研 究 速 報

UDC 621.763 : 669-419.8 : 539.42

CRACK GROWTH RESISTANCE IN FIBRE-REINFORCED /CARBON MATRIX COMPOSITES

繊維強化カーボンマトリックス複合材料の破壊抵抗

Michael JENKINS*, Jun MIKAMI*, Tongshik CHANG* and Akimitsu OKURA*
マイケル ジェンキンス・三 上 淳・張 東 植・大 蔵 明 光

1. INTRODUCTION

Fibre-reinforced/carbon matrix composites, because of their light weight and tailorability, are attractive materials for such applications as refractory linings, advanced heat engine components, high technology aero/space craft parts, brake linings, and biomedical implants[1]. The difficulty and the expense of producing carbon matrix composites by chemical vapor methods (CVI or CVD) have limited the extensive fracture testing of these materials. However, a recently developed manufacturing technique[2-4] has allowed the rapid and relatively inexpensive fabrication of these fibre-reinforced/carbon matrix composites.

In this study the crack growth resistance of two hot-pressed, unidirectional, continuous fibre-reinforced/carbon matrix composites were investigated for various fibre contents (V_F = 0,10,20,30%). The composite materials and their onstituents are presented, followed by the description of the specimen preparation and the testing technique. Finally, the data reduction methods, the results, and the fracture behavior are discussed.

2. MATERIAL

The composites consisted of increasing V_F of unidirectional (UD), continuous SiC or C fibres imbedded in a polygranular carbon matrix. Details of the fibre and the matrix materials are presented in Table I. The simple hot-pressing procedure for fabricating these materials has been described previously by Chang and Okura[2-4].

Table I Fibre and Matrix Specifics

Parameter	Carbon Fibre	SiC Fibre	Carbon Matrix
Manufacturer	Nippon Carbon	Nippon Carbon	Across
Tradename	RM-200	Nicalon	None
Description	Round cross section fibres arranged UD in pre-preg sheets of 35% epoxy resin	Round cross section fibres arranged UD in pre-preg sheets of 35% epoxy resin	40% coke powder from coal and 60% crbonaceous bulk mesophase (16.8% volatile)
Elastic Modulus (GPa)	220	150	6
Ultimate Strength (MPa)	3504 (Tensile)	3000 (Tensile)	12.5 (Bending)
Weibull Strength (MPa)	3764	3300	N/A
Weibull Modulus	6.4	6.3	N/A
Fibre or Particle Diameter (micrometer)	7.05	14.5	3.5

All values were measured or assumed in this study

3. FRACTURE TESTING

3.1 Specimen Preparation

Four chevron-notched and four straight-notched, three point bend specimens for each V_F were tested over a loading span of 40 mm. The notches were oriented transverse to the fibre direction and parallel to the pressing direction as shown in Figure 1. The chevron-notched geometry inherently promotes stable crack growth in even nominally brittle materials[5-8] while the straight-notched geometry is a traditional fracture geometry[9]. The nomenclature and the specimen types are presented in Figure 2.

3.2 Testing Procedure

*Dept. of Industrial Chemistry and Metallurgy, Institute of Industrial Science, University of Tokyo

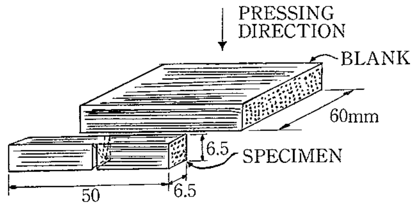

Figure 1　Material blank with specimen and notch orientations

Fracture testing was conducted on a screw-type, displacement-controlled load frame**, using a continuous cross-head speed of 0.5 mm/min. A specially-designed, stiff, steel load fixture was used to ensure the minimum machine compliance necessary for stable crack growth[6]. All tests were conducted in ambient air at room temperature (20°-24° C) and ambient relative humidity (40%-55% RH).

4. TEST RESULTS

Sustained stable crack growth was observed in both the chevron-notched and straight-notched specimens. Figure 3 show representative load versus load point displacment (LPO) histories for the various V_F of the chevron-notched specimens. Figure 4 shows the values of the elastic modulus, E[10], used to determine the effective crack lengths for the calculation of the R-curves.

4.1 Fracture toughness

The apparent fracture toughness, K_{IC}, for chevron-notched specimens of linear elastic materials is calculated[8,11] as:

$$K_{IC} = Y_{min}\ P_{max}/(B\ W^{1/2}) \qquad (1)$$

where Y_{min} is the minimum geometry correction factor for the stress intensity factor[7], P_{max} is the maximum load, B is the specimen thickness, and W is the specimen width. The apparent fracture toughness for the straight-notched specimens is calculated with Equation (1) using the value of the load at crack initiation (first major drop in the load) and the geometry correction factor[9] for the initial notch depth.

The apparent K_{IC} values versus V_F for both notch types are shown in Figure 5. Differences in the apparent K_{IC} are due to the differences in the geometry of the notches and the calculation methods for the apparent K_{IC}.

**Shimadzu Autograph Type IS-2000, Kyoto Japan.

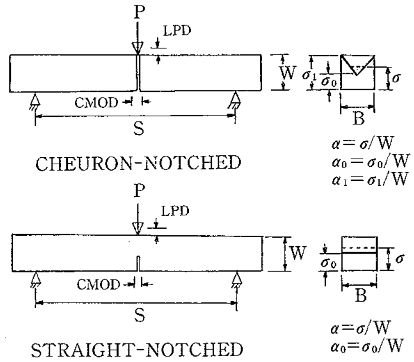

Figure 2　Nomenclature and specimen geometries

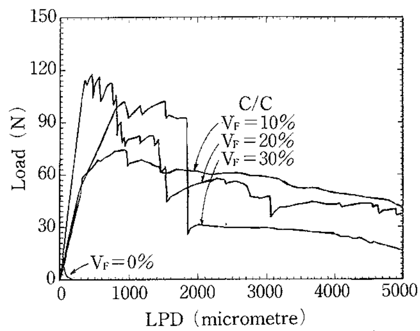

Figure 3　Representative load vs. displacement histories, C/C composite chevron-notched, bend specimens

4.2 Work-of-Fracture

The work-of-fracture, WOF, is determined as [6,12]:

$$WOF = \int P\ dLPD/2A_T \qquad (2)$$

where $\int P\ dLPD$ is the area under the loading curve and A_T is the total projected area of one fracture face. The work-of-fracture values versus V_F are shown in Figure 6. Table II contains comparisons of the fracture toughness and work-of-fracture results of this study with previous fracture studies of C/C composites.

4.3 Crack Growth Resistance

The linear elastic R-curves were developed using the stable crack growth plots of the load versus the LPD for the chevron-notched specimens and the compliance relations[7] to determine the effective crack lengths such that:

$$G = \Delta U/\Delta A \qquad (3)$$

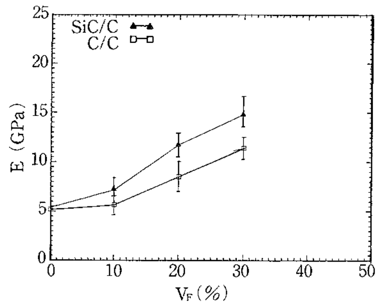

Figure 4　Elastic modulus vs. V_F for the composites

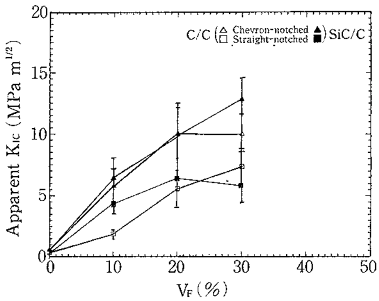

Figure 5　Apparent fracture toughness vs. V_F for the composite bend specimens

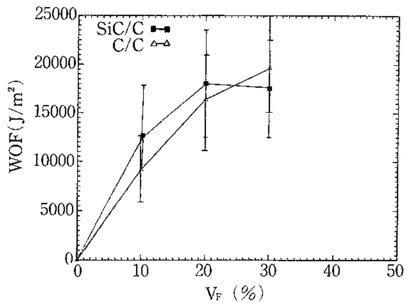

Figure 6　Work-of-fracture vs. V_F for the composite bend specimens

Table II　Comparison of the Fracture Resistance with Other Studies for C/C Composites

Reference	Comment	V_F (%)	K_{IC} (MPa m$^{1/2}$)	WOF (J/m²)
This Study (C/C)	CNBB & UDHP	10	5.78+/−1.58	9168+/−3430
		20	10.0+/−2.14	16372+/−5573
		30	9.98+/−1.68	19594+/−8086
	SNBB & UDHP	10	1.88+/−0.47	—
		20	5.57+/−1.86	—
		30	7.35+/−1.57	—
This Study (SiC/C)	CNBB & UDHP	10	6.88+/−1.32	12362+/−5881
		20	9.93+/−2.85	17900+/−5466
		30	12.8+/−1.81	17514+/−5098
	SNBB & UDHP	10	4.34+/−0.65	—
		20	6.37+/−1.04	—
		30	5.71+/−0.92	—
13)	CNBB & CVI	50	9.61+/−0.79	3856+/− 721
	SNBB & CVI	50	8.27+/−0.93	8685+/−4529
14)	SNBB CVD/F	9	1.16+/− —	276+/− —
	SNBB CVD/FW	50	0.59+/− —	128+/− —

Note: CNBB　: Chevron-Notched, Bend Bar
UDHP　: UniDirectional Fibre, Hot Pressed
SNBB　: Straight-Notched, Bend Bar
CVI　: Chemical Vapor Infiltration

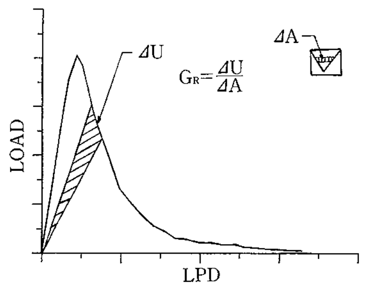

Figure 7　Schematic diagram of the calculation of the strain energy release rate

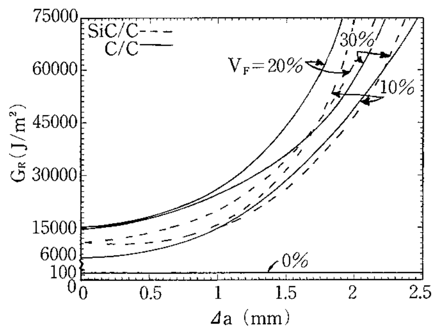

Figure 8　G_R-curves of the composites for increasing V_F

where G is the strain energy release rate as a function of the incremental crack length Δa, ΔU is the linear elastic change in the total strain energy, and ΔA is the incremental change in fractured area. This procedure is shown schematically in Figure 7. The final G_R-curves for all the values of V_F are shown in Figure 8. These curves were produced from numerical least square fits of the individual R-curves calculated at each condition.

5. DISCUSSION OF THE FRACTURE RESULTS

The plot of apparent K_{IC} versus V_F for the straight-notched specimens tends to follow the trend of the strength shown in Figure 9 indicating the relation of the fracture strength and the fracture toughness for the fixed size of the macroflaw. The apparent K_{IC} values for the chevron-notched specimens show no such relation to the strength since crack closure effects artificially raise the calculated value of the apparent K_{IC}. The WOF values tend to

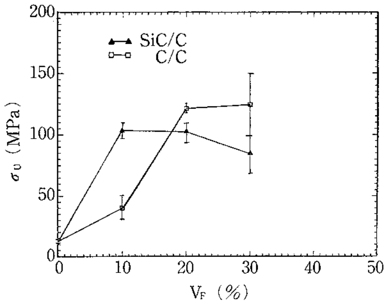

Figure 9　Bending strength vs. V_F for the composites

follow the strength trends indicating that there may also be an optimum V_F for the fracture resistance as well as for the strength.

The rising and nonlinear R-curves of Figure 8 indicate the non linear-elastic fracture resistance of these composites. The R-curves for all the V_F values, after the original difference in initiation energies, eventually show approximately the same increasing slopes and magnitudes, thus indicating that once a crack has initiated, the same type of energy -absorbing crack growth resistance mechanisms exist which are not necessarily dependent on the V_F.

The results of this study, based on linear elastic fracture mechanics (LEFM), are useful for indicating the trends in the fracture resistance behavior as a function of fibre content. However, the results are not valid for engineering design use because the basic assumptions of linear elastic behavior in the analysis methods are violated.

6. CONCLUSIONS

The conclusions may be summarized as follows: i) the fracture resistance of these hot-pressed unidirectional continuous fibre-reinforced/carbon matrix composites generally increases with increasing fibre content, ii) chevron-notched specimens provide the means for studying controlled, stable growth behavior in these materials, iii) LEFM is generally not applicable for analyzing the 'true' fracture characteristics of fibrous composites other than for comparative purposes. Therefore other methods for comparative evaluations must be developed and employed.

(Manuscript received, December 4, 1987)

REFERENCES

1) Fitzer, E. Carbon. 25: 163-190 (1987).
2) Cho, T., Okura, A., in Recent Advances in Composites in the United States and Japan. ASTM STP 864, J. R. Vinson and M. Taya, Eds., 443-464 (1985).
3) Chang, T., Okura, A., in Composites '86: Recent Advances in Japan and the United States. K. Kawata, S. Umekawa, and A. Kobayashi, Eds., Proceedings of Japan and United States CCMIII, Tokyo, Japan, 425-432 (1986).
4) Chang, T., Okura, A., Transactions of the Iron and Steel Institute of Japan. 27: 229-237, (1987).
5) Newman, J.C. Jr. in Chevron-Notched Specimens: Testing and Stress Analysis. ASTM STP 855, J.H. Underwood, S.W. Freiman, F.I. Baratta, Eds., ASTM pp 5-31 (1984).
6) Tattersall, H.G., Tappin, G.J. Mat. Sc. 1:296-301 (1966).
7) Jenkins, M.G., Kobayashi, A.S., White, K.W., Bradt, R.C. "A 3-D Finite Element Analysis of a Chevron -Notched, Three-Point Bend Fracture Specimen for Ceramic Materials," Int. J. Frac. 34:281-295 (1987).
8) Munz, D.G., Shannon, J.L., Jr., Bubsey, R.T., Int. J. Frac. 16: R137-141 (1980).
9) Tada, H., P. Paris, and G. Irwin. The Stress Analysis of Cracks Handbook. Del Research Corporation, Hellertown, PA, (1973).
10) Mikami, J, "The Fracture Resistance Strength of SiC/C and C/C Composites Fabricated by a Hot Pressing Method," Senior Thesis, Shibaura Institute of Technology, to be completed April (1988).
11) Pook, L.P. Int. J Frac. 8:103-108 (1972).
12) Nakayama, J. Jap. J. Applied Physics. 3:422-423 (1964).
13) Unpublished results for a commercial CVI carbon fibre reinforced/carbon matrix composite with an estimated V_F=50%. University of Washington, Seattle, WA, (1987).
14) Guess, T.R., Hoover, W.R. J. Composite Materials. 7: 2-21 (1973).