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The mechanical properties and thermal conductivity of carbon/carbon composites with the fiber/matrix interface modified by silicon carbide nanofibers

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ABSTRACT

For modification, silicon carbide nanofibers (SiCNFs) are uniformly dispersed on the fiber surface of the unidirectional carbon preform. The modified unidirectional carbon preform was then densified to obtain SiCNF–C/C composites by chemical vapor deposition (CVD). The microstructure of SiCNF–C/C composites was investigated. The mechanical properties and thermal conductivity of the modified composites were analyzed as well. Results show that PyC preferentially deposits on the surface of SiCNFs with high degree of order. The interface between carbon fibers and matrix has high texture, resulting in a good bonding between them. The mechanical properties of C/C composites are adjusted. After modification, the fracture mode is changed and the flexural strength is enhanced, especially in vertical direction. The thermal conductivity of modified composites is also enhanced in both vertical and parallel directions.

1. Introduction

Because of the excellent properties such as low density, high specific strength and modulus, high rupture toughness, good thermal shock resistance, high heat of ablation, chemical inertness [1–3], carbon fiber reinforced carbon (C/C) composites have been successfully used in the fields of aviation, aerospace, nuclear power, medicine and so on.

As we all know, the mechanical and thermal properties are the key performance indicators in the field of high-temperature structure materials [4,5]. As for C/C composites, the mechanical and thermal properties mainly depend on the microstructure of the carbon structure. Interface is the transfer bridge, through which load and heat can be transferred in the composites [6]. So the microstate of interface between carbon fibers and matrix has intrinsic correlation with the properties of C/C composites. In recent years, numerous investigations have been carried out to modify the fiber/matrix interface in order to obtain high performance C/C composites.

As quasi-one-dimensional materials with a special structure, carbon nanofibers (CNFs) are widely used in C/C composites for interface modification [7,8]. After being modified by CNFs, the interface microstructure is adjusted and the properties of C/C composites are enhanced [9,10]. Silicon carbide nanofibers (SiCNFs) are the products of extreme anisotropic growth of SiC crystals. SiCNF is the single crystalline component and has less structural defects. Therefore SiCNFs have high tensile strength, high resistance to corrosion and excellent oxidation resistance [11–13]. In this study, SiCNFs were dispersed on fiber surface of the unidirectional carbon preform uniformly. The preform containing SiCNFs was densified by chemical vapor deposition (CVD) to get SiCNF–C/C composites. The structure of fiber/matrix interface was deeply observed and analyzed. The mechanical properties and thermal conductivity of the modified composites were investigated. The modification mechanism of SiCNFs was thoroughly discussed.

2. Experimental

2.1. Preparation of samples

Unidirectional carbon preforms were made from T300 polyacrylonitrile-based (PAN) carbon fiber. The purified SiCNFs used were obtained from Chengdu Organic Chemicals Co. Ltd., Chinese Academy of Science.

The unidirectional carbon fabrics were soaked in acetone for 24 h and then washed repeatedly in deionizer water. This process can remove the sizing agent and other adsorbents on the fiber surface. A mixed solution containing epoxy, alcohol and SiCNFs was prepared, with the mass ratio of 25:25:0.5. The mixed solution was stirred constantly in a water bath at 70 °C to obtain a homogeneous solution. Each carbon cloth was immersed in the mixed solution for 10 min and then dried at room temperature. So SiCNFs uniformly covered on each fiber surface. Next, the carbon fabrics covered with SiCNFs were stacked in the same direction to get the unidirectional carbon preform with fiber content of 32%. CVD was applied to densify the preform to obtain the

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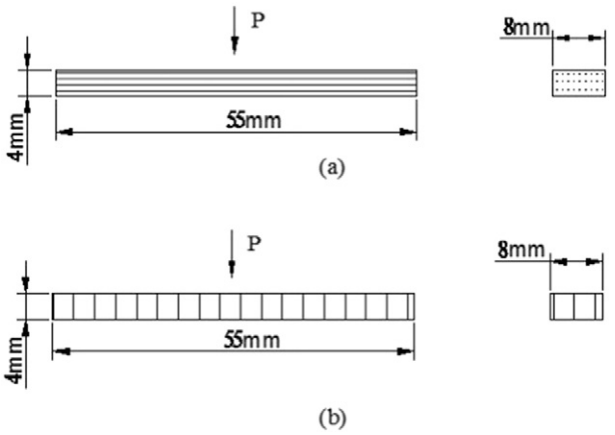

Fig. 1. Flexural test geometry (a) vertical direction; (b) parallel direction.

modified composite (SiCNFs–C/C composite). For the purpose of comparison, a unidirectional C/C composite with the same preform structure was prepared. Finally, the two composites were heated at 2300 °C.

2.2. Characterization

The bulk density of the composites was measured by the Archimedes water immersion method analyzer at room temperature. The structure of SiCNF was observed by transmission electron microscope (TEM). The surface structure of carbon fibers was examined using scanning electron microscope (SEM). The morphology and microstructure of PyC and fiber/matrix interface were studied by polarized light microscopy (PLM) and Raman spectroscopy. The fracture surface was analyzed by SEM.

Flexural testing was performed on a universal testing machine (CSS-44100) equipped with a flexural test fixture, using the three-point bend configuration. A span-to-depth ratio of 10:1 and crosshead speed of 0.5 mm/min were used. Specimens for mechanical testing were machined from composites in a dimension of 55 mm × 10 mm × 4 mm. The cutting direction was divided to the parallel direction and the vertical direction (as shown in Fig. 1).

The thermal conductivity of composites was calculated by the formula:

$$\lambda = 418.68 a c_p d$$

where λ is thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$), a is thermal diffusivity (m^2/s), c_p is specific heat ($J/(kg \cdot K)$) and d is the density of the composite (g/cm^3). Thermal diffusivity, a, was measured by laser flash method on JR-1 type synthetic thermal tester. c_p of carbon materials is 0.171 $J/(kg \cdot K)$ at room temperature. The detection was also divided to the parallel direction and the vertical direction.

3. Results and discussion

3.1. Microstructure of composites

Fig. 2 shows the images of SiCNFs and the carbon fibers which are being covered by SiCNFs. It can be seen from Fig. 2(a) that the diameter of SiCNFs is 80–100 nm and the length is 10–30 um. After surface treatment, SiCNFs have uniformly covered on the surface of the carbon fibers, as shown in Fig. 2(b).

The polished transverse sections of the C/C and SiCNFs–C/C composite viewed by polarized-light microscopy are shown in Fig. 3. For C/C composites, PyC around carbon fibers is in the shape of circular shell and has some homocentric annular cracks, which belongs to the typical smooth laminar (SL) PyC [14]. The interface between SL PyC and carbon fibers is loose with cracks, as shown in Fig. 3(a). For SiCNFs–C/C composites, PyC around carbon fibers has a strong optical reflectivity. The interface between carbon fibers and PyC has a layer of tiny granular PyC. Hydrocarbon gases deposit around this layer of granular PyC with significant growth cone, as in Fig. 3(b). Further observation shows that this layer of tiny particles is PyC with SiCNFs being wrapped inside. Hydrocarbon gases firstly deposit around SiCNFs during CVD. So the coarse conical appears, as shown in Fig. 3(c). These characteristics belong to the rough laminar (RL) PyC with high texture [14]. The fiber/matrix interface is tight and jagged in SiCNFs–C/C composites. Therefore, SiCNFs on carbon fibers have interposed the deposition of PyC.

For further understanding of the microstructure of fiber/matrix interface, Raman spectra were also introduced. There are two main bands in Raman spectra of carbon materials. One is at about 1580 cm^{-1} (G band) corresponding to graphitic in-plane vibration with E_{2g} symmetry and characterizing for the integrality of SP2 hybrid orbital structure. The other is at 1330 cm^{-1} (D band) corresponding to the defect lattice vibration. The reciprocal of G and D band intensity ratio, 1/R, is proportional to graphitization degree [15,16]. The detection points are collected from the skin region of fiber, fiber/PyC interface and PyC, as shown in Fig. 4.

Table 1 shows the 1/R values of two composites at different locations. It can be seen that 1/R value of SiCNF–C/C composites is much higher than that of C/C composites at corresponding locations. It also

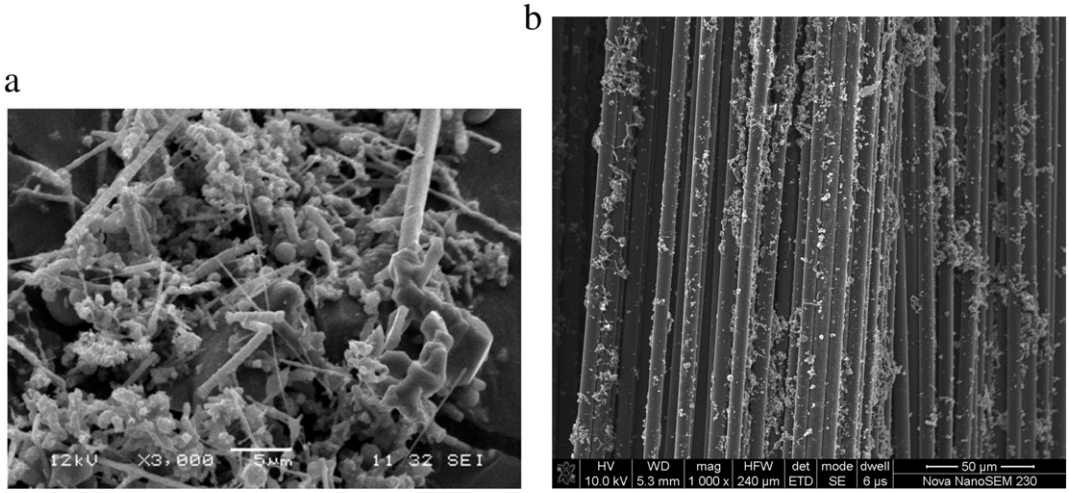

Fig. 2. SEM images of SiCNFs and the carbon fibers covering with SiCNFs (a) SiCNFs (b) Carbon fibers covered by SiCNFs.