Mechanical and Thermal Properties of a Nuclear Grade C/C Composite for an Application of In-Core Structural Materials of VHTR

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1. Introduction

Increase of the operating temperature of high-temperature gas-cooled reactor up to 950°C requires ceramic composites as control rod cladding and guide tubes instead of metallic materials such as Alloy 800H. Carbon-carbon (C/C) composites have been widely used for high-temperature structural applications because they possess excellent mechanical properties even at temperatures higher than 2500°C [1]. Therefore, the C/C composites are considered as structural components of control rod in near-term options for the application of very high temperature gas-cooled reactors (VHTR) [2].

In the application of nuclear core components, the composite should have a high purity and a high degree of graphitization for the irradiation performance. With an aim at the irradiation performance, several C/C composites such as CX-270G and Sigrabond YR series have been developed in Japan and Europe, respectively.

In this study, we evaluated basic thermal and mechanical properties of a nuclear grade C/C composite fabricated by Toyo Tanso, Japan. The nuclear grade CX-270G composite has been developed for the control rod components of HTTR. The properties were evaluated in the parallel and perpendicular directions to the fiber axis.

2. Experimental Procedure

Samples used in this study were machined from CX-270G C/C composite plate (Toyo Tanso Co., Ltd., Japan). Specifications of the composite supplied from vendor are shown in Table 1. The 2D plain-woven composites made by stacking of fiber fabrics generally lead to an anisotropy of properties. Therefore, we evaluated the mechanical and thermal properties in the direction of parallel and perpendicular to the fabric plane as shown in Fig. 1.

For the three point flexural test in either perpendicular or parallel direction, bar specimens with dimensions of 6×2.5×45 mm were cut from composite panels. The span length and the cross-head speed were 30 mm and 0.5 mm/min, respectively. The statistical aspect of flexural strength was evaluated by the two-parameter Weibull analysis. For the Weibull analysis, 25 flexural specimens were tested for each fiber direction. Microstructures for the fracture surface were observed using a scanning electron microscope. Thermal diffusivity was measured by a laser flash method (Netzsch LFA-427) using specimens with dimensions of 12.5 mm in diameter and 3 mm in thickness. Measurement of thermal diffusivity was performed at room temperature to 1200°C in vacuum. Thermal conductivity was calculated by multiplying the thermal diffusivity, the density of the composite, and the heat capacity of graphite.

Table 1. Characteristics of CX-270G C/C composites

Fiber type	PAN
Fiber architecture	2D plain weave
# of filaments	6K
Fiber Vol%	50%
Bulk density (g/cc)	1.69
Matrix formation	Pitch impregnation & pyrolysis.
Graphitization temp.	~3000°C

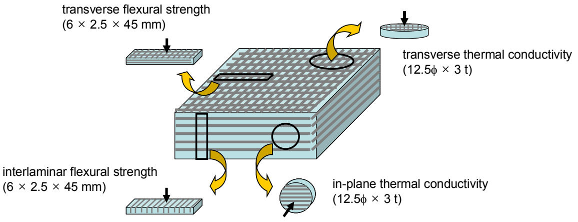

Fig. 1. Preparation of samples for the flexural strength and the thermal conductivity tests.

3. Results and Discussion

Fig. 2 shows typical stress and crosshead displacement curves for loading directions parallel or perpendicular to the fabric plane. In case of the transverse flexural test, the specimen shows graceful, i.e., noncatastrophic, fracture behavior due to the crack bridging and fiber pull-out by carbon fiber reinforcements. Fig. 3 shows an example of the microstructure of the fracture surface exhibiting the fiber full-out. In the interlaminar flexural test, however,

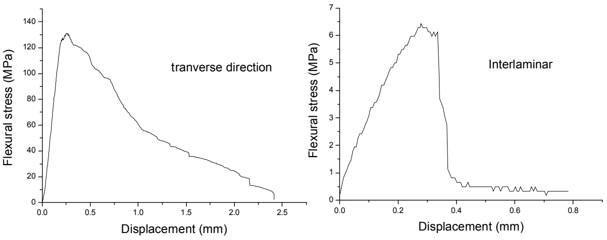

Fig. 2. Flexural stress and crosshead displacement curves for transverse and interlaminar flexural tests.

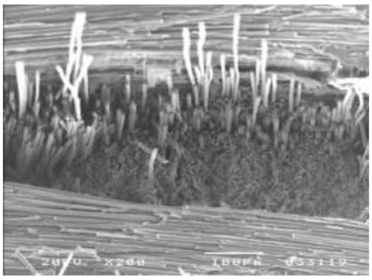

Fig. 3. SEM microstructure for the fracture surface of the sample tested in a transverse direction.

the fracture strength is very low and the sample fails in a brittle manner. This is due to the 2D nature of the composite which is lack of fiber reinforcements through the thickness direction. In some samples of transverse flexural tests, a shear failure in middle plane of the test bars appeared due to the low interlaminar strength of the composite. Therefore, a higher span-to-depth ratio would be needed in the flexural test.

Fig. 4 shows the result of Weibull analyses for the flexural test. The average strength of the composite is 134.2±6.1 and the Weibull modulus is as high as 25.3 in the transverse test. However, in the interlaminar test, the strength is quite low as 6.37±0.7 MPa and the Weibull modulus is also limited to 10.8 due to the brittle failure mode.

Thermal diffusivity and conductivity of the CX-270G composite measured from room temperature to 1200°C is shown in Fig. 5. The composite has a low thermal conductivity in the transverse direction and a high value the in-plane direction. This is attributed to the structure of carbon fiber. As shown in Fig. 6, the high-modulus PAN-based fiber has a strongly anisotropic structure, in which lamellae are entangled with each other longitudinally and folded parallel to the fiber axis. This leads to a high thermal conductivity along the fiber axis and a low thermal conductivity in a radial direction. Therefore, the thermal conductivity in the in-plane direction, in which the long axes of fibers are aligned on the fabric plane, shows a higher value than the transverse direction.

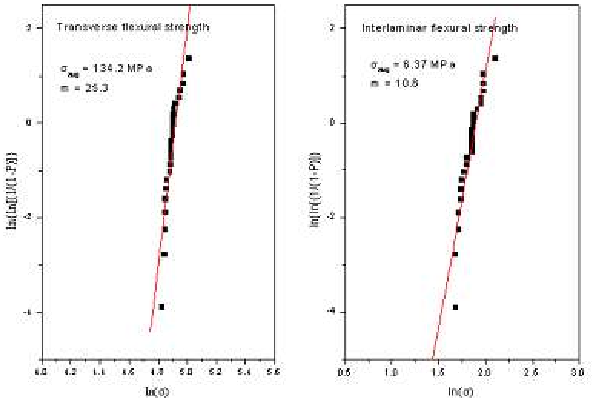

Fig. 4. Weibull plots for the three-point transverse and interlaminar flexural strengths of CX-270G composites.

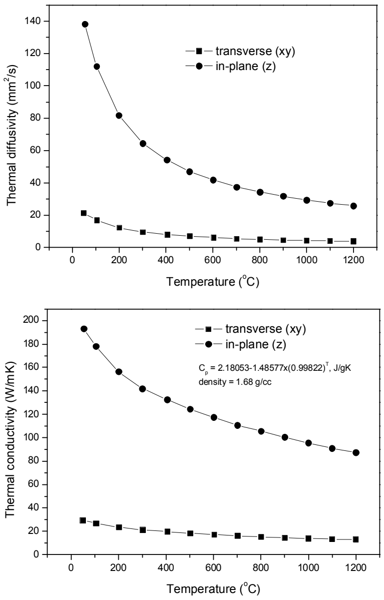

Fig. 5. In-plane and transverse thermal diffusivity and conductivity of the CX-270G composite as a function of temperature.

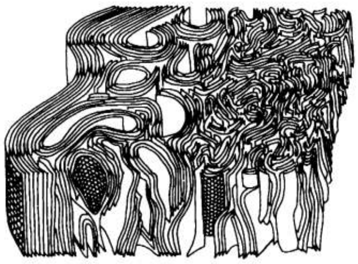

Fig. 6. Schematic three-dimensional structure of PAN-based carbon fiber [3].

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