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Effect of ratio of non-woven cloth to short-cut fiber web of the preform on the flexural properties of C/C composites

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ABSTRACT

The effect of mass ratio of non-woven cloth to short-cut fiber web of needle-punched felt on the flexural properties of C/C composites was investigated. Results show that the flexural strength and modulus increase when the ratio of non-woven cloth to short-cut fiber web change from 7:3 to 6:4, and then decrease when the ratio of non-woven cloth to short-cut fiber web change from 6:4 through 5:5 to full short-cut fiber web. It can be explained on the base of hybrid fiber composites theory. There exists “hybrid synergetic effect” in the C/C composites with needle-punched felt as preform, which results in higher strength of C/C composites only when an optimal mass ratio of non-woven cloth to short-cut fiber web was adopted.

1. Introduction

Carbon and graphite are attractive materials for use at elevated temperatures in inert atmosphere and ablative environments. With the enhancement of strength and modulus of carbon fiber, carbon fiber reinforced carbon matrix (C/C) composites have been developed greatly. The main aim of such materials is to combine the advantages of fiber-reinforced composites such as high specific strength, stiffness and in-plane toughness with the refractory properties of structural ceramics. The excellent retention of mechanical properties at high temperatures has resulted in the exploitation of C/C composites as structural materials in space vehicle heat shields, rocket nozzles and aircraft brakes [1]. However, the mechanical properties of C/C composites depend on the microstructure, architecture, surface treatment and volume fraction of fiber, microstructure of matrix carbon and interface between fiber and the surrounded carbon matrix, etc. [2–6]. Because the strength of C/C composites does not follow the simple law of mixture relationship and due to the twisting and distortion of carbon fibers, variations in fiber orientation, it is very difficult to evaluate the theoretical strength of the obtained C/C composites. As a result, only the trends can be obtained to describe the factors that influence the mechanical properties of C/C composites.

Needle-punched felts, which are composed of non-woven cloths and short-cut fiber webs, have been widely used as preforms of C/C composites. It was reported [7] that fiber type of non-woven cloth, mass ratio of non-woven cloth to short-cut web and unit thickness influence the flexural properties of C/C composites from pressure gradient chemical vapor infiltration (CVI). Unexpectedly, adjusting the mass ratio of non-woven cloth to short-cut web of integrated felt from 7:3 to 6:4 resulted in the increasing flexural strength and modulus of C/C composites. The present work aims to make clear the influence of mass of non-woven cloth to short-cut web on the mechanical properties of C/C composites.

2. Experimental

2.1. Material preparation

When producing needle-punched preforms, the mass ratio of non-woven cloth to short-cut web were adjusted from 7:3, 6:4, 5:5 and full short-cut fiber web. The size of the porous preforms is Ø200 mm × Ø35 mm × 25 mm. After pre-heat treatment, the preforms were densified to about 1.40 g/cm^3 by iso-thermal CVI technique with propylene as carbon source, and nitrogen as dilute and carrier gas at a certain temperature in the range of 900–1050 °C. Then, three periods of impregnation of phenolic resin and carbonisation were carried out till the density of samples was about 1.78 g/cm^3. After densification, all the samples were heat-treated at temperature of 2300 °C for 1 h.

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2.2. Testing methods

Three-point flexure test was carried out on a universal testing machine (CSS-44100) and the procedure was the same as in Ref. [7]. The size of the samples for flexural test is 55 mm × 10 mm × 5 mm. The span was 40 mm and ratio of span-to-thickness was 8:1 [7–9]. The number of effective specimens for each case is not less than five. The load-deflection curves were obtained by driving the crosshead at a speed of 1.5 mm/min and recording the load as a function of time. From these data, the curves relating the fracture stress to strain were obtained and the elastic moduli were calculated from the slope of the curves.

One fractured sample of every kind of C/C composites was chosen for scanning electron microscopic (SEM) investigation (Jeol JSM-5600 LV Scanning Electron Microscopy).

3. Results and discussion

The changes of flexural properties and modulus with the mass ratio of non-woven cloth to short-cut fiber web were shown in Fig. 1. It is found that the flexural strength and modulus increase when the mass ratio of non-woven cloth to short-cut fiber web change from 7:3 to 6:4. And then they decrease when the mass ratio of non-woven cloth to short-cut fiber web change from 6:4 through 5:5 to the full short-cut fiber web. This can be shown directly from the steepness of the line. However, the change of modulus is not so apparent in spite of a same trend. It can be concluded that there exists a proper mass ratio to obtain higher flexural strength and modulus, which is 6:4 in the present work.

From the presented loading-deflection curves in Fig. 2, they show evident step-like fracture for the samples with the mass ratio of 7:3 and 6:4, but it is much more continuous for the composite with its mass ratio of non-woven cloth to short-cut fiber web 5:5 and especially for the full short-cut web one. The SEM images in Fig. 3 show that there are fibers pulled-out from or debonding with the surrounded pyrolytic carbon as well as pyrolytic carbon fracturing in the samples with mass ratios of non-woven cloth to short-cut fiber web 7:3 (Fig. 3a and b) and 6:4 (Fig. 3c and d), which can absorb some energy when fracturing and leads to higher strength and toughness.

Needle-punched felt is made up of several layers of long-fiber non-woven cloth (Fig. 4(a)) and short-cut fiber web (Fig. 4(b)), which are stacked alternatively and were needle-punched to be an integral. With the introduction of "z-direction" fibers by needle-punching, it is much more effective for CVI processing due to the much more diffusion paths [10]. The strength of the non-woven cloth layer should be much higher than that of the short-cut fiber web layer with the same volume fraction due to less porosity and tight fiber in the former. As a result, the C/C composites with needle-punched felt as preforms can be named as "hybrid fiber composites" (as schemed in Fig. 5). When preparing needle-punched carbon fiber felts, it is necessary to have a suitable content of short-cut fiber web to act as the fiber source for needle-punching processing because it is very difficult for needle-punching and much more breakage would be made to the fibers if only the long fibers were used (the critical elongation of carbon fiber is only 1.5–2.1%). In the following, the influence of mass ratio of non-woven cloth to short-cut fiber web was analysed.

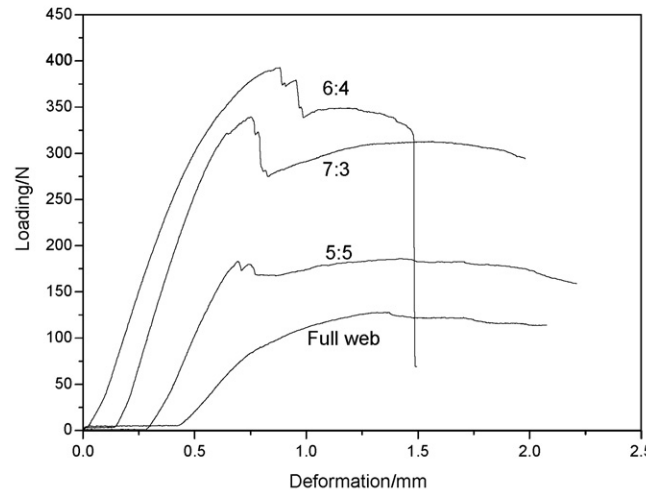

Fig. 2. The typical loading-deflection curve of the obtained C/C composites (the inserted values on the curves are the mass ratio of non-woven cloth to short-cut fiber web).

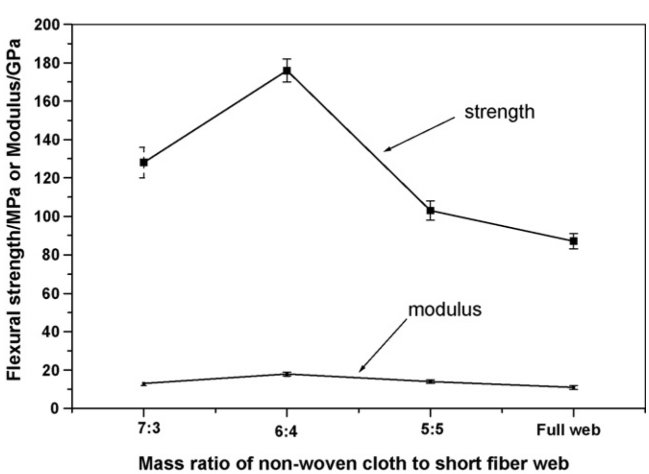

Fig. 1. The relationship of flexural strength and modulus with mass ratio of non-woven cloth to short-cut fiber web.

The strength and fracture strain of the non-woven cloth layer are σ_n and ε_n, respectively. The strength and fracture strain of short-cut fiber web are σ_w and ε_w, respectively (where $\sigma_w < \sigma_n$, $\varepsilon_w < \varepsilon_n$). V_n, V_w, V_m is the volume fraction of non-woven cloth layer, short-cut fiber web layer and carbon matrix, respectively. The strength of the matrix and the bulk C/C composites are σ_m and σ_c. In case of excellent interfacial bonding, the composites strength σ_c can be demonstrated by the equation:$\sigma_c = (1/2)\sigma_w V_w + \sigma_n V_n + \sigma_m V_m$ [11]. Due to the lower strength and fracture strain of the carbon matrix [10,12], the higher fraction of the non-woven cloth layer, the higher composites strength according to the above equation. But it is not the fact. Carbon matrix is the weakest part in the C/C composites, but here it should be the same in the non-woven cloth layer and short-cut fiber web layer. As a result, the effect of the matrix can be ignored. Much more attention should be paid to the non-woven cloth layer and short-cut fiber web layer. Relatively, the short-cut fiber web layer is much weaker. When the mass ratio of non-woven cloth layer is very high, i.e. the content of the short-cut fiber web is very low, the short-cut fiber web layer is easier to fracture, which cause the non-woven cloth layer to undergo most of the loading. Therefore $\sigma_c \approx \sigma_n V_n$. Because of higher mass percentage of non-woven cloth, it would be much more difficult for needle-punching and make much more breakage to the fiber, then a less strength value (σ_n') of the involved non-woven cloth. Therefore, the obtained flexural strength of the composites should be $\sigma_c \approx \sigma_n' V_n$, which is much lower. When the content of the short-cut fiber web is very