MECHANICAL PROPERTIES OF TRI-AXIALLY BRAIDED CARBON FIBER COMPOSITE —K. Ozawa, Y. Katoh, L.L. Snead, J.W. Klett (Oak Ridge National Laboratory), and W.E. Windes (Idaho National Laboratory)

OBJECTIVE

The main objective of this study is to investigate the axial and inter-laminar mechanical properties of the tri-axially braided carbon fiber composite.

SUMMARY

Tensile, inter-laminar shear and trans-thickness tensile properties of tri-axially braided carbon fiber-reinforced carbon matrix (C/C) composites were evaluated. The C/C composites exhibited the quasi-ductile behaviors with initial elastic behavior, second linear portion and non-linear region. Tensile properties of the C/C composites such as ultimate tensile strength, elastic tensile modulus, and proportional limit stress depended on the axial fiber volume fraction. Relatively low inter-laminar shear (2.2 MPa) and quite low trans-thickness tensile (0.7 MPa) strength obtained, which indicates the very weak strength of carbon matrix itself.

PROGRESS AND STATUS

Introduction

Carbon-based composites are promising materials for high heat flux applications in fusion plasma devices because of their high temperature mechanical properties, high thermal conductivity, superior thermal shock resistance, low activation properties, and maturity as industrial materials [1, 2]. Particularly, pitch-based continuous carbon fiber reinforced carbon matrix (C/C) composites are considered suitable for fusion applications due to their superior thermal conductivity and irradiation resistance compared with C/C composites using carbon fibers from other production routes [3]. Although properties of C/C composites have been most extensively studied among various ceramic matrix composites, they are in fact highly dependent on the fiber type, reinforcement architecture, and the matrix forming process. The primary purpose of this study is to investigate the axial and inter-laminar mechanical properties of pitch fiber, pitch matrix C/C composite in a tri-axially braided architecture.

Experimental Procedure

The C/C composite samples were fabricated in Oak Ridge National Laboratory. The reinforcement fiber was P-25 mesophase pitch carbon fiber manufactured by Amoco BP Chemical Co. Ltd. The fiber bundles were tri-axially braided with 0° and $\pm 55^o$ braiding angles. These fiber bundles were impregnated with A-240 petroleum pitch (Ashland Petroleum Company). The densification cycles of impregnation, carbonization, and graphitization were conducted four or five times. The density of the composites was 1.3-1.5 g/cm^3, and the longitudinal fiber volume fraction was ~30%.

Tensile specimens were machined from the composite plates so that the longitudinal direction was parallel to 0° direction. Edge-loaded contoured specimens were used (Fig. 1 (b)). Tensile tests were conducted following the general guidelines of ASTM standard C1275-00. For the testing at ambient temperature, specimens were clamped by wedge grips with aluminum end tabs on both faces of the gripping sections in order to prevent compression buckling at the edges of the specimens. The strain was determined by averaging the readings of strain gauges bonded to both faces of the center gauge section. The crosshead displacement rate was 0.5 mm/min for all tests. The tensile Young's modulus of the composites, E, was defined as a tangential modulus of the initial linear segment at 5-25 MPa. The proportional limit tensile stress (PLS) was defined as the maximum stress to satisfy $(E\varepsilon_{meas.}-\sigma_{meas.}) / \sigma_{meas.} \leq 0.05$, where $\sigma_{meas.}$ is the applied stress at strain $\varepsilon_{meas.}$ [4]. The ultimate tensile strength (UTS) was defined as failure load divided by the original gauge cross-section.

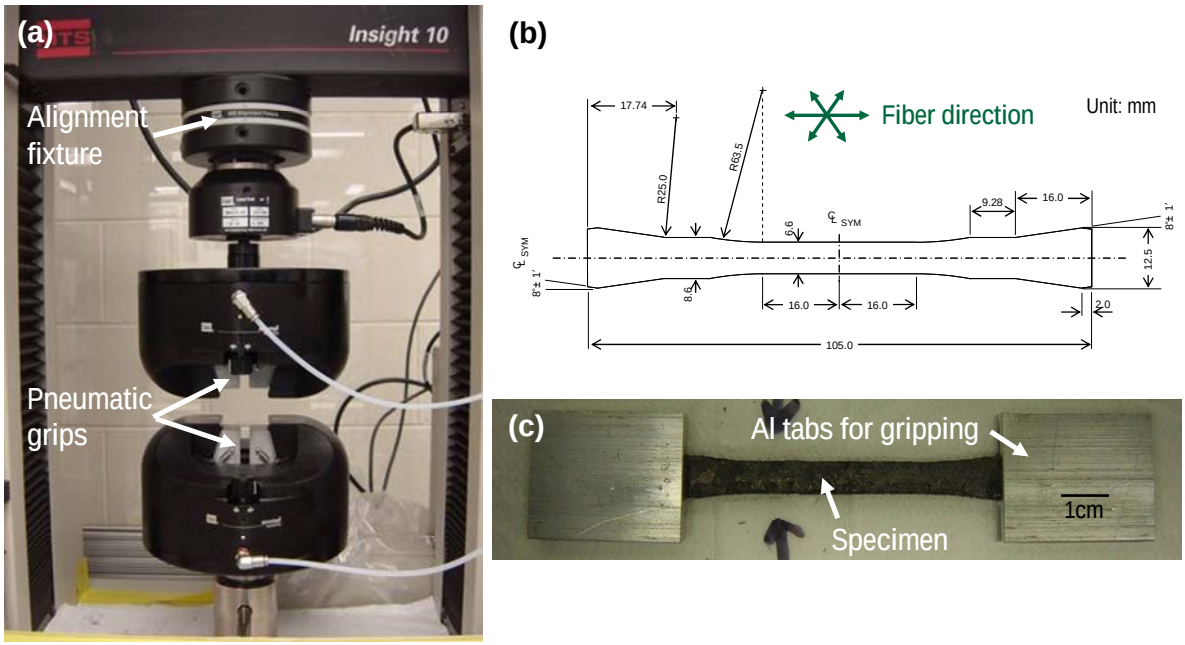

Fig. 1: (a) Tensile test apparatus with the alignment fixture, (b) schematic design of tensile test specimen used in this study, and (c) tensile test specimen with aluminum tabs.

Double notched shear test method was selected to evaluate inter-laminar shear strength, in accordance with ASTM standard C1292-00. Notched specimens (20.0^L x 4.0^W x 3.0^T mm with 6.5 mm notch separation) were loaded in compression parallel to the fiber longitudinal direction at a constant crosshead rate of 0.5 mm/min (Fig. 2). All tests were conducted at room temperature in air. Teflon sheets were used for providing lateral support to prevent the specimen buckling. Inter-laminar shear strength was defined as the maximum load divided by the fracture surface area. In this study, the fracture surface area was estimated by the notch separation multiplied specimen width because of the difficulty to measure the original fracture surface area after each test. Details on the test procedure and other related issues (such as notch effect and size effect) are described elsewhere [5, 6].

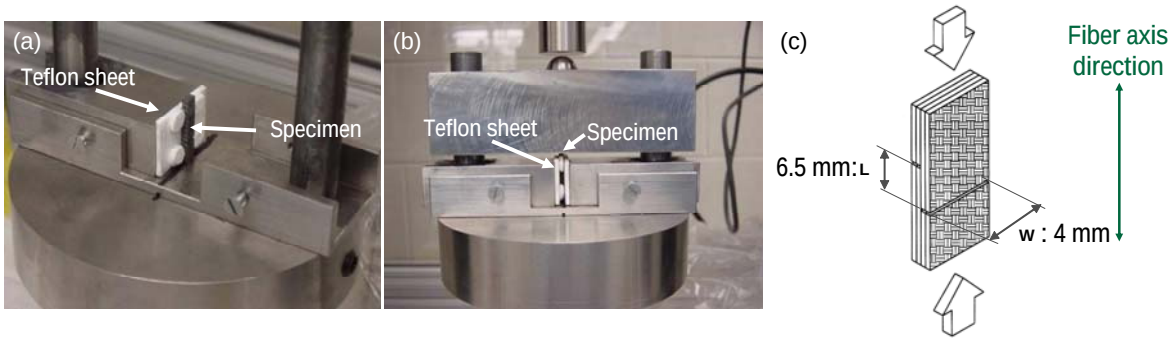

Fig. 2: (a), (b) Apparatus for the double notched shear test, and (c) schematic image of double notched shear test specimen.

Trans-thickness tensile test was conducted following the guidelines of ASTM standard C1468-06. 5.0^L x 5.0^W x 3.0^T specimen was adhered by epoxy glue to a pair of holders, with 5 mm square faces (Fig. 3). The holders were connected to the load train using a pair of universal joints to promote self-alignment of the load train during the movement of crosshead to minimize sample bending. All tests were conducted with the crosshead speed of 0.5 mm/min at ambient temperature. Trans-thickness tensile strength was defined as the maximum load divided by specimen length multiplied specimen width.

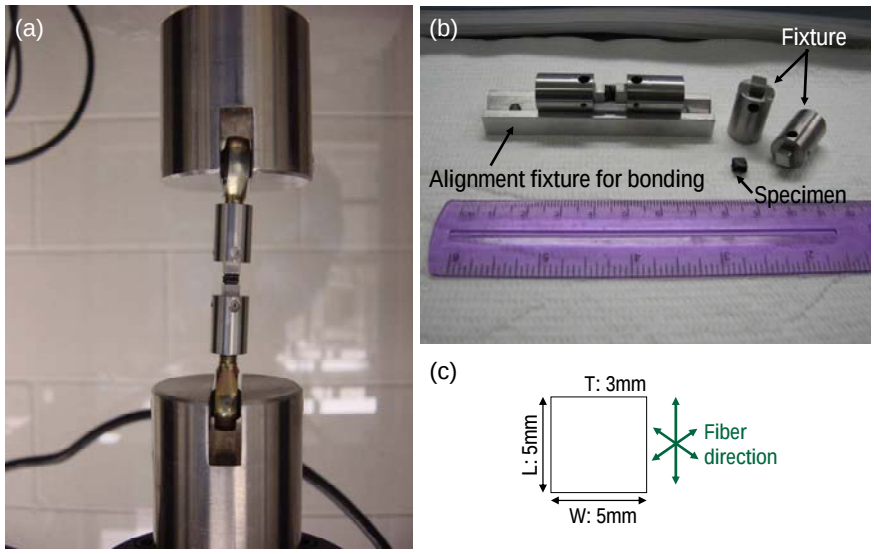

Fig. 3: (a), (b) Apparatus for the trans-thickness tensile test, and (c) schematic design of trans-thickness tensile test specimen

Results and Discussion

Tensile properties

Fig. 2 exhibits the typical tensile stress-strain curves of tri-axially braided C/C composites. The tensile properties are also summarized in Table 1. All specimens were fractured by delamination. Each of the curves for the composites exhibits quasi-ductile behavior consisting of an initial proportional region that corresponds to the elastic deformation, a second linear portion during which matrix cracks in transverse fiber bundles progressively develop, and a further non-linear portion due to domination of the matrix cracks in the longitudinal fiber bundles and the fiber failures. Tensile strength of 100~200 MPa, elastic tensile modulus of 90~130 GPa, and proportional limit stress of 50~130 MPa were obtained.

These significant differences of tensile properties (UTS, E, PLS) in each composite are primary attributed to the effective fiber volume content in the loading axis. It is well known that the ultimate tensile strength is proportional to the axial fiber volume fraction, according to the global load shearing theory by Curtin [7], indicating below:

$$\sigma_{\mathrm{u}} = V_f \sigma_{\mathrm{c}} \left(\frac{2}{m+2} \right)^{\frac{1}{m+1}} \left(\frac{m+1}{m+2} \right) \tag{1}$$

$$\sigma_{\mathrm{c}} = \left(\frac{\sigma_0^m \tau L_0}{r} \right) \tag{2}$$

with σ_u being the ultimate tensile strength, σ_c the characteristic strength, σ_0 the Weibull mean strength, m the Weibull modulus, τ the frictional sliding resistance, V_f the fiber volume fraction, L_0 the gauge length, and r the fiber radius, respectively. In order to examine the relationship between the tensile strength and the axial fiber volume fraction, each specimen was cut possibly near at the fractured position, and the cross-sectional optical images were carried out to determine the axial fiber volume fraction. As plotted in Fig. 5 (a), it was confirmed that the large differences in axial fiber content provided the differed tensile strength in each composite and that the tensile strength is almost proportional to the axial volume fraction.

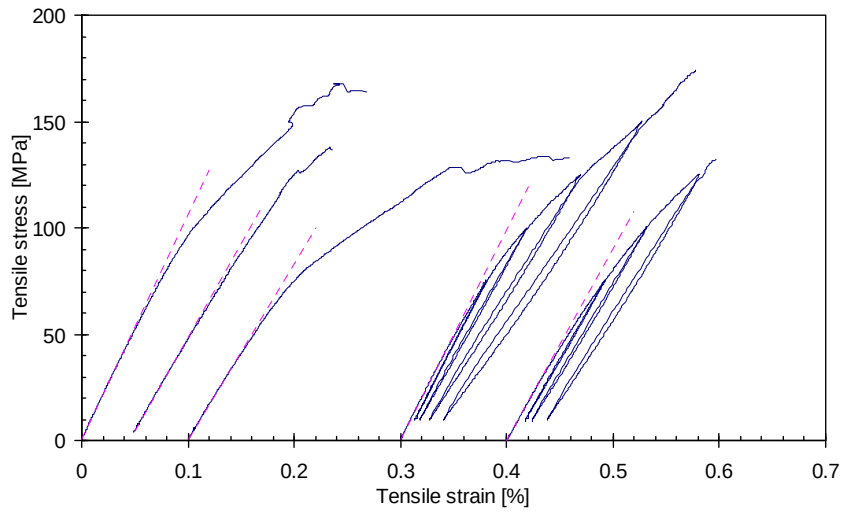

Fig. 4: Typical tensile stress-strain monotonic/unloading-reloading curves of tri-axially braided C/C composites. The curves have been sifted for clarity.

Table 1: Tensile properties of tri-axially braided C/C composites.

Tensile Modulus (E)	Proportional limit stress (PLS)	Ultimate tensile strength (UTS)	Fracture strain	# of valid tests
93 ± 15 GPa	**72 ± 22 MPa**	**143 ± 28 MPa**	**0.261 ± 0.107 %**	**14**

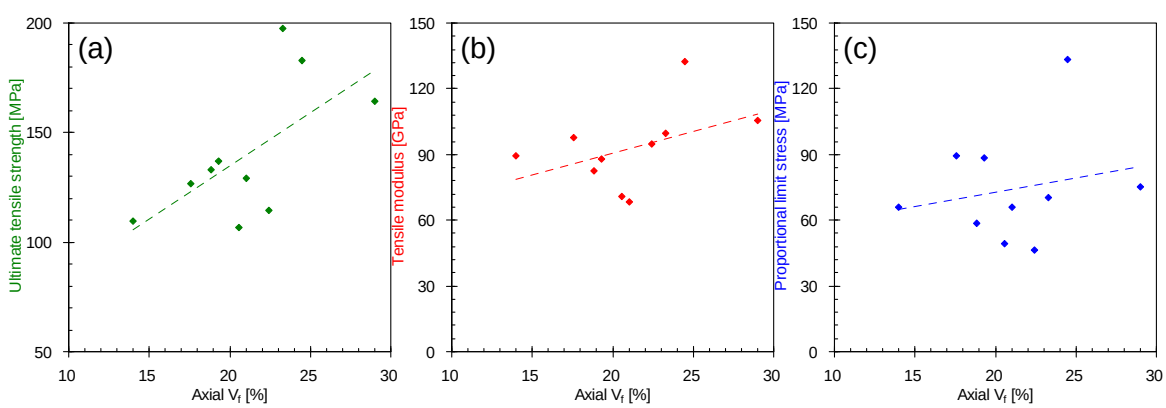

Fig. 5: Dependence of axial volume fraction on (a) UTS, (b) E, and (c) PLS.

As with the tensile strength, the difference of the tensile Young's modulus and proportional limit stress in the composites may be also attributed primarily to the axial fiber volume content (Fig. 5 (b), (c)). Compared with the 0° axial loading fiber bundles, the influence of the $\pm 55^o$ fiber bundles on tensile modulus might be much smaller, so tensile modulus can be roughly described as the following using the role of mixture:

$$E = E_f V_f + E_m (1 - V_f) \tag{3}$$

where E_f, E_m denotes the Young's modulus of fiber and matrix, respectively. Additionally, the Young's modulus of the matrix presumed to be smaller than that of the fiber (159 GPa). Therefore, the tensile modulus of the composites can be dependent on the axial fiber volume fraction.

The analytical model of the PLS in 3-D composite systems is currently unavailable. But in 2-D composite systems, it is well known that both of the PLS and the matrix cracking stress rely on the axial fiber volume fraction [8, 9]. In addition, it is confirmed that the stresses were dependent on the axial fiber volume content and they were strongly related in three directional SiC/SiC composites [10]. Therefore, in the case of the tri-axially braided C/C composites, the similar behavior seems to be occurred.

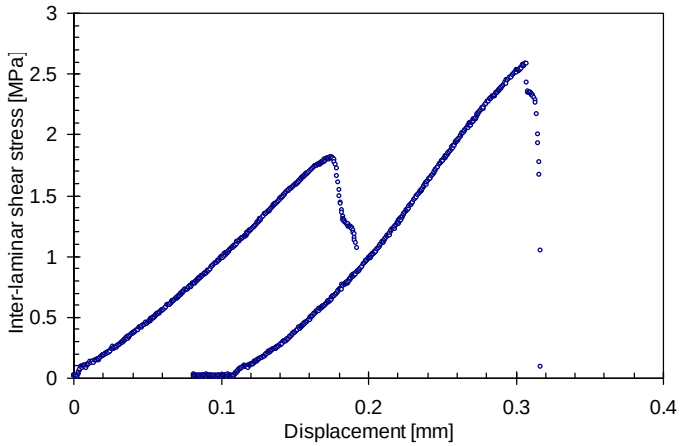

Fig. 6: Loading curves of the double notched shear test. The curves have been sifted for clarity.

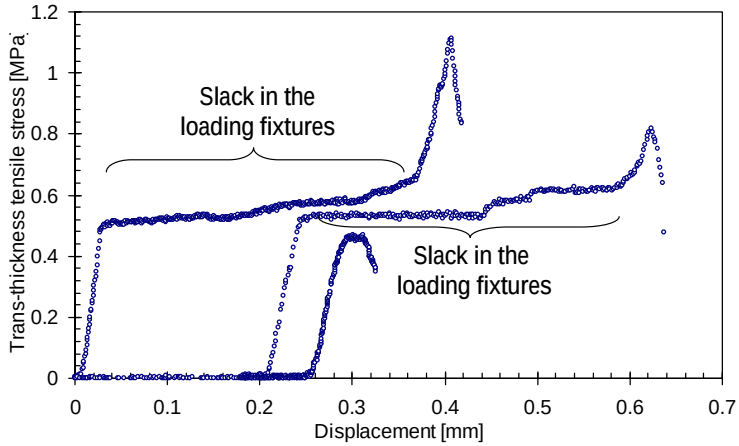

Fig. 7: Stress-displacement curves of trans-thickness tensile tests. The curves have been sifted for clarity.

<u>Inter-laminar shear and trans-thickness tensile property</u>

The loading curves of the double notched shear test were shown in Fig. 6. The curves showed almost linear responses and then shear fractures were occurred. The average inter-laminar shear strength of 2.2±0.6 MPa were measured. Fig. 7 also exhibits the stress-displacement curves of the trans-thickness tensile test. In the curves linear behaviors except the slack in the loading fixtures were measured. Eight tests were conducted and average trans-thickness tensile strength of 0.7±0.4 MPa were obtained. Those relatively weak strengths can be primary due to the low carbon matrix strength itself in addition to the inner porosity.

References

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