Springer

Journal of Mechanical Science and Technology 23 (2009) 8~13

Journal of Mechanical Science and Technology

www.springerlink.com/content/1738-494x
DOI 10.1007/s12206-008-0929-0

Effect of postpeak tension-softening behavior on the fracture properties of 2-D carbon fiber reinforced carbon composite †

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(Manuscript Received February 14, 2008; Revised July 17, 2008; Accepted September 26, 2008)

Abstract

The fracture properties of commercial carbon fiber reinforced carbon (C/C) composites (CCM190C, CCM191C) that have different interfacial shear strength were investigated. Postpeak tension-softening phenomena were observed through the fracture mechanics test for these composites. The failure manner in the fracture process zone was primarily fiber pull-out for CCM190C and fiber breakage for CCM191C, respectively. It was confirmed that the scale of pseudo strain hardening for CCM190C with low interfacial shear strength was larger than that of CCM191C. The bridging energy at the postpeak part and the total energy consumed to produce a unit area of fracture surface were calculated based on the J-based technique. The bridging energy at the postpeak part accounted for 12.3% of the total energy consumed to produce a unit area of fracture surface for CCM190C. From this result, it can be deduced that the effect of the postpeak bridging energy on the fracture toughness is large for CCM190C. In contrast, the contribution of the postpeak bridging energy for the total energy per fracture surface was very small for CCM191C.

Keywords: Postpeak tension-softening relation; Pseudo strain hardening; J-based technique; Fracture process zone; Bridging energy

1. Introduction

Fiber reinforced composites occupy a central role in the development of new materials and overcome many of the limitations of traditional materials. Especially, carbon-carbon (C/C) composites have been the focus of substantial research efforts in recent years because carbon materials have high strength and stiffness potential as well as high thermal and chemical stability.

A feasible approach for improving mechanical properties of brittle materials is through the enhancement of fracture toughness. The reinforcement of brittle materials with high strength fibers can yield composites of very high toughness. This was first demonstratd using carbon fibers in glass-ceramic matrices [1-3]. Fiber bridging in a zone immediately behind the crack tip and multiple cracking around the crack tip are primary mechanisms for the toughness improvement. The bridging causes a postpeak tension-softening relationship in fracture test. Pseudo strain hardening in fiber reinforced composites is associated with the multiple cracking phenomenon of the brittle matrix [4].

Most of the other indirect methods introduced for the measurement of the tension-softening relation to date are based on monitoring of the bridging zone growth and crack propagation resistance curve (R-curve) [5, 6]. The determination of R-curves requires knowledge of the exact location of the fracture process zone tip. However, it is difficult to identify the accurate extent of the fracture process zone in quasi-brittle materials such as C/C composites which are provided in this research. The J-based technique overcomes this shortcoming by measuring the crack tip opening dis-

† This paper was recommended for publication in revised form by Associate Editor Chongdu Cho

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placement [7, 8]. The objective of this research is to estimate for fracture properties of C/C composite while considering the bridging zone, referred to as the fracture process zone, using the J-based technique.

2. Experimental

2.1 Materials and specimen

Commercial C/C composites, made by Nippon Carbon Co. Ltd. (CCM190C, CCM191C), were used in this study. These composites were manufactured by first laying, moulding and curing 10 prepregged two dimensional plain weave fabrics, as shown in Fig. 1, and then by carbonization and graphitization at 2,000℃. The two types of composites differ only in their interfacial shear strength. Interfacial shear strengths for CCM190C and CCM191C are 13 ㎫ and 18 ㎫, respectively.

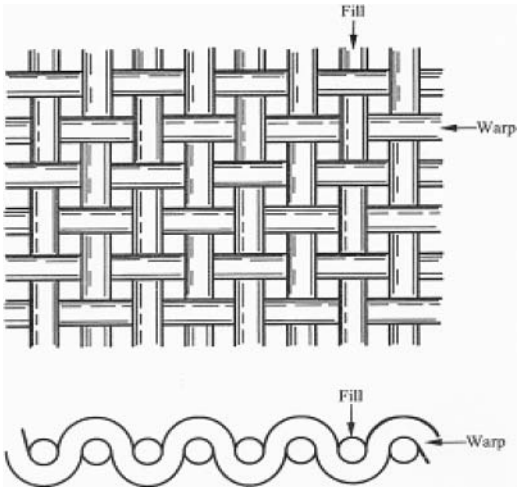


Fig. 1. Schematic configuration of plain weave fabric.

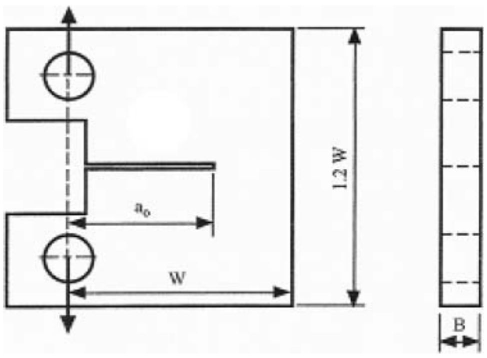


Fig. 2. CT specimen configuration of C/C composite.

Fracture testing employs a standard fracture mechanics geometry (compact tension (CT) specimen) in opening mode (mode Ⅰ) for these composites [9, 10]. The dimension of CT specimen is shown in Fig. 2. Notches were cut with a 0.6 ㎜ thick diamond saw and then extended about 1 ㎜ with a very thin saw made from a razor blade to finally yield a sharp crack. The resulting tip radius was 10 ㎛. The initial crack depths, a_o, were machined to about 32 ㎜ and 36 ㎜.

Specimen for tension testing is shown in Fig. 3. Two types of tensile specimens (double edge notched type and unnotched type) were used in this tension test. In this study, each specimen was named as in Table 1 to distinguish their configurations.

2.2 Test method

Fracture mechanics tests were conducted to obtain the J integral value for C/C composites using the CT specimens, where two different notch depths were tested. These tests were conducted on an Instron-testing machine at a crosshead speed of 0.2 ㎜/min. Load, P, and load-line displacement, δ, were recorded continuously up to complete fracture during the tests.

Table 1. Designated specimens in specific dimensions.

	Specimen	W (㎜)	W-a_o (㎜)	W-2a (㎜)	B (㎜)
CCM190C	CT190	50	14 (a_1=36) 18 (a_2=32)		3
	UT190	10.2		10.2	3
	UT190N	10.2		8.2	3
CCM191C	CT191	50	14 (a_1=36) 18 (a_2=32)		3
	UT191	10.2		10.2	3
	UT191N	10.2		8.2	3

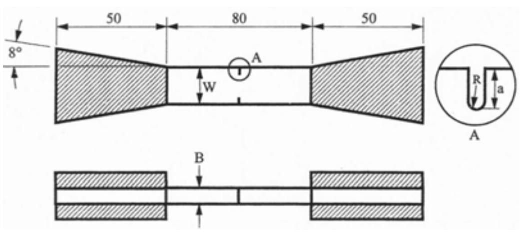


Fig. 3. Uniaxial tension specimen configuration of C/C composite.

The load was detected by a load cell and the load-line displacement was estimated from the crosshead displacement because of its very large displacement-to-failure.

Tensile tests were performed based on ASTM E 8 with an Instron universal testing machine at room temperature [11]. Crosshead speed was 0.2 ㎜/min in axial tensile tests. Load and displacement were measured by load cell and clip gage, respectively.

Fracture surfaces of all specimens were observed by using a scanning electron microscope (SEM) to understand microstructures and fracture mechanisms of C/C composite.

3. Results and discussion

Fiber reinforcement of brittle materials is one the most promising ways to substantially improve fracture resistance. Fracture resistance characterization is needed for mechanical performance prediction and for design against fracture and cracking failure in these materials. Li [7] and Li et al. [8] have proposed a novel J-based fracture testing technique to characterize the fracture behavior of concrete. This technique has been recognized to be adequate for fracture analyzing in concrete and ceramic matrix composites. In this chapter, we present the results on analyzing the data for C/C composite, based on the technique briefly introduced by Li [7].

J-integral contour is presented in Fig. 4 for a material where the crack tip singularity coexists with the fracture process zone. The J-integral path independent property requires [12]

$$J_\infty = J_b + J_{tip} \tag{1}$$

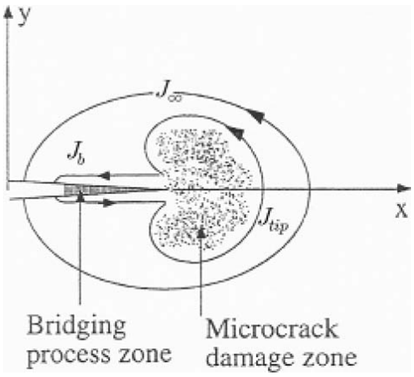


Fig. 4. Principle of J-based testing technique, showing J-integral contour for a material.

where J_∞ is the energy release rate associated with far-field loading, J_b is the energy consumed by the development of the fracture process zone and J_{tip} is the crack tip singularity.

Applying the J-integral analysis to the terms J_b and J_{tip}, Eq. (1) can be expressed by [12]

$$J_\infty = \int_0^{\delta_t} \sigma(\delta)\,d\delta + \frac{K_{tip}^2\left(1-\nu^2\right)}{E} \tag{2}$$

where δ_t is the crack opening displacement, K_{tip} is the crack tip stress intensity factor, and E and ν are Young's modulus and Poisson's ratio.

Differentiating Eq. (2) with respect to δ_t, the stress, σ, may then be determined from [12]

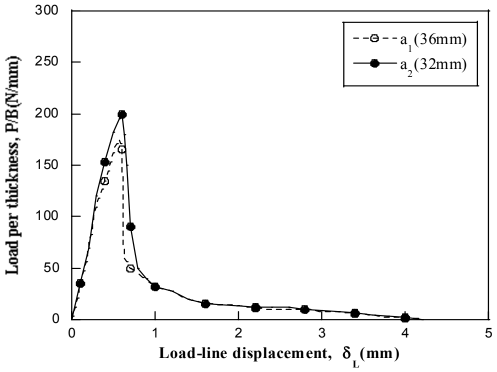
$$\sigma(\delta_t) = \frac{\partial}{\partial \delta_t}\left| J_\infty(\delta_t) - \frac{K_{tip}^2\left(1-\nu^2\right)}{E}\right| \tag{3}$$

Thus, if J_∞ and K_{tip} can be determined, δ_t can be obtained experimentally, and then the σ-δ relationship can be derived from Eq. (3). On the other hand, the J-integral value can be evaluated by conducting tests on two specimens with different crack depth by using the following equation [12] :

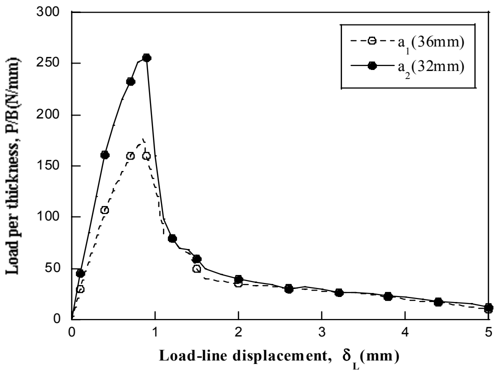
$$\begin{aligned} J_\infty(\delta_L) &= \frac{1}{a_2 - a_1}\int_0^{\delta_L}\left(\frac{P_1}{B_1} - \frac{P_2}{B_2}\right)d\delta_L \\ &= \frac{S(\delta_L)}{a_2 - a_1} \end{aligned} \tag{4}$$

where B is the specimen thickness, S (δ_L) is the area under the P/B- δ_L curve, and P and δ_L are load and load-line displacement.

Typical P/B- δ_L curves for different notch depths are shown in Fig. 5 for CT190 and CT191 composites. In both cases are an initial linear elastic region is followed by nonlinear load increase to a maximum, followed by continuous load decrease. It is the noncatastrophic decrease in load that gives these materials the appearance of being very tough. For these specimens, the P/B- δ_L curves for the long notch depth join with those for the short notch depth approximately at the load-line displacements of 0.96 ㎜ (CT190) and 1.26 ㎜ (CT191). It is known that the traction-free crack starts to grow at the deformation level [12]. Similar curves have been reported for the test of glass ceramics [1]. The J_∞ values of CT190 and CT191

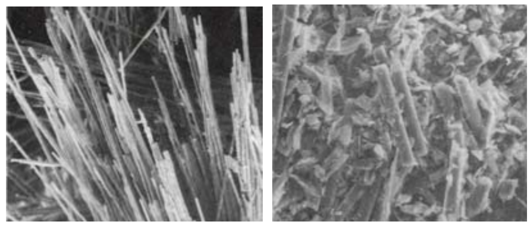


(a) CT190 (τ =13 ㎫)



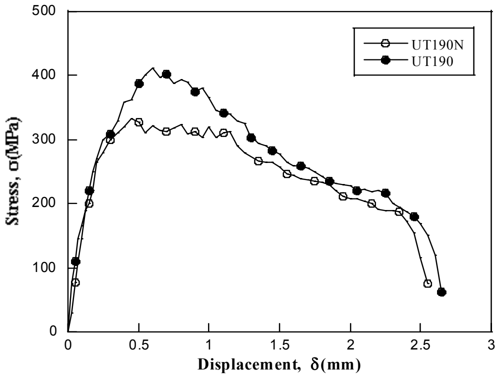
(b) CT191 (τ =18 ㎫)

Fig. 5. Load versus load-line displacement curves for different prenotch depth, showing results of CT190 and CT191.

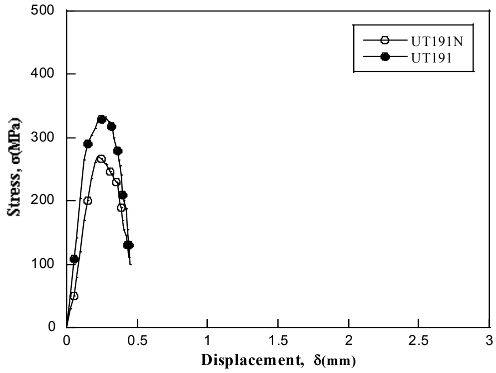


(a) CT190 (τ =13 ㎫) (b) CT191 (τ =18 ㎫)

Fig. 6. SEM photographs of fracturesurfaces for CT190 and CT191.



(a) CCM190C



(b) CCM191C

Fig. 7. Stress-displacement curves for notched and unnotched specimens of CCM190C and CCM191C.

can be calculated by Eq. (4), and the values were $4.50\,kJ/m^2$ and $14.02\,kJ/m^2$, respectively. For CT191 relatively higher interfacial shear strength specimen, the value was more than three times that of CT190. This result indicates that the interfacial shear strength can significantly affect the toughness and fracture behavior of C/C composite.

Fracture surfaces were observed by SEM, and representative examples are shown in Fig. 6 for CT190 and CT191. In CT190, carbon fibers were pulled out and most fibers were bare on the fracture surface. Thus, it can be deduced that the toughening of CCM190C is mainly caused by the fiber pull-out and bridging processes in the wake of the propagating crack tip. On the other hand, for CT191 limited fiber pull-out and bridging were observed, and the fracture surface was almost covered by matrix carbon and broken carbon fibers. This means that the fiber/matrix interface bonding in CCM191C is to be strong enough for the crack to propagate into the fiber. It is obvious that the toughness enhancement in CCM191C was closely associated with the fiber breakage in the fracture process zone.

Fiber bridging may be characterized by the relationship between the traction acting across a crack plane, σ , and the average separation distance of the crack faces, δ , and therefore the relation can be obtained from a direct tension test [7, 8, 12]. Fig. 7

shows the typical stress-displacement curves obtained from an axial tensile tests for CCM190C (UT190N, UT190) and CCM191C (UT191N, UT191). For the tensile test the stress was obtained from the measured load divided by the net cross-sectional area of the specimen. Notched and unnotched specimens of each case showed similar behavior under axial tensile load. In both cases an initial linear elastic region is followed by nonlinear load increase to a maximum. It is obvious that all specimens used in this tensile test failed with a pseudo strain-hardening. CCM190C (Fig. 7(a)) shows a larger pseudo strain-hardening region than that of CCM191C (Fig. 7(b)). Particularly, the different shapes of the postpeak stress-displacement curves imply significant differences in the fracture mechanisms and effects of reinforcement of these composites. Also, these phenomena indicate that the interfacial shear strength can significantly affect the tensile behavior of the C/C composite. Relative lower interfacial shear strength will facilitate fiber pull-out and bridging process in the wake of the propagating crack tip. In contrast, relatively higher interfacial shear strength will suppress the fiber pull-out in the fracture process zone and can contribute to occurrence of fiber breakage.

The energy consumed by the development of the fracture process zone at postpeak, J_b, can be evaluated from the area ABDF under the stress-displacement curve as shown in Fig. 8. The area ABDF can be determined from the alternative area ABCE.

The values of J_b, J_{tip} and J_∞ were calculated for five specimens and the averages were listed in Table 2. The J_b values of notched and unnotched specimens were almost the same. This result suggests that the presence of notch can not significantly affect the J_b value at the postpeak part. The bridging energy, J_b, of CCM190C is 0.554kJ/㎡ and the ratio of the J_b to the

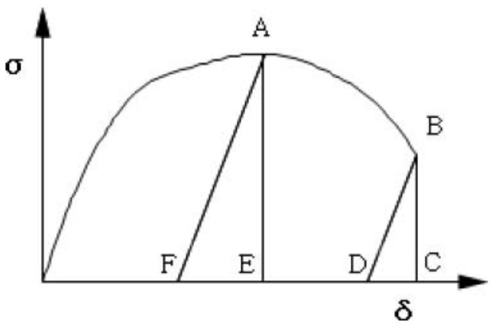


Fig. 8. Schematic illustration for calculation of postpeak bridging energy.

total fracture energy consumed to produce unit area of fracture surface, J_∞, is 12.3%. This result obtained from tensile test of CCM190C implies that the effect of the bridging energy at the postpeak part on the fracture toughness is not negligible. On the other hand, the ratio of CCM191C is only 0.37%, and the contribution of J_b for the total fracture energy per fracture surface is very small, but CCM191C showed relatively higher J_∞ value because of high crack tip singularity (J_{tip}). For CCM190C, the J_∞ is lower than that of CCM191C, despite a number of fiber pull-outs and bridging process, and is responsible for low crack tip singularity caused by relatively lower interfacial shear strength.

4. Conclusions

Fracture properties of commercial carbon fiber reinforced carbon matrix composites (CCM190C, CCM191C) using the J-based technique were investigated. The fracture properties of these C/C composites could be appreciated by the J_b and J_∞ values. However, it must be emphasized that the J-based technique application is restricted to the postpeak part of the stress-displacement relationship.

The important role of interfacial shear strength of C/C composite was emphasized through the present work. Considering that the interfacial shear strength for CCM191C was higher than that of CCM190C, there should be a close relationship between the interfacial shear strength and fracture toughness. For CCM190C, the total fracture energy (J_∞) which is lower than that of CCM191C is responsible for low crack tip singularity (J_{tip}) caused by relatively lower interfacial shear strength.

The different shapes of the postpeak stress-displacement curves imply significant differences in the fracture mechanisms and effects of reinforcement of these composites. It is obvious that the failure manner in the fracture process zone is primarily fiber

Table 2. Various fracture energies calculated for CCM190C and CCM191C.

Material	J_b (J/㎡)	J_{tip} (kJ/㎡)	J_∞ (kJ/㎡)
CCM190C	554 (Ave.) 548 (Notched) 560 (Unnotched)	3.946	4.50
CCM191C	52 (Ave.) 51 (Notched) 53 (Unnotched)	13.968	14.02

pull-out for CCM190C and fiber breakage for CCM191C, respectively. This is illustrated by the SEM micrographs showing the fracture surfaces.

The interfacial shear strength has been shown to play an important role in the design of the pseudo strain-hardening property to improve the fracture toughness of C/C composite.

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