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Interface and thermal expansion of carbon fiber reinforced aluminum matrix composites

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Abstract: Two kinds of unidirectional PAN M40 carbon fiber (55%, volume fraction) reinforced 6061Al and 5A06Al composites were fabricated by the squeeze-casting technology and their interface structure and thermal expansion properties were investigated. Results showed that the combination between aluminum alloy and fibers was well in two composites and interface reaction in M40/5A06Al composite was weaker than that in M40/6061Al composite. Coefficients of thermal expansion (CTE) of M40/Al composites varied approximately from $(1.45-2.68)\times10^{-6}$ K^{-1} to $(0.35-1.44)\times10^{-6}$ K^{-1} between 20 °C and 450 °C, and decreased slowly with the increase of temperature. In addition, the CTE of M40/6061Al composite was lower than that of M40/5A06Al composite. It was observed that fibers were protruded significantly from the matrix after thermal expansion, which demonstrated the existence of interface sliding between fiber and matrix during the thermal expansion. It was believed that weak interfacial reaction resulted in a higher CTE. It was found that the experimental CTEs were closer to the predicted values by Schapery model.
Key words: aluminum matrix composites; thermal expansion; coefficient of thermal expansion; interface

1 Introduction

Carbon fiber reinforced aluminum matrix composites have high specific strength, high specific stiffness, high thermal conductivity and low coefficient of thermal expansion (CTE)[1−3]. The CTEs of high modulus fiber reinforced metal matrix composites are theoretically near to zero, which may satisfy demands of space structure components, such as antenna boom for the Hubble space telescope[4]. Understanding the thermal expansion behavior of composites is desirable not only for the fundamental knowledge required in developing new materials, but also for the practical purpose of predicting the properties of composites.

The thermal expansion behavior of continuous fibers reinforced metal matrix composites is influenced by many factors, including properties of the matrix and fibers, content and arrangement of fibers, interfacial properties, and thermal stress due to the mismatch of the CTE between the fibers and matrix and so on[5−7]. Interface plays an important role in the load transfer and stress relaxation. Due to the fall of the interfacial bonding strength and the increase of thermal stress along the fibers direction with the increase of temperature, sliding or debonding occurs at interfaces. All of these will affect the restriction of fibers on the matrix and lead to the change of CTEs as temperature varies[8−9].

At present, carbon fiber reinforced aluminum matrix composites have been wildly investigated[1−3]. However, most researches of the composites are still focused on mechanical properties and only a few investigations on thermal expansion behavior are reported[10]. Moreover, the thermal expansion behaviors are also affected by the interface. Therefore, in this work, a research on interface and thermal expansion behaviors of C_f/Al composites was carried out. Two kinds of unidirectional PAN M40 carbon fiber (55%, volume fraction) reinforced 6061Al and 5A06Al composites were fabricated by the squeeze-casting technology, and their interface structure and thermal expansion properties were investigated.

2 Experimental

2.1 Materials

Unidirectional M40 fibers (55%, volume fraction) reinforced aluminum matrix composites were prepared by squeeze casting method. 6061Al and 5A06Al were used

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as matrix alloys. The chemical compositions of two alloys are listed in Table 1. The basic properties of M40 fibers and matrix alloys are listed in Table 2. The composites were annealed at 330 °C for 0.5 h.

Table 1 Chemical compositions of aluminum alloy (mass fraction, %)

Alloy	Cu	Mg	Mn	Fe	Si
6061	0.43	0.75	0.22	0.36	1.26
5A06	−	5.8−6.8	0.5−0.8	−	−

Alloy	Zn	Ti	Cr	Al
6061	<0.15	<0.05	0.04	Bal.
5A06	−	0.02−0.1	−	Bal.

Table 2 Properties of carbon fiber and aluminum alloy

Material	Density/ $(g{\cdot}cm^{-3})$	Tensile strength/MPa	Elastic modulus/ GPa	Longitudinal CTE/$(10^{-6}\ K^{-1})$
M40	1.76	4 410	377	−1.2
6061	2.70	125	71	23
5A06	2.64	314	66.7	24.7

2.2 Testing

The morphology of composites was observed by ZEISS 40MAT optic microscopy and S−4700 scanning electron microscopy (SEM). The interface characteristics of the composites were investigated by PhilipsCM−12 transmission electron microscopy (TEM). The CTE measurement was carried out on a Dilatometer 402C. The diameter of cylinder sample was 4 mm and the length was 25 mm. During the CTE measurement, the sample was heated from 20 °C to 450 °C with a rate of 5 °C/min. The helium atmosphere was maintained at a flow rate of 50 mL/min to ensure the equilibrium of temperature and prevent the oxidation of samples.

3 Result and discussion

3.1 Microstructure of M40/Al composites

The fiber volume fractions of M40/6061Al composite and M40/5A06Al composite were both evaluated and found to be about 55%. Fig.1 shows typical optical micrographs of as-cast C_f/Al composites. As shown in Fig.1, the two composites were free of common cast defects, such as porosity and shrinking cavities. The carbon fibers were distributed relatively uniformly in the aluminum matrix, indicating that composites were dense and macroscopically homogeneous.

It is well established that the properties of composite are associated with its matrix, reinforcement

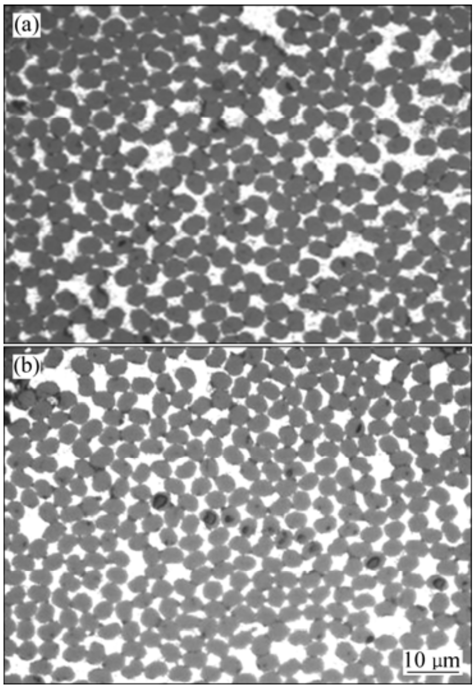

Fig.1 Optical microstructures of C_f/Al composites: (a) M40/6061Al; (b) M40/5A06Al

and especially the interface. Efficient load transferring to reinforcement or not is dependent on the nature of the interface between the matrix and the reinforcement. Fig.2 gives the interface of M40/6061Al composite and M40/5A06Al composite. The combination between Al alloy and fibers was well and no interfacial debonding was observed in two composites by TEM observation. It should be noted that discontinuous needle-shaped aluminum carbide phases (Al_4C_3) were evident at the interface, which resulted from the reaction between carbon fiber and aluminum. Fortunately, interfacial reactant can improve the interfacial bonding and then impose high mechanical restraint on matrix thermal expansion[11]. There appeared large amounts of Al_4C_3 at the fiber/matrix interfaces in M40/6061Al composite, which were 300−500 nm long and 20−50 nm wide, as shown in Fig.2(a). In the M40/5A06Al composite, as shown in Fig.2(b), only a very small amount of Al_4C_3 phases were found, which were about 50 nm long and 10 nm wide, and their amounts and sizes were less than those in M40/5A06Al. This means that interface reaction in M40/6061Al composite is stronger than that in M40/5A06Al composite. Generally, a weak reaction between fibers and aluminum results in weak bonding at their interfaces, so interface bonding in M40/5A06Al composite should be weaker than that in M40/6061Al composite. The variation of interface bonding in the composites could affect their thermal expansion behavior.

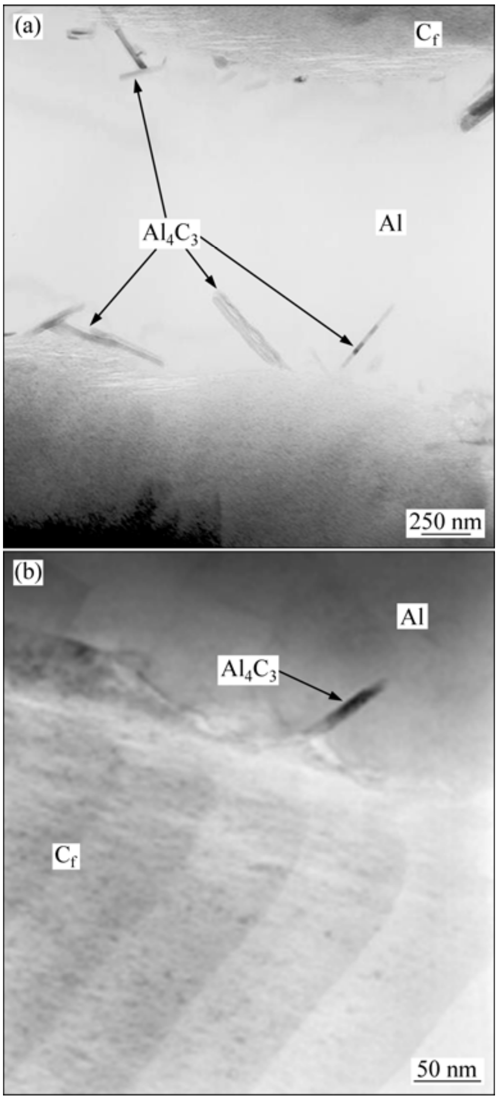

Fig.2 TEM images at interfaces of C_f/Al composites: (a) M40/6061Al; (b) M40/5A06Al

3.2 Thermal expansion behavior of M40/Al composites

Fig.3 shows CTE vs temperature curves of annealed M40/6061Al composite, annealed M40/5A06Al composite and as-cast M40/6061Al composite. The CTEs of composites were $(0.3-2.7)\times10^{-6}$ K^{-1}, which were much lower than that of the aluminum alloy $(23-25)\times10^{-6}$ K^{-1} in the same condition. This should be due to the mechanical restraint imposed by fibers on the thermal expansion of the aluminum alloy[12]. As shown in Fig.3, the CTEs of three composites varied approximately from $(1.45-2.68)\times10^{-6}$ K^{-1} to $(0.35-1.44)\times10^{-6}$ K^{-1} between 20 °C and 450 °C, and decreased slowly with the increase of temperature. The CTE of M40/6061Al composite was lower than that of M40/5A06Al composite and CTE of M40/6061Al composite decreased slightly after annealing.

As it is known, the thermal expansion behavior of

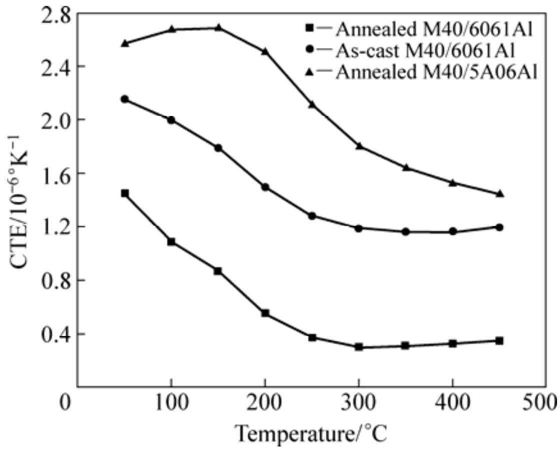

Fig.3 Temperature dependence of CTEs for M40/6061Al composite and M40/5A06Al composite

C_f/Al composite is determined by the thermal expansion of aluminum matrix and the restriction of carbon fiber through interfaces. Therefore, interface has an important influence on thermal expansion behavior of Cf/Al composites. In order to verify the function of interface to thermal expansion behaviors of the composites, surface of sample after thermal expansion test was observed. As presented in Fig.4, fibers were protruded significantly from the matrix. This demonstrated that interface sliding existed at the interface between fiber and matrix during the thermal expansion[13−14]. It is believed that low interfacial sliding resistance reduces the restriction of carbon fibers on the matrix during thermal expansion. As shown in Fig.3, interface reaction in M40/5A06Al composite is weaker than that in M40/6061Al composite. A weaker reaction between the fiber and matrix results in lower interfacial resistance. Therefore, weak interfacial reaction reduces the restriction of carbon fibers on the matrix. In such condition, thermal strain of composites is mainly dominated by free expansion of aluminum alloy matrix. CTE of 6061Al alloy is slightly lower than that of 5A06Al alloy. Therefore, M40/6061Al composite has a lower CTE than M40/5A06Al composite.

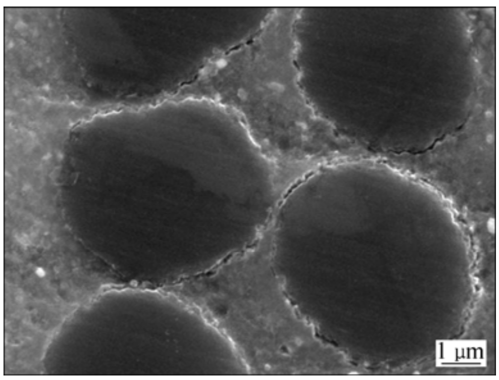

Fig.4 Fibers protruding significantly from matrix after thermal expansion

It is considered that annealing treatment can effectively relieve thermal mismatch stress at interface and reduce residual tensile stress in aluminum matrix. Reliving of thermal mismatch stress at interface means that the restriction of carbon fibers on the matrix is reduced. Meanwhile, reducing the residual tensile stress in aluminum matrix results in the fact that thermal expansion of aluminum matrix is inhibited. Under role of these two factors, CTE of composite decreased after annealing. Therefore, annealing treatment led to decline in CTE of composites. So, CTE of M40/5A06Al composite became lower after annealing.

Many models, such as ROM, Turner and Schapery model, are usually employed in the field of prediction of the thermal expansion for unidirectional fiber reinforced composites[15−16]. Without the consideration of stress transfer at interfaces, the CTE of fiber reinforced composites can be simply predicted by the ROM. However, for more precise predictions in usual cases, the stress interaction at the interfaces may not be neglected and ROM is thus no longer valid. The hydrostatic pressure assumption is adopted and the residual stress generated during composite fabricating is neglected in Turner model. Thus, the real stress of composites cannot be precisely predicted by Turner model. Based on energy considerations, Schapery model considers the stress interaction between fiber and matrix, and it is usually in a good accordance with experiments. When matrix alloy in composite is in the elastic stage, Schapery model may be expressed as

$$\alpha_{\mathrm{c}}=\frac{\varphi_{\mathrm{f}}E_{\mathrm{f}}\alpha_{\mathrm{f}}+\varphi_{\mathrm{m}}E_{\mathrm{m}}\alpha_{\mathrm{m}}}{\varphi_{\mathrm{f}}E_{\mathrm{f}}+\varphi_{\mathrm{m}}E_{\mathrm{m}}} \tag{1}$$

where α, φ and E are referred to the CTE, the volume fraction and the elastic modulus, respectively. The properties of the composite, fiber and matrix are denoted by c, f and m subscripts, respectively.

In this work, CTE and elastic modulus of M40 fiber are -1.2×10^{-6} K^{-1} and 377 GPa, respectively, and 23×10^{-6} K^{-1}, 24.7×10^{-6} K^{-1} and 71 GPa, 66.7 GPa for 6061Al and 5A06 matrix alloy, respectively. Theoretical CTE of M40/6061Al composite and M40/5A06Al composite calculated by Eq.(1) are 2.12×10^{-6} K^{-1} and 2.16×10^{-6} K^{-1}, respectively which are in a good accordance with experiment (1.09×10^{-6} K^{-1} and 2.68×10^{-6} K^{-1} at 20−100 °C).

4 Conclusions

1) The combination between aluminum alloy and fibers was well in two composites, and interface reaction was weaker in M40/5A06Al composite than that in M40/6061Al composite.

2) CTE of unidirectional M40/Al composites varied approximately from $(1.45-2.68)\times10^{-6}$ K^{-1} to $(0.35-1.44)\times10^{-6}$ K^{-1} between 20 °C and 450 °C, which were in a good accordance with Schapery model.

3) Weak interfacial reaction reduced the restriction of carbon fibers on the matrix, in the lower CTE of composite with high reaction than with low reaction.

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