (a) Interface before HTDT; (b) Interface after HTDT; (c) Precipitates after HTDT

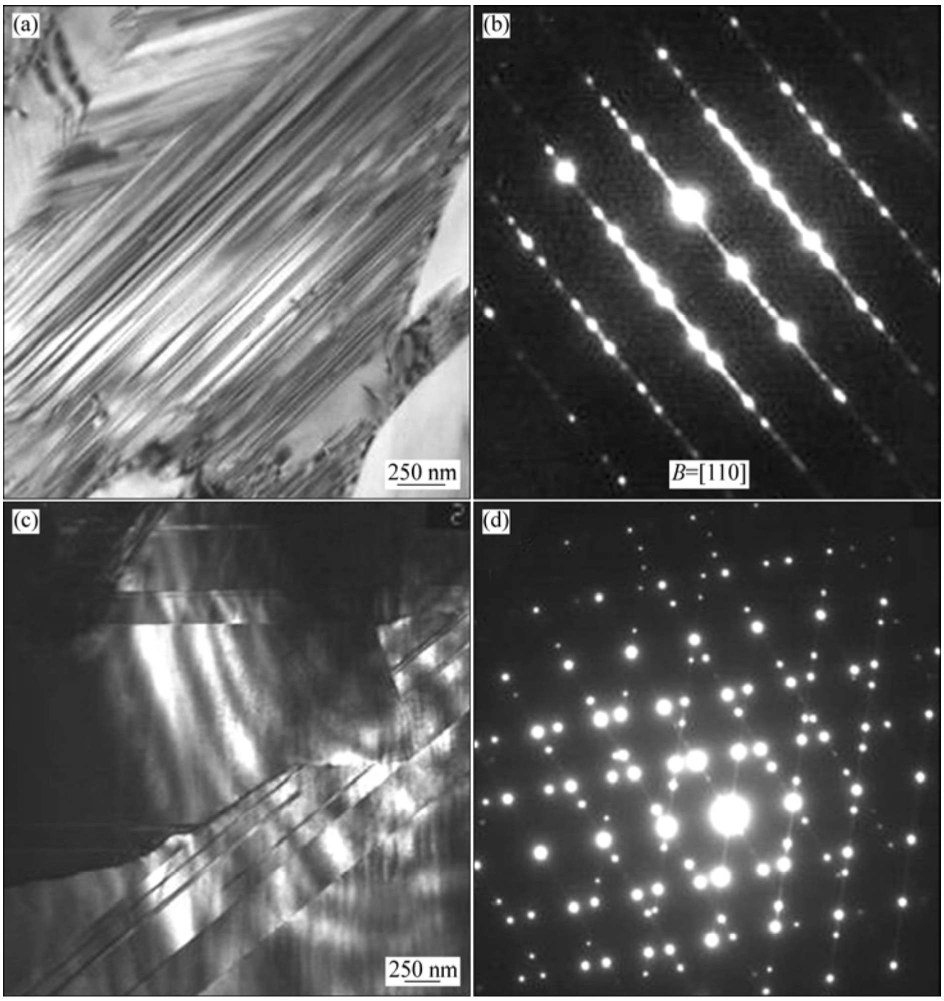

Fig.3 Defects of Si particle: (a) Stacking fault; (c) Twins; (b), (d) SAD pattern

3.2 Effect of HTDT on properties of Al-Si alloy

The bending strength of the 3D-Al-Si alloy is 247.3 MPa, which is improved by 6% compared with that of Al-Si alloy before HTDT (223.4 MPa), as shown in Fig.4. However, the elastic modulus of 3D-Al-Si alloy is 87 GPa, similar to that before HTDT. Elastic modulus is the characteristic of the materials, but independent of the heat treatment method.

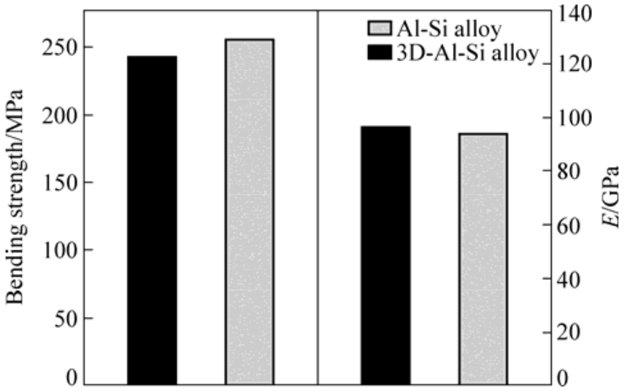

Fig.4 Mechnical properties of Al-Si and 3D-Al-Si alloys

Generally, the dispersion particles can transfer but can not undertake the loading. However, 3D-structure can transfer and undertake the loading, which improves strength. The 3D-structure can interlock with the Al, which can impede the expansion of cracks and release the stress at the interfaces.

CTEs of Al-Si alloy and 3D-Al-Si alloy at different temperatures are shown in Fig.5. It is obvious that CTE of 3D-Al-Si alloy is lower than that of Al-Si alloy in all stages. CTE of 3D-Al-Si alloy between 20 °C and 100 °C is 7.7×10^{-6}/°C, decreased by 7% compared with that of Al-Si alloy (8.3×10^{-6}/°C).

The thermal expansion properties of alloys are associated with the matrix, particles and microstructure. According to particles distribution, alloy can be designated into dispersion or interconnection. Interfacial

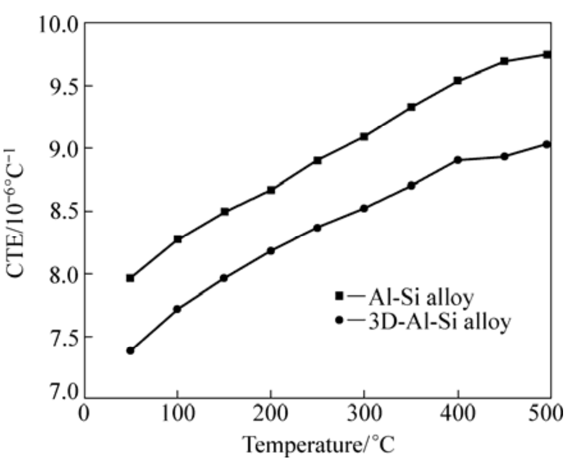

Fig.5 CTEs of Al-Si and 3D-Al-Si alloys

bonding of interconnection for instance 3D-structure, is better than dispersion[18]. From Fig.2, fine dispersed Si precipitates at Si-Al interface and in Al in 3D-Al-Si alloy would be obstruction to Al thermal expansion, which is favorable for descending of CTE.

The formation of 3D-structure is beneficial to thermal conduction due to the reduction of Si-Al interfaces. Moreover, dissolution and precipitation of Si improve Si-Al interface, which will be conducted to thermal conduction. 3D-Si and Al will be extra channel for conduction of phonon in Si and free electron in Al. However, Si precipitates and sub-grain introduce more interfaces into 3D-Al-Si alloy, which impedes the heat transferring. Therefore, the thermal conductivity of 3D-Al-Si alloy is similar to that of the alloy before HTDT, as shown in Fig.6.

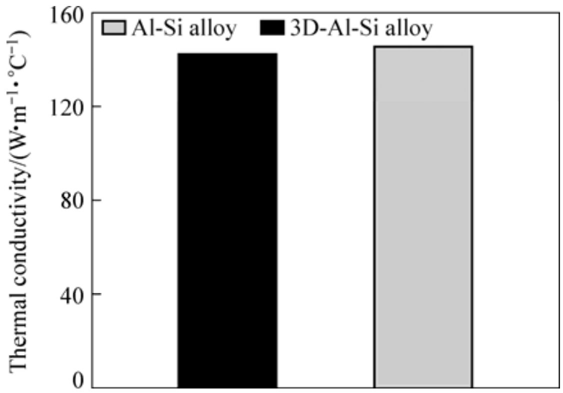

Fig.6 Thermal conductivity of Al-Si and 3D-Al-Si alloy

4 Conclusions

1) Observations show that irregular Si particles in Al alloy have transformed into three dimensional net structures and formed 3D-Al-Si alloy.

2) Clean and straight Si-Al interfaces have changed into smooth curves, which improves the interfacial bonding. Moreover, dispersed Si precipitates at the Si/Al interface and in Al alloy.

3) Mechanical performance of 3D-Al-Si alloy is improved by 6% compared with that of Al-Si alloy, but the elastic modulus changes a little.

4) The CTE of the 3D-Al-Si alloy is 7.7×10^{-6}/°C at 100 °C, which is 7% lower than that of the Al-Si alloy. Thermal conductivity of Al-Si alloy changes a little after HTDT.

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