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Fabrication and fracture toughness of macro-toughening-designed composite①

Qin Shuyi(秦蜀懿), Zhang Guoding(张国定), Wang Wenlong(王文龙)
State Key Lab of Metal Matrix Composites,
Shanghai Jiao Tong University, Shanghai 200030, P. R. China

Abstract: A macro-structure-toughened SiC particle reinforced LD2 aluminum alloy matrix (SiC_p-LD2/LD2) composite was designed and fabricated based on considering the main factors which result in low room temperature fracture toughness of conventional metal matrix composites. Its room temperature fracture toughness was tested using three-point bending samples with single edge notches. Compared with conventional SiC_p/LD2 composites fabricated by stirring casting in case of same particle size and similar reinforcement volume fraction, this composite has a higher room temperature fracture toughness K_Q. It shows strong resistance to crack propagating. The crack in it can propagate stably for a long time on the maximum load, therefore abrupt fracture occurring in most conventional composites can be avoided. Bending fractography (SEM) shows that the fracture mechanism of this material is different from SiC_p/LD2 composite and the deformation of the unreinforced LD2 matrix and the SiC_p-LD2/LD2 interface debonding are the main toughening mechanisms of this composite.

Key words: metal matrix composite; fractures; crack propagation; interface **Document code: A**

1 INTRODUCTION

Particle Reinforced Metal Matrix Composites (PMMCs) have high specific strength, specific modulus, elevated temperature properties, resistance to wear and low cost. However, companied low ductility and toughness is one main obstacle to their application for engineering[1,2]. Many studies on SiC particle reinforced aluminum alloys[3~6] show that the addition of particle not only refines matrix grain but also results in high density dislocations in the matrix near the interface. Particles block long-distance-slip of the dislocations in the matrix, thus decreasing the in situ ductility of the matrix and making the matrix be in a high and complicated triaxial stress condition, then, the tensile strength and yield strength of the matrix are increased. However, when the microcrack forms in the material, the matrix in a high triaxial stress condition can not blunt the crack efficiently and the main crack will link and propagate quickly. This is the main reason for low toughness of PMMCs. Many analyses on fractograghies of SiC particle reinforced aluminum alloys show that these materials also fracture ductilly but the fracture surfaces are rather plane and tear ridges form in the matrix between particles rather than dimples[3,7,8]. Moreover, particle cluster and fracture during the preparation and processing of the composite also can decrease toughness of PMMCs. According to the study of Friend[9], there are two ways to improve toughness of MMCs. One is to increase the crack nucleation energy and the other is to increase the crack propagating energy. He indicated that it is difficult to increase the crack nucleation energy of the composite due to the low strain to failure of ceramic reinforcement. Therefore, it is an efficient way to improve toughness , especially resistance to crack propa-

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gating of PMMCs, if there is enough non-deformed matrix between reinforcements to absorb fracture energy and interdict crack. Generally, distance between particles is often far less than the plastic zone size to blunt crack in PMMCs. If some composites with high particle volume fraction can be obtained in some areas of the bulk material and the other unreinforced areas between these composites can blunt crack efficiently, then not only the reinforcements will strengthen the matrix enough but also toughness of the material can be improved. Recently, some laminate PMMCs have been studied based on this thought and the results show that these materials have excellent impact toughness[10~12]. In the present work, a LD2 aluminum alloy reinforced with high volume fraction column-shaped SiC_p-LD2 composites (noted as SiC_p-LD2/LD2) was designed and fabricated. Compared with a uniform conventional SiC_p/LD2 composite fabricated by stirring casting, it has higher room temperature fracture toughness and shows strong resistance to crack propagating. The maximum load on it can maintain for a long time. This is different from conventional composites in which the crack can form and propagate quickly.

2 EXPERIMENTAL

LD2 aluminum alloy is selected as the matrix. Vacuum pressure infiltration method is employed. The composite with high particle volume fraction in partial areas (see Fig. 1) can be fabricated when the experimental parameters are controlled properly. The particle is 14 μm nominally sized. The mean particle volume fraction in the bulk material is 18% approximately. At the same time, a SiC_p/LD2 composite with same sized particle and 15% volume fraction is fabricated by conventional stirring casting and cast as rods with a diameter of 37.5 mm.

The two composites are hot-extruded as rods with a diameter of 12 mm by a 10:1 ratio at 400 ℃. Rectangle-shaped samples, 50 mm × 10 mm × 5 mm, are cut along the extruded direction for three-point bending, then single edge notches of 4 mm in depth and 80 μm in width are cut along the thickness direction. The fracture toughness K_Q is tested by three point bending method[13]. All samples are soluted at 520 ℃ for 1 h, then quenched in 20 ℃ water followed by 8 h of artificial aging at 160 ℃ (T6). Bending test is processed on a SCHENCK testing machine. The pressure head descends at a rate of 0.1 mm/min. Three samples are tested for each material. To verify if the tested K_Q is valid K_{IC}, the yield strength $\sigma_{0.2}$ and elastic modulus E are also tested (The tensile sample is of a gauge diameter of 6 mm and a gauge length of 40 mm and the tensile rate is 0.1 mm/min). Bending fractographies of the two composites are observed in a Cambridge Instruments S360 Scanning Electron Microscope (SEM).

3 RESULTS AND DISCUSSION

3.1 Optical microstructures

Fig. 2 shows the optical microstructures of the two composites. In SiC_p-LD2/LD2 composite (Figs. 2(a) and (b)), the melted LD2 matrix has infiltrated into the vacant between particles completely. The deformations of SiC_p-LD2 bar

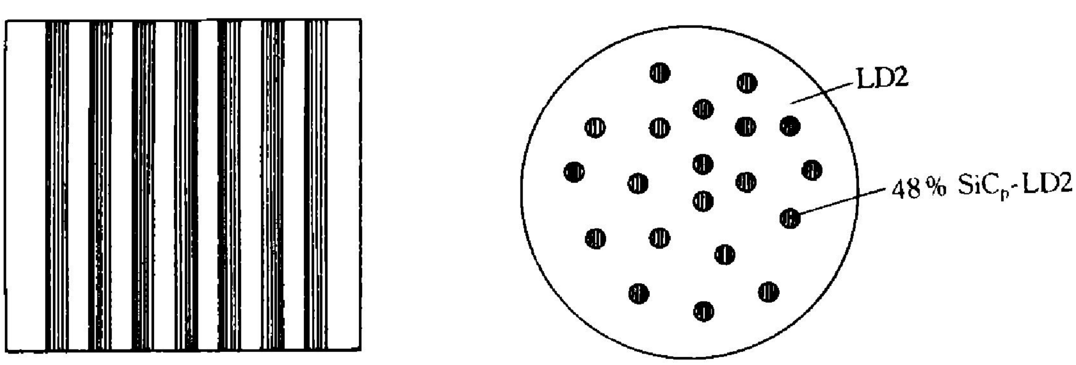

Fig. 1 Schematic of structure-toughened composite

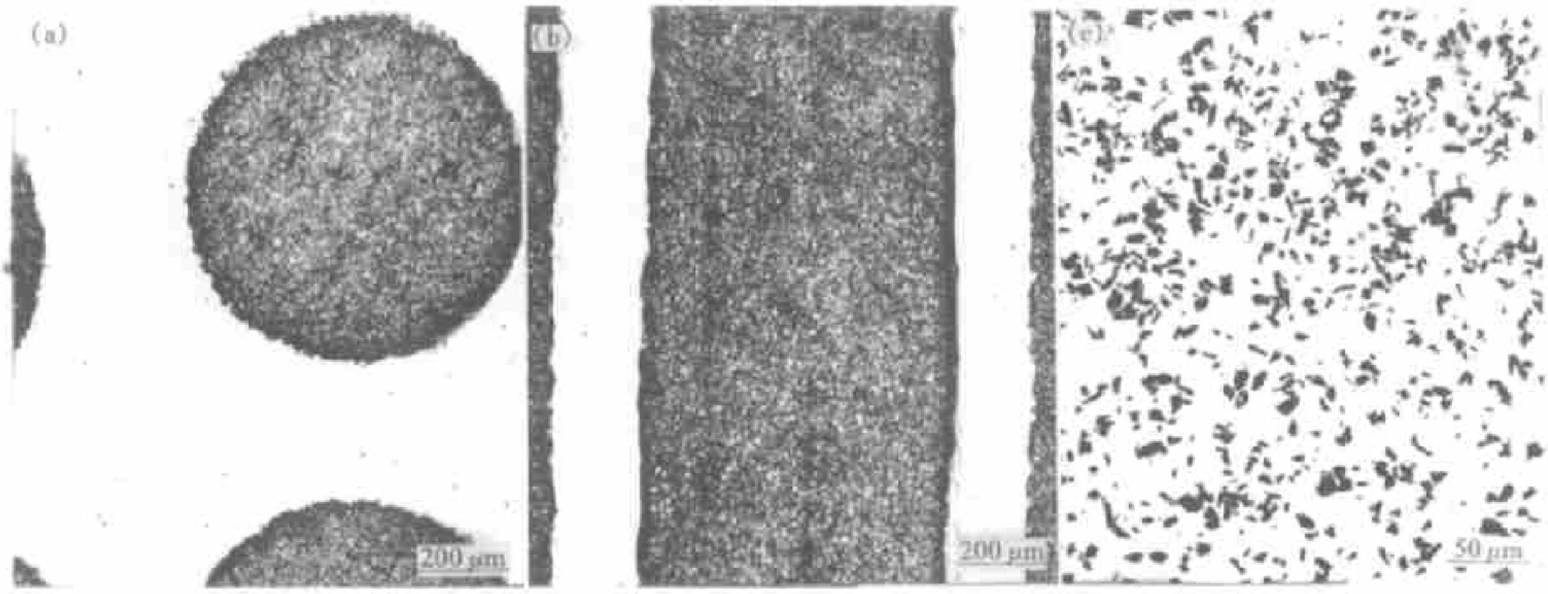

Fig. 2 Optical microstructures of composites
(a)—SiC_p-LD2/LD2, perpendicular to extruded direction;
(b)—SiC_p-LD2/LD2, parallel to extruded direction;
(c)—SiC_p/LD2, parallel to extruded direction

and LD2 matrix are uniform and continuous after hot extruded. It is confirmed that the selected infiltration and extruded parameters are proper. In SiC_p/LD2 composite (Fig. 2(c)), particles distribute uniformly and have no cluster along the extruded direction so that K_Q testing deviation can be avoided.

3.2 Mechanical properties

Fracture toughness K_Q data of the two composites are shown in Table 1. The tested K_Q is not valid K_{IC} because the sample's width is less than $2.5(K_Q/\sigma_{0.2})^2$. K_Q of SiC_p-LD2/LD2 composite is slightly higher than that of SiC_p/LD2 composite. However, φ_f of the former is also higher than that of the later and it is known that fracture toughness of PMMCs decreases with increasing φ_f rapidly. So, toughness of the former is better than that of the later. The deviation of the tested data of SiC_p-LD2/LD2 is very small. It is shown that this macro-toughening-designed composite has a stable fracture toughness. The effect of microstructure change on toughness of SiC_p-LD2/LD2 is less than that of conventional PMMCs.

3.3 Fracture mechanism

Fig. 3 shows the crack opening displacement (COD)-load curves of the two composites under bending load. It is evident that composite SiC_p/LD2 fractures abruptly. The main crack formation and growth are instantaneous (point D in Fig. 3). However, the fracture of SiC_p-LD2/LD2 composite is by stages. Because the strain to failure of the SiC_p/LD2 bars with high particle volume fraction is much low (Fig. 4 (b)), the main crack will form in the first layer SiC_p/LD2 bar on a slightly lower level of load (point A in Fig. 3, corresponding with A—A section in Fig. 4(a)), but gradually grows on a higher level of load (points B and C in Fig. 3, corresponding with B—B and C—C sections in Fig. 4(a) and

Table 1 Room temperature fracture toughness of composites

Fracture toughness	SiC_p-LD2/LD2			SiC_p-LD2		
	Specimen No. 1	Specimen No. 2	Specimen No. 3	Specimen No. 1	Specimen No. 2	Specimen No. 3
K_Q ($MPa \cdot m^{1/2}$)	23.3	23.7	23.4	20.5	21.5	22.6
Mean data		23.5			21.5	

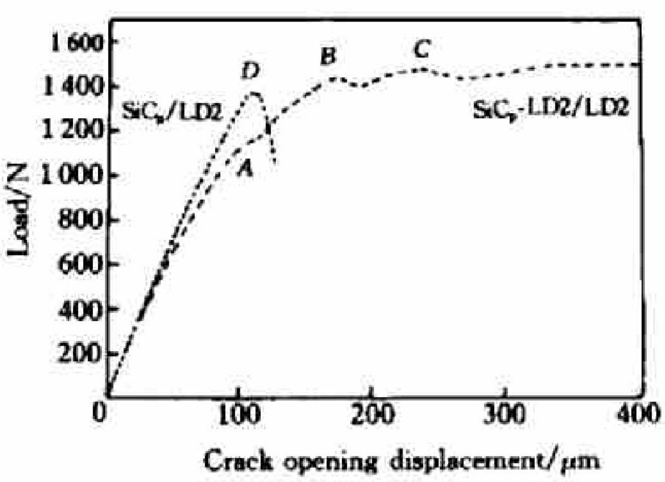

Fig.3 COD vs load curves of composites

propagates for a long displacement on the maximum load stably (at the end of the curve A-B-C in Fig.3, the composite does not fail yet). Compared with its fractographs (Fig.4(a)), it can be seen that the main crack firstly forms on A—A section. When the crack rapidly grows to contact the ductile LD2 alloy, the matrix near the failure SiC_p-LD2 bar begins to deform and absorb fracture energy. The second cracks then form and propagate along the (SiC_p-LD2)/(LD2) interface perpendicular to the cross section. The applied load must increase to deform the matrix and make the second cracks propagate until the second layer bars fracture (B—B section in Fig.4(a)). Similar procedure happens until the third layer bars fracture (C—C section in Fig.4(a)). In Figs.4(c) and (d), it can be seen that in fact, debonding of the (SiC_p-LD2)/(LD2) interface is the failure of SiC_p-LD2 composite near the interface. Therefore, after all SiC_p-LD2 bars fractured, they still bear part of load to make the second crack propagate along longitudinal direction. The load is thus maintained on the maximum for a long time. So, the deformation of the ductile unreinforced LD2 matrix between SiC_p-LD2 bars and the (SiC_p-LD2)/(LD2) interface debonding toughen the SiC_p-LD2/LD2 composite cooperatively. This kind of fracture model can protect this composite from the disadvantage of conventional PMMCs in which disastrous

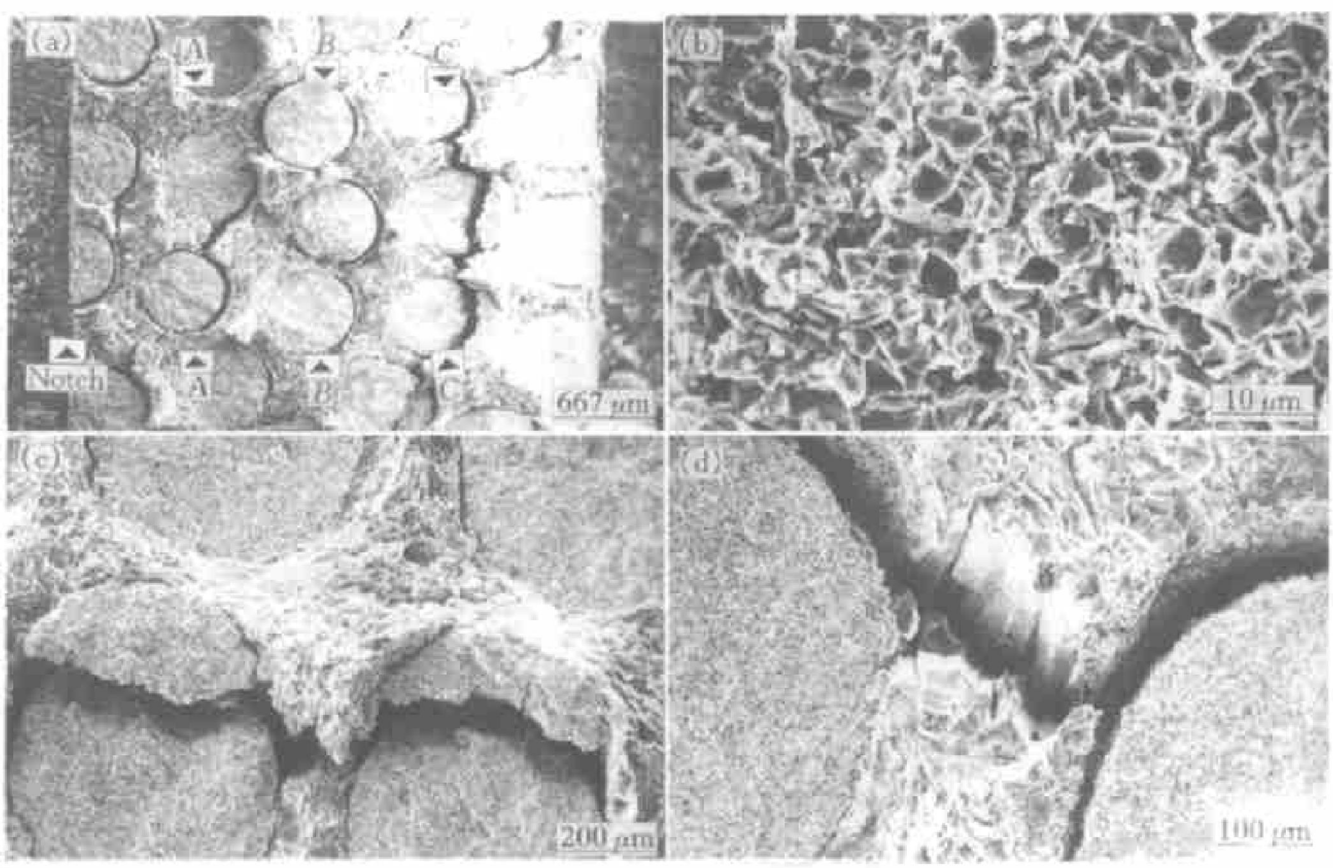

Fig.4 Fractographs of SiC_p-LD2/LD2 composite (SEM)
(a)—Low magnification; (b)—Fracture surface of SiC_p-LD2 bar; (c) and (d)—Interface debonding

failure often occurs on the maximum load abruptly.

4 CONCLUSIONS

(1) Processing parameters being controlled well, a macro-structure-toughening-designed SiC_p-LD2/LD2 composite was fabricated successfully.

(2) Compared with a conventional SiC_p/LD2 composite, the toughened composite has a higher room temperature fracture toughness.

(3) The fracture procedure of the toughened composite is by stages and the maximum load on it can maintain for a long time. This can avoid the disadvantage of conventional PMMCs in which disastrous failure often occurs on the maximum load abruptly.

(4) The deformation of the unreinforced LD2 matrix between SiC_p-LD2 bars and the (SiC_p-LD2)/(LD2) interface debonding are the main toughening mechanisms of the designed composite.

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