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Characterization of Strength and Fracture Toughness of Nuclear Graphite Using Subsize Specimen

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1. Introduction

Graphite is a key material for the fourth generation nuclear energy system. The mechanical property database for new grades of graphite must be developed to support the design and integrity assessment of core components [1].

Small specimens have been used for the evaluation of irradiated structural material to reduce irradiation volume, personal dose, and post-irradiation testing costs [2]. The graphite usually shows a brittle or quasi-brittle behavior in failure. Therefore, the mechanical properties of graphite are expected to show a large scatter and size dependence. The use of subsize specimen needs to be justified for physical & mechanical testing.

The objective of this study is to investigate the size effect and statistical characteristics in the strength and fracture toughness of NBG-18 nuclear graphite by using subsize specimen.

2. Experimental

2.1. Material and Specimens

The test material was NBG-18 vibrationally-molded nuclear grade graphite. The filler coke is coal tar pitch derived with a maximum filler particle size of 1.6 mm.

Three sets of cylindrical subsize specimens, 4 mm(φ) x 17.8 mm(L), 8 mm(φ) x 27.9 mm(L), and 12 mm(φ) x 45.7 mm(L), were machined from a billet. The standard specimens with 15.9 mm diameter whose strength data were used as reference data, were from the same billet.

2.2. Experimental Methods

The measurement of tensile fracture strength for NBG-18 was made following the procedure of ASTM C 781-A4. The metal heads were bonded to the specimen ends with epoxy adhesive. To obtain fracture toughness, edge-notched three-point bend round bar specimens were fabricated from the broken subsize tensile specimens after tension testing. A specially designed jig was used for three-point bending tests to measure fracture toughness from the broken halves. The tensile and three-point bending specimens were all tested in an electro-mechanical universal testing machine. The strain rate for the tension testing was 2.4 x 10^{-4}/s and the crosshead displacement rate for the three-point bending fracture toughness tests was 0.25-0.51 mm/min.

3. Results and Discussion

3.1. Fracture Strength and Weibull Statistics

The fracture strength data ranged from 15.4 MPa to 28.2 MPa, the mean values are on a simple trend line as shown in Fig. 1.

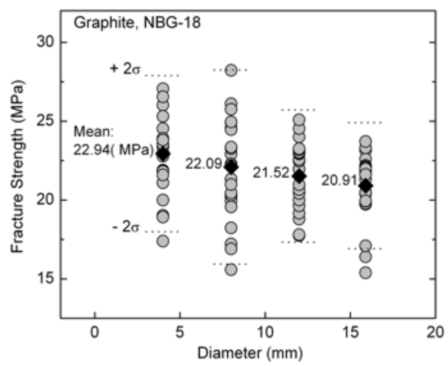

Fig. 1. The variation of tensile fracture strength of NBG-18 graphite with a variation of specimen diameter.

A two-parameter Weibull statistical model described in Eq. (1) is adopted to the analysis of fracture strength data, as well as to the treatment of fracture toughness data:

$$P_f = 1 - \exp[-V(\sigma_f / \sigma_0)^m] \quad (1)$$

Where P_f is the cumulative probability of fracture; σ_f is the measured fracture strength; σ_0 is the characteristic stress (scale parameter equivalent to the stress level at 63.2% failure probability), V is the volume of specimen, and m is the shape parameter(Weibull modulus).

The measured Weibull modulus of each sample was in the range of 7.7 – 10.9.

3.2. Fracture Toughness

The fracture toughness data were obtained from the broken tensile specimens to guarantee the property to be obtained from the same material as that for strength, as well as to develop the technology for specimen reuse. A linear elastic equation for stress intensity factor has been developed for the edge-notched round bar specimens under three-point bend loading [3]. A correction was made on the calculated stress intensity factor to consider notch–root radius and notch-tip shape effect following the procedures established in earlier studies [4, 5].

Fig. 2 displays the fracture toughness data (K_Q) with respect to the specimen diameters. These facture toughness data does not show any size effect: the mean fracture toughness values for the subsize specimens with the diameters of 4 mm, 8mm and 12 mm were 1.26, 1.21, and 1.25 MPa√ m, respectively.

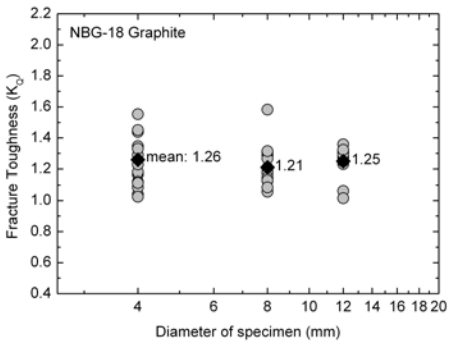

Fig. 2. The variation of fracture toughness of NBG-18 graphite with a variation of specimen diameter.

Despite similar mean fracture toughnesses being obtained for different specimen sizes, the Weibull modulus increased from about 8 to 12.4 as the specimen diameter increased from 4 to 12 mm.

3.3. The Size effect

The failure process of graphite is usually considered to be a function of the stressed volume. For identical material with different sizes but uniform loading distribution, except for the magnitude of the loading, and with an identical survival probability, Eq. (1) yields

$$\sigma_{f_2} = \sigma_{f_1} (V_2 / V_1)^{-1/m} \qquad (2)$$

where subscripts 1 and 2 denote material with different sizes. Eq. (2) is a Weibull size-effect equation that predicts the fracture strength of graphite or other materials of similar fracture characteristics, which indicates the strength of a material is a function of specimen size or stressed volume.

Fig. 3 displays the size effect on strength of NBG-18 graphite.The slope of the log scale plot which corresponds to $-1/m$ is only -0.02. The Weibull modulus for NBG-18 is expected to be about 50, according to the Weibull statistics model, Eq. (2). This is about 5 times larger than the Weibull modulus measured from the tensile fracture strength data. Earlier experimental studies for size effect in graphite also showed much smaller size effect than that would have been expected based on the Weibull distribution for the tensile specimens [6, 7].

The small-sized tensile specimens were often observed to be weaker than larger size specimens, on the contrary to the expectation based on the Weibull theory. The diameters of specimens for tensile tests were less than ten times filler particle size of NBG-18 graphite. Therefore, it can be deduced that the diameter of small tensile specimen may have played a role in the lack of a significant size effect.

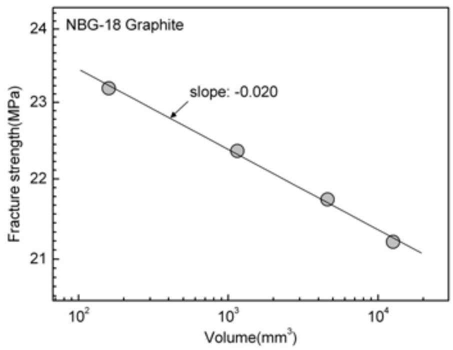

Fig. 3. Correlation between specimen volume and fracture strength in NBG-18 graphite. The slop of best fit line in this diagram corresponds to -1/*m*.

4. Summary and Conclusions

The tensile fracture strength and fracture toughness of NBG-18 nuclear grade graphite were evaluated using subsize specimen technique. The mean fracture strength decreased from 22.9 MPa to 21.5 MPa as the diameter increased from 4 mm to 12 mm, which further decreased to 20.9 MPa for the 15.9 mm diameter standard specimen. The size effect in these experimental data was much smaller than that predicted by the Weibull statistics. The mean fracture toughness values were in a narrow range of 1.21–1.26 MPa, and indicated no noticeable size effect. Both fracture strength and toughness data show similar Weibull moduli around 10. The mild or no size effect in fracture strength and toughness indicates that the error incurred by using small specimens will be minimal, which, along with a scaling or size-compensating technique, can support the extensive use of subsize specimens.

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