FRACTURE AND CRACK GROWTH BEHAVIORS OF NUCLEAR GRADE GRAPHITES

Eung-Seon Kim and Yong-Wan Kim

Nuclear Hydrogen Reactor Technology Division, Korea Atomic Energy Research Institute, Daedeok-daero 1045, Dukjin-dong, Yuseon-gu, Daejeon, 305-353, Korea

Introduction

Graphite will be used in very high temperature gas-cooled reactors (VHTR) not only as a moderator and reflector but also as a major structural component due to its excellent neutronic, thermal and mechanical properties. During a normal operation, these graphite components are subjected to various loadings such as external force and internal stresses resulted from neutron irradiation-induced dimensional and material property changes and a thermal gradient. Fracture mechanics-based structural integrity assessments of graphite components may be required to understand the mechanisms and failure criteria of a nuclear grade graphite for the VHTR. In this work, the fracture toughnesses and strain energy release rate of selected nuclear grade graphites were investigated.

Experimental

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 nuclear graphites

Grade	Coke type & size	Molding method	Density (g/cm^3)	σ_C (MPa)
IG-110	Petroleum (20μm)	Isostatic	1.78	79
IG-430	Coal Tar (10μm)	Isostatic	1.82	89
NBG-17	Coal Tar (Max. 800μm)	Vibrational	1.86	75
NBG-18	Coal Tar (Max. 1600μm)	Vibrational	1.85	72
NBG-25	Petroleum (Max. 60μm)	Isostatic	1.82	104

For fracture tests, we used a straight-through notched 3 point bending specimen with the size of 200 mm in length (L), 15 mm in thickness (B) and 20 mm in width (W). The notch length to width ratio, a_0/W was 0.4 and the span to width ratio, S_o/W was 0.8. Fracture tests were conducted using a 30 kN capacity universal testing machine with a crosshead speed of 0.01 mm/min at ambient air. Fracture toughness, K_{Ic} and strain energy release rate, G_I were measured based on the tentative ASTM standard for graphite [1].

The fracture toughness was calculated from the maximum load, P_{max} as follows:

$$K_{Ic} = g\left[\frac{P_{max} S_0}{BW^{3/2}}\right]\left[\frac{3[a/W]^{1/2}}{2[1-a/W]^{3/2}}\right]$$

where g = 1.9381 - 5.0947(a/W) + 12.3861$(a/W)^2$ -19.2142$(a/W)^3$ + 15.7747$(a/W)^4$ - 5.127$(a/W)^5$. Strain energy release rate, G_I was calculated by the compliance method as follows:

$$G_I(a_n) = \frac{P^2}{2B}\frac{\delta C}{\delta a}$$

where $a_n = a_{n-1} + [(W - a_{n-1})/2 \times (C_n - C_{n-1})/C_{n-1}]$, $\delta C = (C_n - C_{n-1})$ and $\delta a = (a_n - a_{n-1})$. At first, data lying in the linear portion of the load-displacement curve were fitted to a linear line. The beginning of crack propagation was considered to be the point where displacement departs from the calculated linear line by 0.002mm. The crack initiation point during the fracture test was observed using direct current potential drop (DCPD) method and a telescope with 45 magnifications.

Results and Discussion

The typical load-displacement curve for the IG-110 is shown in Fig. 1. The point of onset of the main crack initiation, **B** observed by the telescope and an optical microscope. Generally, the point was near the intersection between the load-displacement curve and 0.002 mm offset line. Also, the DCPD voltage began to increase at the point. For all the graphites, microcracks were observed in the frontal portion of the notch tip at about 70~80 % of the maximum load as reported by Sakai [2]. Some of the microcracks joined and grew to the main crack. The crack extension was about 0.5 mm till the maximum load reached.

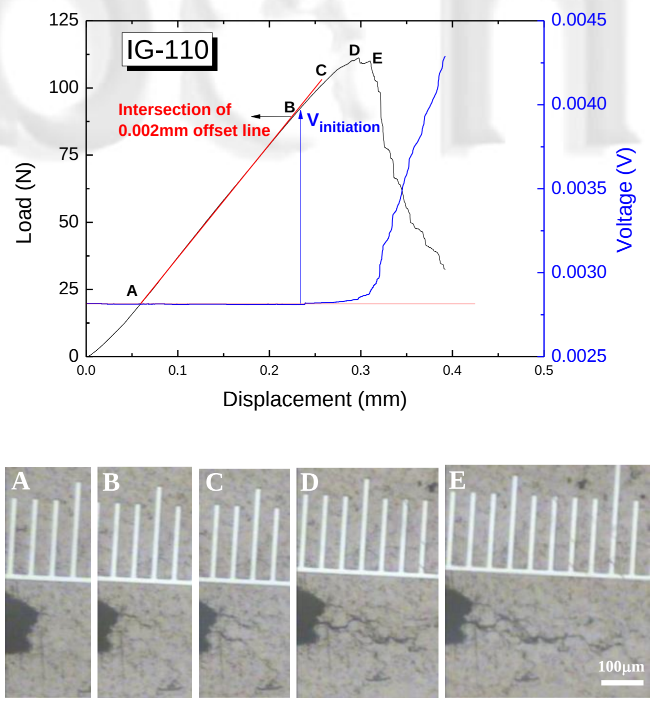


Fig. 1 Typical load-displacement curve for IG-110 and microcracks formation in the notch tip.

The fracture toughness results for the graphites are shown in Fig. 2. The lowest value of K_{Ic} was 0.82 $MPam^{1/2}$ for the IG-110 with low density, elastic modulus and high porosity. In the case of the IG-430, NBG-17 and NBG-25 having higher density than the IG-110, the values of K_{Ic} were around 1.07 $MPam^{1/2}$ and higher than that of the IG-110. Although the density of the NBG-18 is nearly equal to that of the NBG-17 but the K_{Ic} value of the NBG-18 was 1.34 $MPam^{1/2}$, much higher than that of the NBG-17.

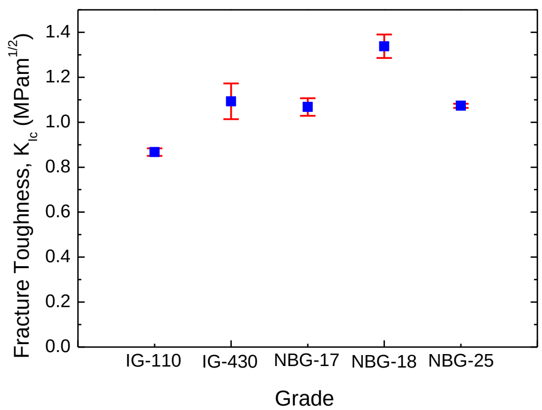


Fig. 2 Fracture toughness, K_{Ic} of nuclear grade graphite.

Fig.3 shows the strain energy release rate-crack extension curves for the nuclear grade graphite. Except for IG-430, as the coke particle size increased the G_I value was higher for a given crack extension. This trend reflects that the greater extent of energy was dissipated in the coarser-grained graphite during crack propagation by irreversible processes such as microcracking in the frontal process zone, irreversible slip deformation along the basal planes, crack bridging in the crack wake and branching as shown [3,4]. Typical shielding mechanisms observed using a scanning electron microscope (SEM) were shown in Fig. 4.

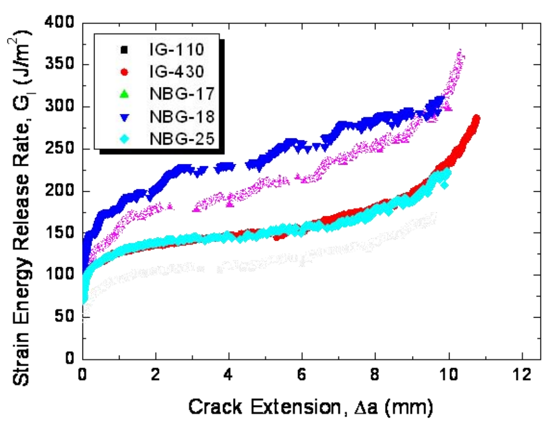
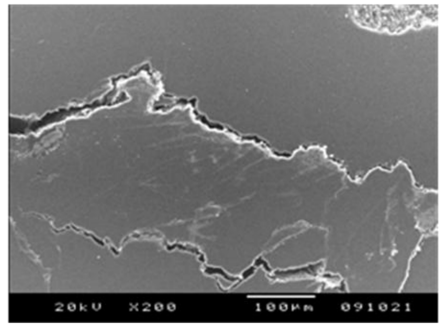
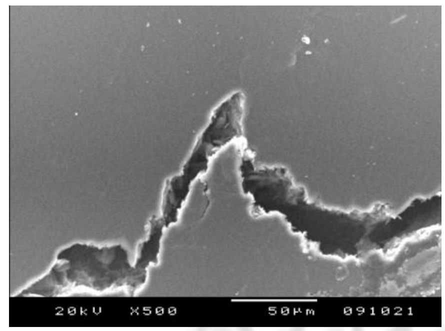


Fig. 3 Strain energy release rate, G_I of nuclear grade graphite



(a)



(b)

Fig. 4 SEM micrographs showing (a) the crack branching and (b) the high crack tortuosity in NBG-18.

Conclusions

The fracture tests were performed for commercially available nuclear grade graphites at ambient temperature and the results are summarized as follows;

1. The main crack initiated at about 70 % of the maximum load and extended about 0.5 mm till the maximum load reached.
2. The nuclear grade graphites with the coarser coke particles showed higher fracture toughness and much better resistance to the crack propagation.

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