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Mixed Mode I-II Fracture Behavior of Selected Nuclear Graphites

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1. Introduction

Due to its excellent neutronic, thermal and mechanical properties, graphite has been used in nuclear reactor cores, not only as a moderator and reflector but as a major structural component. During reactor operation, the graphite components are subjected to combined loading such as external forces and internal stresses resulting from irradiation-induced dimensional and material property changes and due to thermal gradients. Fracture mechanics-based structural integrity assessments of graphite components may require understanding the mechanisms and failure criteria of graphite under both single mode and mixed mode loading. In this study, in order to gain an understanding of the effects of mixed mode loading on the fracture behavior, the fracture behavior under mixed mode I-II were examined for selected nuclear graphite using a notched disk specimen.

2. Experiment

2.1 Materials

Five nuclear grade graphites were used in this study: IG-110 and IG-430 produced by the Toyo Tanso Co, Ltd, Japan and NBG-17, NBG-18 and NBG-25 produced by the SGL Carbon Group, Germany. The main properties of the graphites are summarized in Table 1.

Table I: Typical properties of the five graphites

Grade	Coke type & size	Molding method	Density (g/cm^3)	$\sigma_{Compressive}$ (MPa)
IG-110	Petroleum (20μm)	Isostatic	1.78	81.3
IG-430	Pitch (10μm)	Isostatic	1.82	
NBG-17	Pitch (Max. 00μm)	Vibrational	1.86	75.7
NBG-18	Pitch (Max. 1800μm)	Vibrational	1.81	72
NBG-25	Petroleum (Max. 60μm)	Isostatic	1.86	105.4

2.2 Mixed mode fracture tests

For mixed mode fracture tests, we used centrally notched disk specimens with the size of 30 mm in diameter and 3 mm in thickness. The notch length and width were 9 mm (i.e., a/R=0.3) and 1 mm, respectively.

The specimens were loaded diametrically using a 30 kN capacity universal testing machine with a crosshead speed of 0.125 mm/min at ambient air. Fracture toughness under mixed mode I-II were obtained simply changing the notch inclination angle (β) from 0^o to 30^o with respect to the loading direction. The stress intensity factors under Hertzian contact were calculated modifying the non-dimensional stress intensity factors in the combined mode subjected to a concentrated force in the disk test [1,2]:

$$K_{I,IIc} = N_{I,II} \frac{P_c}{Rt} \sqrt{\frac{a}{\pi}}$$

$$N_{I,II} = N_{I,IIp} \frac{1-(b/R)^2}{\delta_{I,II}}$$

The contact width b was measured using the pressure sensitive paper Prescale (Fuji Film Co.).

3. Results and Discussion

3.1 Load-displacement curve

Figure 1 shows typical load-displacement curves for various notch inclination angles.

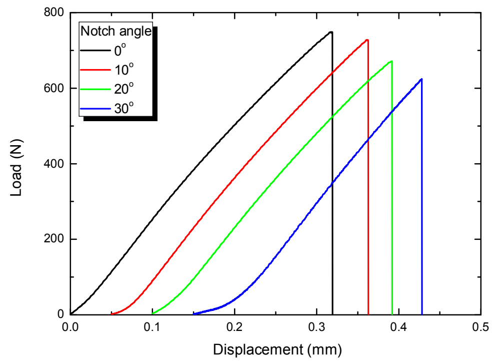
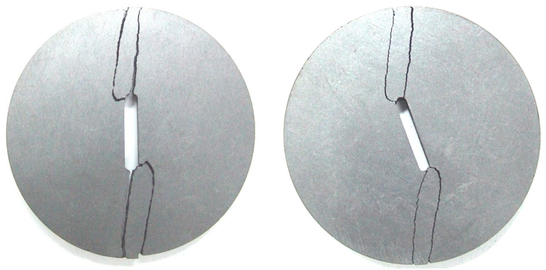


Fig. 1. Load-displacement curves with increasing notch inclination angles for IG-110.

The fracture load decreased as the notch inclination angle increased. The dependence of the fracture load on the notch inclination angle in the mixed mode loading condition can be understood by examining the stress distribution of notch tip formulated by Atkinson [3]. For pure mode I (β = 0^o), the tensile tangential stress is maximum but the shear stress is zero so that the crack propagates only under the influence of the tangential stress as shown in Fig. 2. (a). However, for mixed mode I-II loading ($0^o < \beta < 30^o$), the shear stress is positive with a maximum value at around $\beta = 30^o$ and the tangential stress is still tensile. The sharp crack initiated by the shear deformation at the notch tip might intensify the tangential stress so that the crack could be propagated in mode I at relatively low fracture load with increasing the notch inclination angle as shown in Fig. 2. (b).



(a) (b)

Fig. 2. Typical crack paths under (a) mode I and (b) mode I-II ($\beta = 20^o$) for IG-110.

2.4 K_I-K_{II} curve

The results of mode I-II fracture toughness testing for five grades of nuclear graphite are summarized in Table 2.

Table 2: Results of mixed mode I-II fracture toughness tests

Grade	β (degree)	K_{Ic} or K_I ($MPam^{1/2}$)	K_{IIc} or K_{II} ($MPam^{1/2}$)
IG-110	0	0.64	0
	10	0.54	0.48
	15	0.42	0.70
	20	0.25	0.82
	25	0.07	0.95
	30	-0.11	1.00
IG-430	0	0.78	0
	10	0.64	0.64
	15	0.47	0.79
	20	0.30	1.00
	25	0.08	1.08
	30	-0.18	1.21
NBG-17	0	0.83	0
	10	0.70	0.63
	15	0.54	0.91
	20	0.31	1.05
	25	0.09	1.27
	30	-0.18	1.32
NBG-18	0	0.92	0
	10	0.74	0.68
	15	0.56	0.96
	20	0.35	1.19
	25	0.09	1.28
	30	-0.18	1.42
NBG-25	0	0.80	0
	10	0.66	0.60
	15	0.49	0.83
	20	0.31	1.04
	25	0.09	1.15
	30	-0.17	1.20

As shown in Fig. 3, the ratios of K_{IIc}/K_{Ic} were in the range of 1.5~1.6 regardless of the coke type and size. These ratios are which is a little larger than the reported value of 1.24 for IG-11 [4].

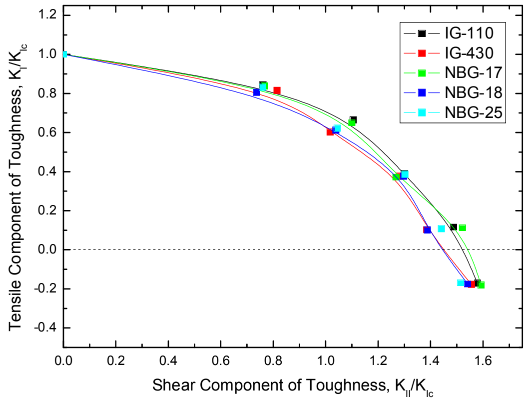


Fig. 3. Normalized mode I and mode II stress intensity factors for mixed-mode fracture tests.

3. Conclusions

The mixed mode I-II fracture behavior of selected nuclear graphites was examined at room temperature in an ambient air environment and the results are summarized as follows;

1. The fracture loads of the nuclear graphites decreased as the notch inclination angle increased under the mixed mode I-II loading due the sharp crack initiation by the shear deformation at the notch tip.

2. The values of K_{IIc}/K_{Ic} were in the range of 1.5~1.6 regardless of the grade of nuclear graphites.

Acknowledgement

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