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Mechanical behavior of SiC foam-SiC particles/Al hybrid composites

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Abstract: The hybrid SiC foam-SiC particles/Al double interpenetrating composites to be used as the brake materials of high speed train were fabricated by squeeze casting technique. The influence of the type of matrix on the mechanical properties and the fracture mechanism of the hybrid composites was investigated. The interface bond in the hybrid composites is good for the composites have the unique double interpenetrating structure. The ductile matrix resists the propagation of the microcracks in the struts. During the microcrack propagation process, the energy absorption and the fracture surface area are increased, which increases the ductility of the hybrid composites. The compressive strength of the hybrid composite reinforced by the SiC with the total volume fraction of 53% is 660 MPa, which is higher than that of traditional composite reinforced by single SiC particles.

Key words: double interpenetrating hybrid composite; fracture mechanism; energy absorption; crack deflection; mechanical behavior

1 Introduction

Metal matrix composites attract attention for the brake materials because of their integrated physical properties and superior mechanical strength. Among them, particle-reinforced and interpenetrating aluminum matrix composites have shown promises as candidates for such applications[1−4]. Generally, the volume fraction of particles has to be very high in order to make friction coefficients match the compressive strength between the brakes when SiC_p/Al composites are used as the tribology materials[5−7]. However, SiC particles in composites are easily pulled out and shed from the matrix, which reduces the tribology property of the composites[8]. At high temperature, the matrix is easily softened and the SiC particles move with matrix, so the particles lose the reinforcement ability, and the wearable property and compressive strength of composites are dramatically decreased.

The interpenetrating composites reinforced by three-dimensional ceramic networks, such as SiC foams, have better tribology properties and larger high temperature strength than traditional SiC_p/Al composites containing same content of SiC reinforcement since the network reinforcement not only restricts the movement of the soft matrix, but also endures the load[9−12]. Nevertheless, high-volume-fraction fine SiC foams with continuous cell are difficult to attain simultaneously, and it is difficult to produce such interpenetrating composites to meet the requirements of the brake materials. The novel composite which is called SiC foam-SiC particles/Al hybrid composite can overcome the shortcomings of single SiC foam reinforced composites by substituting the aluminum matrix in the cell of the SiC foam with SiC_p/Al composites[13−16]. Recently, many research mainly focuses on the fabrication of the interpenetrating composites, but the theoretic report of the double interpenetrating hybrid composites is absent. So, it is necessary to develop the advancing double interpenetrating composites in order to meet the demand of the high speed train. In this work, the hybrid composites are fabricated by squeeze casting technology. The fracture mechanism, and the influence of matrix on

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the mechanical behavior are investigated in order to apply them in the tribology materials.

2 Experimental

The hybrid composites were fabricated by modifying an established procedure[13]. First, the SiC foams with a cell size of about 2 mm, shown in Fig.1(a), were produced by a solid-state sintering process through the polymer foam replication method[17]. The SiC foam is made up of cells and struts that consist of triangular central opening holes and strut walls. Furthermore, there are numerous continuous tiny cavities in the strut walls as shown in Fig.1(b), which makes the struts have a three-dimensional reticular structure similar to that of the foams. This special reticular structure was deliberately designed in the experiment in order to increase interfacial bond between the matrix and struts for the interface area plays important roles in the mechanical bond, such as the interface bond between silicon carbide and aluminum. Second, SiC particles with mean particle size of 20 μm were dispersed in the SiC foam cells to form a hybrid preform by the vibration method. The volume fraction of SiC of the foams was 16.4%, and the corresponding total SiC volume fraction in the composites was 53%. The processing route used for the fabrication of composites is squeeze casting method[11]. The preform and the mould were preheated to 800 ℃ and 300 ℃, respectively. Meanwhile, aluminum matrix was molten, degassed, and cleaned in a graphite crucible, and heated to 750 ℃. The last stage was to place the preheated preform into the mould and squeeze the molten aluminum alloy into the preform with 120 MPa pressure to prepare the composite.

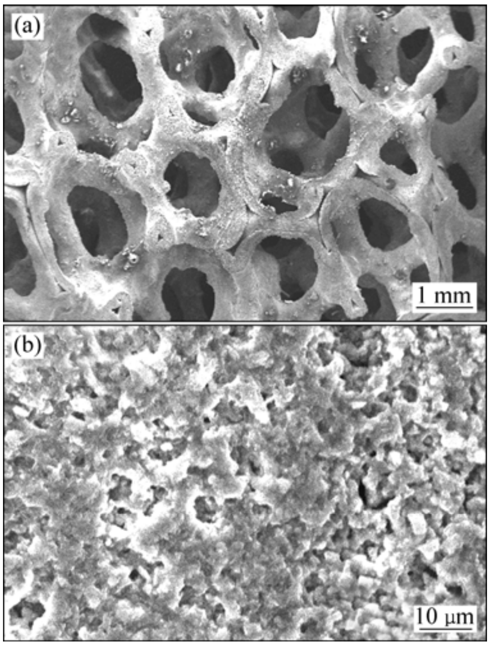

Fig. 1 Morphologies of SiC foam reinforcement: (a) Macro-appearance; (b) Surface of strut

The microstructure of the composites was examined with an MEF4A optical microscope (OM) and an S360 scanning electron microscope(SEM). Compressive test specimens were manufactured by the thread spark cutting technique. The sizes of specimens were 15 mm×15 mm ×30 mm. All the tests were conducted in an Instron testing machine at a strain rate of 5×10^{-3} s^{-1}.

3 Results and discussion

3.1 Microstructure

It is found that the hybrid composites are composed of the gray SiC particles, the white aluminum alloy matrix and the gray SiC foam struts, as shown in Fig.2. The SiC particles distribute uniformly in the cells of SiC foam, but they are not found in the triangle holes of the struts. The SiC particles cannot be placed into the holes because the particles are larger than the cavities in the strut walls. And the axis direction of the triangle holes is not open to the SiC particles, so the SiC particles cannot enter into the triangle central holes of the struts. Because the strut walls are reticular, the walls have an interpenetrating structure, and the struts are changed into the metal-ceramic composites after aluminum infiltrates the cavities of the struts. Such an interpenetrating structure, which is called local interpenetrating structure, will boost the bonding of the SiC foam struts to aluminum in the triangle holes and in the cavities, decreasing the concentration of residual stresses. In addition, a SiC foam network makes the overall hybrid composites have an interpenetrating structure. The structure which is called the overall interpenetrating structure, restricts the SiC particles and aluminum in the foam cells. The composites having both the local interpenetrating structure and the overall interpenetrating structure are called double interpenetrating structure composites. With the special double interpenetrating structure, the composites will attain the unique properties.

3.2 Mechanical properties

Fig.3 shows the relationship between the compressive stress and strain of composites constituting of different matrix. The compressive strength, the yield strength and the elastic modulus of SiC foam-SiC particles reinforced composites with ZL109 aluminum alloy matrix are higher than those of composites with pure aluminum matrix, but the ductility of the former is lower than that of the latter. The compressive strength of the ZL109 aluminum alloy matrix hybrid composite reinforced by SiC with the total volume fraction of 53% and the corresponding SiC foam with the volume fraction of 16.4% is 660MPa, which is not found in the traditional aluminum matrix composites reinforced by the single SiC particles with the same content. Compared with those of pure aluminum matrix, for a given strain, the compressive strength of the ZL109 aluminum matrix is higher, and the ductility is lower. Therefore, the compressive strength of the composites with the brittle ZL109 aluminum silicon alloy matrix is higher than that of composites with pure aluminum matrix. It can be seen that the matrix plays important role in the composites.

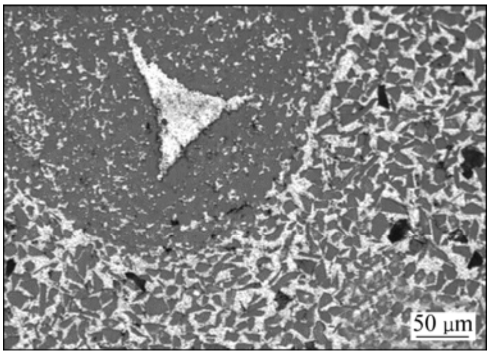

Fig.2 Morphology of hybrid composites

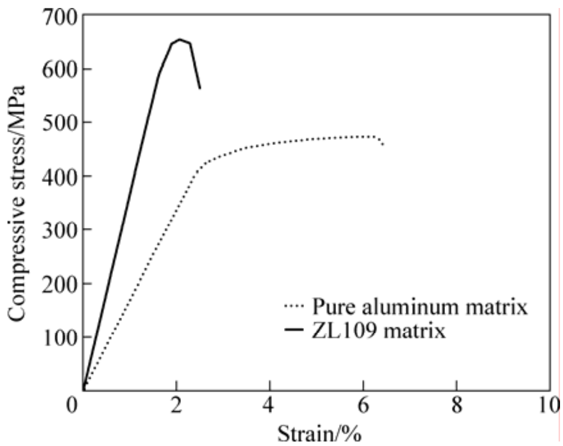

Fig.3 Relationship between stress and strain for composites reinforced by different matrix

Furthermore, the compressive strength and the ductility of composites depend on the failure process. SiC foam, SiC particles and aluminum matrix can endure the compressive load at the same time when the SiC foam-SiC particles/Al hybrid double interpenetrating composites are compressed. The structural compressive load support ability of the reinforcements depends on their respective morphology. SiC particles which are dispersed in matrix have low ability of compressive load support for particles are discontinuous in the hybrid composites, which makes particles go with the soft matrix during the deformation of the composites [3]. The SiC foam reinforcement having three-dimensional structure cannot move with the aluminum matrix, so the SiC foam and aluminum matrix are the primary support elements in the composites. At the initial stages, when the compressive stress is below the material-dependent critical magnitude called yield strength, the composites behave elastically. The elastic modulus of composites with ZL109 aluminum silicon alloy matrix is higher than that of composites with pure aluminum matrix for the modulus of silicon alloy is higher than that of pure aluminum. The microcracks propagate in SiC ceramics firstly when the strain of the hybrid composites reaches the yield strain of SiC ceramics because of its low ductility. Moreover, there are many defects in the struts of SiC foam for the struts have large dimension and include many differently orientated SiC crystal and glass ceramics. So, the microcrack spreads in the struts of SiC foam. Both of SiC foam-SiC particles hybrid reinforced composites with pure aluminum and ZL109 aluminum silicon alloy matrix have approximate initial yield strain for the failure of SiC foam reinforcement dominates the behavior of the hybrid composites. In the course of the plastic deformation of the hybrid composites, the microcrack propagates, converges at the main crack and absorbs energy supplied by the external compressive load. The matrix infiltrating the micro-hole of the strut deflects the crack from a straight path, leading to a dramatic increase in crack length, which makes the fracture surface of the struts of SiC foam present many different ladder planes (Fig.4). At the same time, the aluminum matrix behind the advancing crack tip bridges the crack, tending to hold it closed. Then, the fracture surface area is increased, the energy absorption and the ductility of composites become much greater. When the

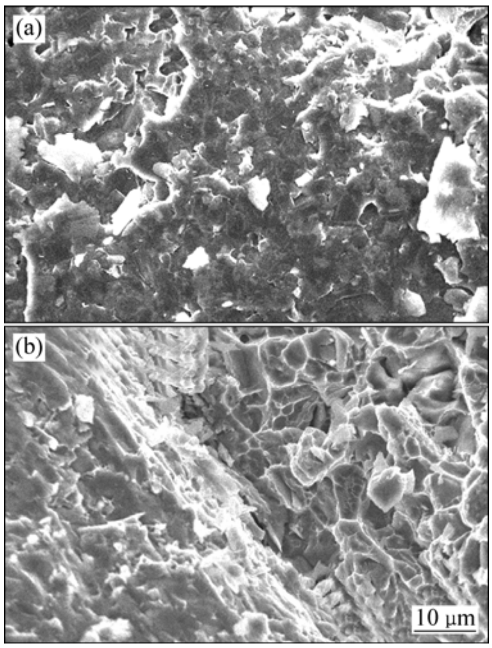

Fig.4 Fractographs of SiC foam-SiC particles/Al hybrid composites: (a) Foam strut; (b) Interface

main crack spreads into the interface between the strut and the matrix in the foam cell, the main crack overspreads into the matrix in the cell instead of along the surface of the struts for the interface bond is good.

For a given content of the constituent phases, the compressive strength of composites varies significantly depending on the continuity of brittle ceramic phase. For the brittle ceramic phase, less compliant phase is continuous, and the deformation of metal phase is constrained because the ductile metal phase surrounded by less compliant phase has low elastic modulus. Thereby, as the hybrid composites are compressed, the restriction of SiC foam reinforcement on aluminum matrix in the hybrid composite is much stronger than that of discrete particles on matrix in particles reinforced composites, and the compressive strength of the hybrid composites is higher compared with traditional particles reinforced composites. Therefore, the role of phase morphology in determining the compressive strength of the hybrid composites is important.

Fig.5 shows the fractographs of SiC particles reinforcement and matrix. It is found that SiC particles and the matrix have good interface bond because little primary surface of SiC particles can be observed. Many dimples which contact with the ductile fracture of the matrix are found from the fracture surface of composites with pure aluminum, as seen in Fig.5(a). Thereby, the pure aluminum matrix undergoes a number of deformations when the hybrid composites fail. But on the fracture surface of the composite with ZL109 matrix, the characteristics of the tough fracture cannot be observed obviously for the matrix is brittle, as shown in Fig.5(b). The results show that the ductile matrix can resist the failure of the composites, but the brittle matrix and SiC ceramic reinforcement fracture simultaneously when the composites fail. The ductile matrix resists the propagation of the microcracks in the struts. During the microcrack propagation process, the energy is absorbed by the ductile matrix by the means of deflecting the cracks from a straight path, leading to a dramatic increase in crack length. At the same time, the ductile matrix behind the advancing crack tip bridges the crack, tending to hold it closed. Then, the fracture surface area is increased and energy absorption becomes much greater, which in turn increases the ductility of the hybrid composites. So, the hybrid composites with pure aluminum matrix are more ductile than the composites with the brittle ZL109 aluminum matrix.

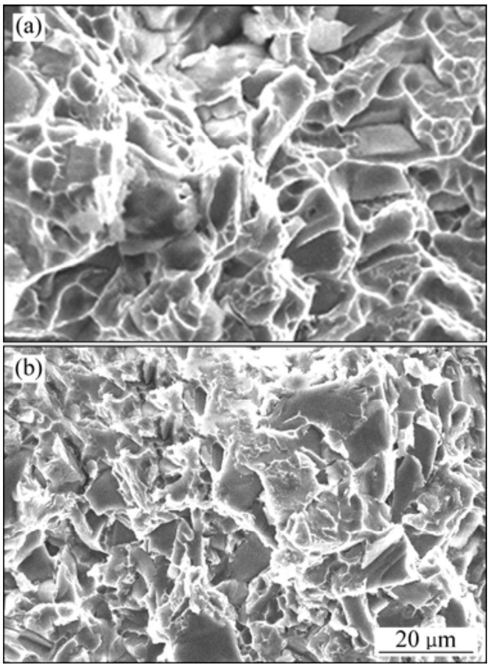

Fig.5 Fractographs of SiC particle and matrix in composites with different matrix: (a) Pure aluminum; (b) Aluminum silicon alloy ZL109

4 Conclusions

1) The hybrid SiC foam-SiC particles/Al composites with special double interpenetrating structure are fabricated by the squeeze casting technology. The compressive strength is 660 MPa, which is much higher than that of the traditional composite reinforced by SiC particles.

2) With the increase of the ductility of matrix, the ductility of the hybrid composites is increased, while the compressive strength and modulus are decreased. The ductile matrix resists the propagation of the microcracks in the struts by the way of energy absorption and microcrack deflection, which increases the plasticity of the composites.

3) The interface bond in the hybrid composites is good for the hybrid composites have the unique double interpenetrating structure.

References

[1] WANG Li-dong, FEI Wei-dong, JIANG Lu-sheng, YAO Chong-kai. New aluminum matrix composite with much lower coefficient of thermal expansion and higher strength [J]. J Mater Sci Lett, 2002, 21(9): 737−738.

[2] KWON S J，GOO B C. A study on the friction and wear characteristics of brake pads for A1 MMC brake disc [J]. Key Eng Mat, 2000, 183(1): 1225−1229.

[3] XU Xiao-jing, CHEN Kan-min, DAI Feng-ze, CAI Lan. Investigation on superplasticity of SiC particulate reinforced aluminum matrix composite [J]. Acta Metall Sina, 2002, 38(5): 544−548.

[4] BIERMANN H, KEMNITZER M, HARTMANN O M. On the temperature dependence of the fatigue and damage behavior of a particulate-reinforced metal-matrix composite [J]. Sci Eng A-Struct, 2001, 319: 671−678.

[5] ZHANG Qiang, CHEN Guo-qin, WU Guo-hui, XIU Zi-yang, LUAN Bo-feng. Property characteristics of a AlNp/Al composite fabricated by squeeze casting technology [J]. Materials Letters, 2003, 57: 1453−1458.

[6] ALPAS A T, ZHANG J. Wear rate transition in cast aluminum

silicon alloys reinforced with SiC particles [J]. Script Metall, 1992, 26: 505−509.
[7] ALLPAS A T, ZHANG J. Wear regimes and transitions in Al_2O_3 particulate reinforced alum inum alloys [J]. Mater Sci Eng A, 1993, A181: 273−279.
[8] PRAMILA B N, RAMASESLI B S, SURAPPA M K. Dry sliding wear of A356−A1−SiC_p composites [J]. Wear, 1992, 157: 295−299.
[9] WILSON S, ALPAS A T. Effect of temperature on the sliding wear performance of Al alloys and A1 matrix composites [J]. Wear, 1996, 198: 270−278.
[10] MISEREZ A, MÜLLER R, ROSSOLL A, MISEREZ A, MÜLLER R, ROSSOLL A, WEBER L, MORTENSEN A. Particle reinforced metals of high ceramic content [J]. Mater Sci and Eng A, 2004, A387−389: 822−831.
[11] CLARKE D R. Interpenetrating phase composites [J]. J Am Ceram Soc, 1992, 4: 739−759.
[12] DAEHN G S, STARCK B, XU L, ELFISHAWY K F, RINGNALDA J, FRASER H L. Elastic and plastic behavior of a co-continuous alumina/aluminum composite [J]. Acta Mater, 1996, 1: 249−455.
[13] ZHAO Long-zhi, ZHAO Ming-juan, CAO Xiao-ming, ZHANG Jin-song. Thermal expansion of a novel hybrid SiC foam-SiC particles-Al composites [J]. Composites Science Technology, 2007, 67(15/16): 3404−3409.
[14] ZHAO Long-zhi, ZHAO Ming-juan, CAO Xiao-ming, ZHANG Jin-song. Investigation of thermal physical properties of the hybrid SiC foam /SiCp/Al composites [R]. MRS International Materials Research Conference. Chongqing, 2008, 6.
[15] ZHAO Long-zhi, ZHAO Ming-juan, CAO Xiao-ming, ZHANG Jin-song. Effect of SiC particles on mechanical properties of SiC foam-SiC particles/Al hybrid composites [C]. Innovation and Sustainability of Modern Railway Proceeding of ISMR’ 2008. Nanchang: China Railway Publishing House, 2008: 545−550.
[16] XING H W, CAO X M, HU W P, ZHAO L Z, ZHANG J S. Interfacial reactions in 3D-SiC network reinforced Cu-matrix composites prepared by squeeze casting [J]. Materials Letters, 2005, 59: 1563−1566.
[17] SCHWARTZWALDER K, SOMERS H, SOMERS A V. Method of making porous ceramic articles: US3090094 [P]. 1963−05−21.

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