"The Effect of Fiber Orientation on Mechanical Properties of Unidirectional C/C Composite with Resin derived Char Matrix"

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Abstract

Mechanical properties of carbon/carbon composite are strongly affected by reinforcing fiber orientation. In this paper, unidirectional reinforced C/C composites were made from high modulus PAN based carbon fiber and furfuryl alcohol condensate derived carbon which are heat-treated at 1000°C and 3000°C. Flexural tests in 4-point bend were carried out for specimens with 10mm in width, 1mm in thickness and (50-80)mm in length. Young's modulus at off-axis followed well the theory of anisotropic lamina. Strength at high off-axis angle was described well by Tsai-Hill or maximum stress theory, while the

strength at low off-axis angle was higher than the estimated value.

Introduction

Carbon Fiber reinforced carbon composite (C/C composite) is a strong candidate materials for space application, for the first wall of fusion reactor and for turbine etc$^{1)}$.

Mechanical properties of C/C composite depend on not only of the fiber, but also of the matrix microstructure, as reported elsewhere$^{2)}$. In addition to the effect of fiber and matrix microstructure, the angle between carbon fiber and crack propagating direction (off-axis angle) plays an important roll in mechanical properties. It is very important to clear the effect of off-axis angle on mechanical properties of the composite from the view point of designing and applying it to structural components. In a field of FRP, we can find many papers dealing with the effect of the off-axis angle, however, we can find only one paper addressing on C/C composite$^{3)}$. In this paper, the effect of off-axis angle on mechanical properties are investigated using unidirectional reinforced (UD) C/C composite with a thermo-setting resin derived char as a matrix.

Experimental

UD composite was made by wet winding technique. The detailed techniques were shown elsewhere$^{4)}$. Carbon fiber used was a high modulus carbon fiber (M-40; Torayca). The matrix precursor was furfuryl alcohol condensate (Hitafuran 302, Hitachi Chemical Industry Co.). The cured polymer composite was carbonized at 1000°C, and then graphitized at 3000°C. The composite was characterized by flexural strength in 4-point bending configuration. The dimensions of the bend specimen were about 10mm in width, 0.5-3mm in thickness and 50-80mm in length. The outer and inner spans of the bend test were 40mm and 13mm respectively, and the cross head speed was 0.1mm/min. The fractured surface of the composite was examined by a scanning electron microscope (SEM).

Results and Discussion

The Young's modulus is shown in Fig.1 as a function of the off-axis angle and heat treatment temperature. The difference in Young's modulus for longitudinal direction between FRP (HTT 100°C), composites heat treated at 1000°C (HTT 1000°C) and HTT 3000°C is attributed mainly to the changes of volume fraction and Young's modulus of the matrix. The Young's modulus at various off-axis angle followed well the theory of the anisotropic lamina$^{5)}$.

Before the test for off-axis strength, shear strength and the transverse fracture strength were measured. The shear strength by the short beam bend test (span to depth ratio: < 10) was about 9-10MPa both for carbonized and graphitized composites. The transverse strength of these composites were measured to be about 5MPa and 8MPa respectively. The values for the carbonized composite are smaller than there of glass like carbon which is supposed to be the similar material as the matrix of the carbonized composite$^{6)}$. Macroscopic observation reveals some micro-cracks in the matrix parallel to the fiber direction. The strength of the composites may result from these cracks in the matrix.

The orientation dependence of fracture strength in off-axis tests on carbonized and graphitized UD composites was shown in Fig.2 and Fig.3, respectively. The strength of carbonized composite decreased steeply with the increase of off-axis angle as can be seen in Fig.2. The strength of graphitized composite decreased with increase of the off-axis angle also. However, it does not satisfy the Tsai-Hill Criterion and/or the maximum stress theory[7]. The values measured were much higher than those expected theoretically.

The microstructure of fractured surfaces of the composites were shown in Fig.4. The fractured surface was generally flat in longitudinal and transverse tests. However, many steps were observed on the fractured surface of the off-axis of 10-30°. The step indicates a mixed fracture mode of shear and longitudinal tensile fractures. As schematically illustrated in Fig.5, a bridging process may be suggested. If the doted area in Fig.5 (left side figure) is assumed to carry all of the applied load and thus the critical stress over the doted area is supposed to be the longitudinal strength, the apparent strength of the composite (σ) is given by

$$\sigma=P/(b\ t)=\sigma_L{}^*\{1-(L/b)\tan\theta\}$$

where, P;applied load, b;width of the specimen, t;thickness, $\sigma_L{}^*$;longitudinal strength of the composite, L;inner span of the 4-point bending, θ;off-axis angle. Calculated for each testing condition are illustrated in Fig.2 and Fig.3 by doted lines. In case of the composite of HTT 3000°C, the calculated value agreed well with the measured value. On the other hand, it did not well satisfy the expectation in the carbonized composite. The difference between carbonized and graphitized composites depends on the nature of used matrix. In conclusion, the main reason for higher strength value at low off-axis angle is controlled by the bridging effect of fibers lain over the inner-span of

4-point bending.

Outside of the bridging occurrence (around 40°) in graphitized composite, the measured strength is higher than that estimated from Tsai-Hill criterion too. The discrepancy may be explained as follows; out-of-plane coupling stress will be initiated from the stress distribution in a anisotropic bending beam. This coupling force lead to a twisting of the specimen, thus change of the stress direction will occur. In such a case, symmetric cross-ply or angle-ply laminates is effective for diminish the twisting[5)]. However, preparation of the specimen is not so easy, because of the anisotropic carbonization shrinkage introduces delamination and microcracking.

Conclusion

UD C/C composite was made from high modulus PAN based carbon fiber and furfuryl alcohol condensate derived carbon matrix which were heat-treated at 1000°C and 3000°C. 4-point bending test was carried out for determining both failure strength and Young's modulus. Young's modulus at off-axis satisfied well the theory of anisotropic lamina. Strength at high off-axis angle followed Tsai-Hill or maximum stress theory, whereas the strength at low off-axis angle was higher than that theoretically estimated. The reason of the insutisfuction will mainly depend on the fibers lain over the inner-span of the 4-point bending. Around 45°, the measured strength of graphitized composite is still higher than that of estimated strength. The discrepancy may depend on the out-of-plane coupling stress initiated from the stress distribution in a anisotropic bending beam.

Literature

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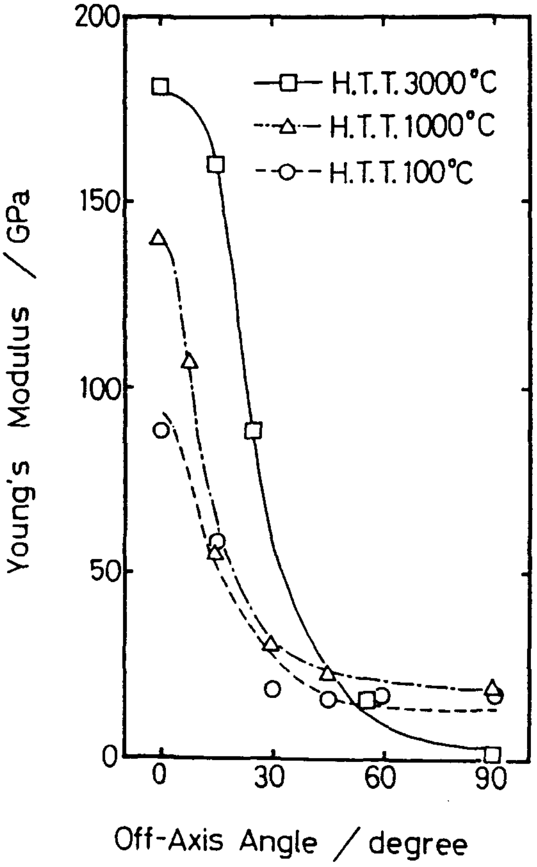


Fig. 1: Orientation dependence of off-axis angle on Young's modulus of unidirectional C/C composites.

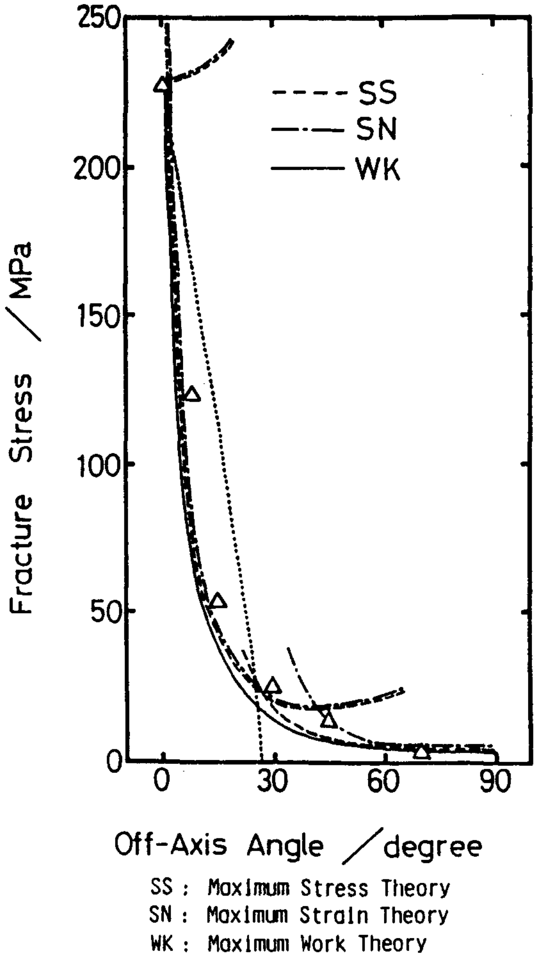
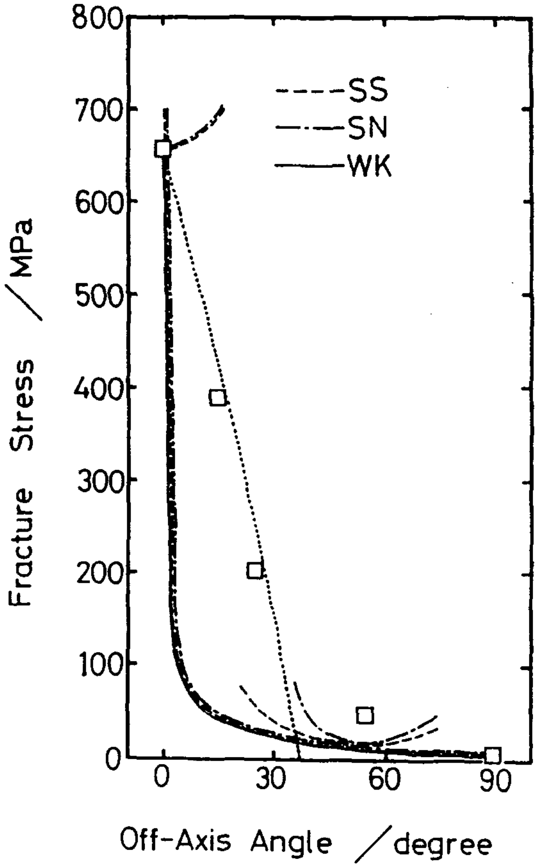


Fig. 2: Orientation dependence of off-axis angle on fracture strength of carbonized unidirectional C/C composite.



SS : Maximum Stress Theory
SN : Maximum Strain Theory
WK : Maximum Work Theory

Fig. 3: Orientation dependence of off-axis angle on fracture strength of graphitized unidirectional C/C composite.

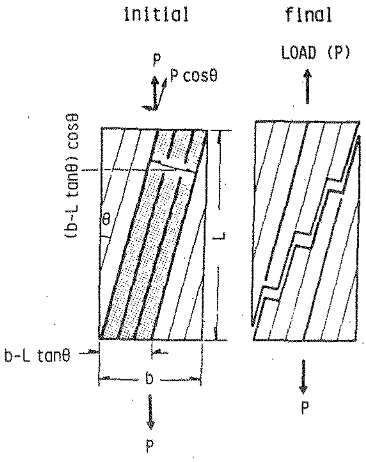


Fig.4: SEM micrographs of fractured surface in off-axis tests.

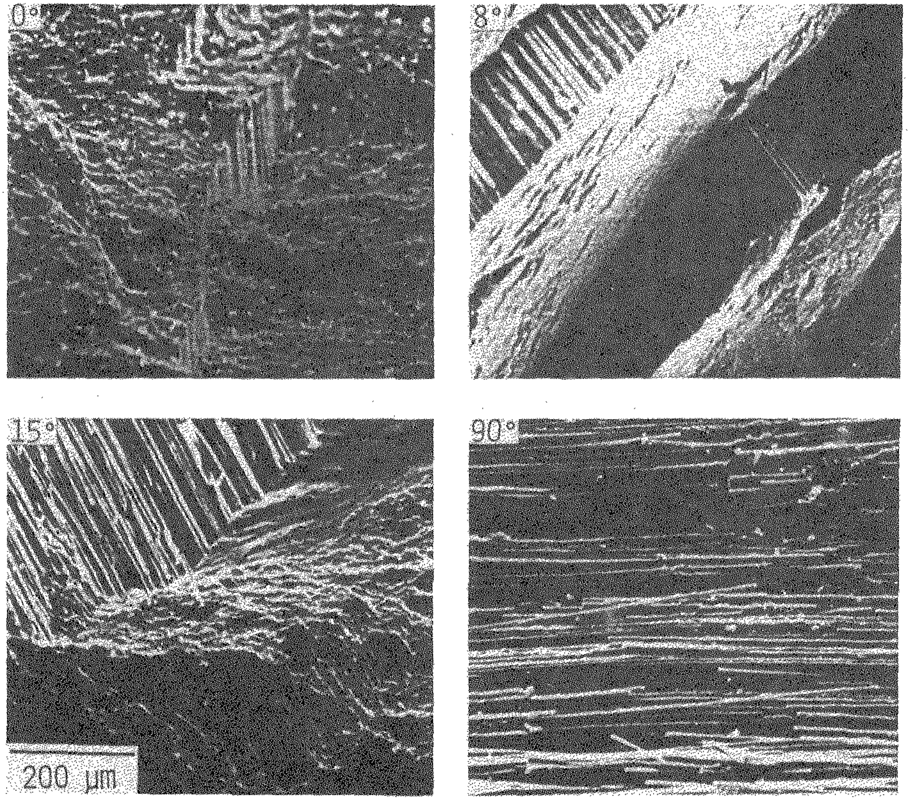


Fig.5: Schematic illustration of the bridging effect on the off-axis testing of the UD composite.