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High temperature compression properties and failure mechanism of 3D needle-punched carbon/carbon composites

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ABSTRACT

This paper reports the high temperature compression properties and failure mechanism of 3D needle-punched C/C composites. The results show that the stress–strain curves show non-linear and plasticity failure feature after 600 °C. The compression properties decrease significantly with increasing the temperature due to material oxidation. The composite exhibits shear fracture at the angle of 45°. The major damage patterns are the tearing of 90° oriented fibers and shear failure of 0° oriented fibers on the shear surface. After 600 °C, the local and plastic failure feature becomes more obvious. The composite is oxidized obviously and fiber/matrix interfacial adhesion is decreased significantly.

1. Introduction

3D needle-punched structure is produced from woven fabrics and non-woven webs by the through-thickness needling technique, having an advantageous combination of high interlaminar properties and low cost processing. 3D needle-punched carbon/carbon (C/C) composites are obtained from the carbon fiber perform by the method of infiltration, with low density and excellent high-temperature mechanical properties. In recent years, the use of 3D needle-punched C/C composites is growing rapidly in aircraft, automobiles, marines and other complex high-temperature structural components [1–3].

Much effort has been spent on performance characterization of 3D needle-punched carbon/carbon composites. For example, Li et al. [4] showed that the C/C composite produced from chopped fibers/resin carbon had the low tensile strength due to its poor microstructure and the strong interfacial bonding between resin carbon and carbon fibers. Zhang et al. [5] conducted thorough research on compressive fracture behavior of 3D needle-punched C/C composites. Their results showed that the transverse and longitudinal compressive strength of composites with dual matrix are bigger than that with single matrix. Failure modes of composites under transverse and longitudinal compressive loading were shear and extension, respectively. Cai et al. [6] studied the bending properties of 3D needled C/C composites and their results showed that the flexure strength of composites was 98 MPa. Cao et al. [7] studied the flexural behaviors of needled C/C composites before and after heat-treatment, and discussed the fracture mechanism. Chen et al. [8] studied the influence of needle-punched felt structure on the flexural properties of C/C composites. The results indicated that flexural strength and modulus increased when mass ratio of non-woven cloth to short-cut fiber web changed from 7:3 to 6:4. Luo et al. [9] showed that the composites behaved in obvious pseudo-plastic fracture, and the composite with plain cloth structure possessed the highest flexural strength. Nie, et al. [10] investigated the ablative properties of 3D needled C/C–SiC composites and showed that various ablation processes including sublimation, thermo-chemical denudation, and oxidations occurred in different sections. In addition, Mouritz, et al. [11–15] thoroughly investigated the properties of 3D z-pinned composites including modeling of the internal geometry, characterization of mechanical properties, damage development and failure mechanisms during static and dynamic testing. However, little work has

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been done on the high temperature mechanical properties and the understanding of the failure mechanism of 3D needle-punched C/C composites.

It is valuable to study the high temperature properties and failure mechanism of 3D needle-punched C/C composite, because of its wide potential applications in engineering, especially in aerospace structures. For example, the composite structures for space shuttles or hypersonic aircrafts in flight may be exposed to high temperature up to 900 °C. Some researchers [16–18] found that changes in the interior structure and mechanical response of composite materials may occur under such high temperature conditions. Therefore, a full understanding of their mechanical properties under coupling conditions of mechanical loading and elevated temperatures is important to the safety and reliability of composite structures.

This paper presents an experimental study on the high temperature compression properties of 3D needle-punched C/C composites. The damage and fracture morphology of composites after failure are observed from the macroscopic and microscopic views and the failure mechanism is demonstrated. Furthermore, the influences of the testing temperature on the compression properties and failure mechanism are also analyzed. The aim of our study is to establish the database and provide an experimental basis for the potential applications of 3D needle-punched C/C composites at high temperatures.

2. Materials and samples

3D needle-punched preform was prepared using T700, 12 K carbon fiber non-woven cloths (450 g/m^2) and fiber web (50 g/m^2) as the feed stocks by lamination and punching processes in the through-thickness direction. The density of the preform is about 1.15 g/cm^3.

3D needle-punched performs were firstly heat-treated at 2000 °C for 2 h, and then densified by chemical vapor deposition (CVD) at the temperature of 1300 °C under the pressure of 1 kPa. Natural gas was used as pyrocarbon precursor and H_2 was adopted as carrier and diluent gas. The density of the obtained 3D needle-punched C/C composites is 1.72 g/cm^3. The composites are then cut as rectangle shapes for compression tests at different high temperatures. As shown in Fig. 1, the dimensions of the tested samples are 8 mm (length) × 8.0 mm (width) × 12.0 mm (thickness) and the detail specifications of the tested samples are summarized in Table 1.

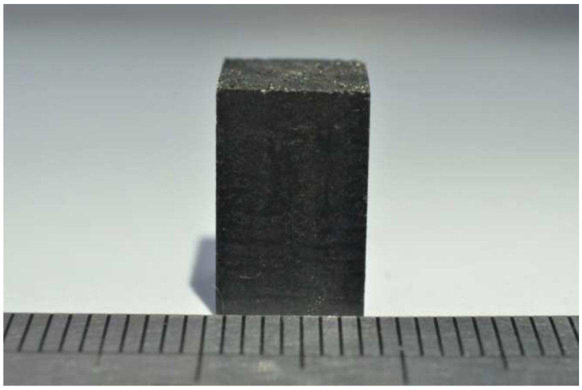

Fig. 1. The compression sample.

Table 1
Details of compression samples.

Sample no.	Test temperature (°C)	Length (mm)	Width (mm)	Height (mm)	Weight (g)	Density (g/cm^3)
HC1	25	8.00	7.76	11.87	1.2566	1.705
HC2	300	7.94	7.79	12.74	1.3487	1.711
HC3	600	8.03	8.00	12.62	1.3939	1.719
HC4	700	7.99	7.97	12.40	1.3630	1.726
HC5	800	7.99	7.86	12.00	1.2944	1.716
HC6	950	8.02	7.92	12.50	1.3716	1.727

3. Experimental procedure

Since there are no standards of compression test for the 3D needle-punched C/C composites at high temperature (especially up to the 950 °C), the sample configuration and test procedure were followed by the Chinese HB 7571-1997 and ASTM E209 regarding metal materials. The compression tests at six different temperatures (25 °C, 300 °C, 600 °C, 700 °C, 800 °C, 950 °C) were conducted on a high-temperature electronic testing machine (WDW-100). The composite was compressed in the longitudinal direction at different temperatures. At high temperatures, a box high temperature furnace (GWX-1200) and a guarded hot ceramic fixture have been developed by modifying the one specified at room temperature so that the new devices can be used under high temperature conditions. The furnace was controlled by the GWX-1200B control cabinet and heated by resistance wire to ensure the high temperature environments during all experiments. The temperature raises at a rate of 3 °C per min. When the temperature reached the preset value, kept the warm for 30 min and then measured the high-temperature compression properties of composites. The deformation was measured by an extensometer directly fixed on the top of the connecting rod of the fixture. The experimental results obtained were deemed accurate and reliable as there was no deformation for the ceramic fixture. Observed through the window on the furnace, the damage evolution and failure of composites could be caught in the process of the experiment. The crosshead speed was set at 0.5 mm/min. The applied load was released to zero after the test force reach to 30 kN or the sample fractures totally. During the measurements, the load and deformation for all samples were automatically logged by computer. At least three samples were tested at each temperature level and the average values of the experimental results were obtained. The experimental procedure is shown schematically in Fig. 2.

4. Results and discussion

4.1. Typical stress–strain curves at different high temperatures

Fig. 3 shows the stress vs. strain curves of composites tested at 25 °C, 300 °C, 600 °C, 700 °C, 800 °C, and 950 °C, respectively. It can be found that the temperature have significant impact on the stress vs. strain response. The curves go down gradually with the increase of the testing temperature and the peak stress declines one by one. All the curves increase linearly at the initial stage, but with different slopes. In a certain stress, the curves transit to nonlinear stage, indicating the damage and internal cracks of composites are expanding slowly. At room temperature (25 °C), the materials behave almost in a linear manner up to failure and have no clear yielding in the whole loading process. At 300 °C, the slope of the curves reduces significantly due to the performance degradation of the matrix carbon. When the curves attain the peak stress, the curve declines rapidly and the material also shows clear brittle failure feature. At 600 °C, the curves keep the same trend as those in 25 °C and 300 °C. However, due to the oxidation of