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THE FRACTURE TOUGHNESS OF GRAPHITE
DOUBLE CANTILEVERED BEAM SPECIMENS

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THE FRACTURE TOUGHNESS OF GRAPHITE
DOUBLE CANTILEVERED BEAM SPECIMENS

L. O. Slind

ABSTRACT

A double cantilever beam specimen was calibrated and found useful in determining the plane strain fracture toughness of SGBF nuclear graphite. G_{Ic} , the plane strain energy release rate, and K_{Ic} , the plane strain stress intensity factor, were determined to be 1.18 in.-lb/in.² and 1386 $\sqrt{\text{in.-lb/in.}^2}$, respectively at room temperature. These values are for with-the-grain fractures only.

The theory of fracture mechanics is discussed in the abstract.

Two sections discuss the calibration of the double cantilever beam.

It's application to fracture is discussed. The last section

discusses the application of the results to the design of

THEORY OF FRACTURE

Of the three methods of fracture mechanics, the energy

in the crack is the most fundamental. It is the energy

the crack is released due to the extension of the crack in pure

shear. The energy released is proportional to the crack length. Experiments with

specimens of various materials have shown that the energy released is

proportional to the square of the crack length. This is the basis of

the energy release rate.

INTRODUCTION

Nuclear graphite at room temperature is a brittle material since very little plastic deformation occurs prior to crack initiation. Naturally, such behavior poses a potential problem and graphite components must be designed to avoid such behavior.

Fracture mechanics is a promising approach to engineer around the brittle fracture problem. Briefly, the application of fracture mechanics will permit control of brittle fracture by limiting the applied stress to a value which is compatible with the fracture characteristics of the material. One of the most important characteristics is fracture toughness, a measure of a material's ability to resist fracture.

This paper reports on the feasibility of using a double cantilever beam, DCB, specimen for measuring the plane strain fracture toughness of nuclear graphite. The theory of fracture toughness is described in the first section. The following two sections discuss the calibration of the double cantilever beam specimen and its application to fracture toughness testing. The last section contains a discussion on the application of the results and suggestions for future work.

THEORY OF FRACTURE TOUGHNESS

Griffith⁽¹⁾ theorized that a brittle material, such as glass, contains defects in the form of microcracks. He proposed that crack propagation would occur when the strain energy released during extension of a crack is greater than the surface energy of the newly formed segment of the crack. Experiments with thin glass specimens having artificially introduced cracks showed that the calculated surface energy agreed within one order of magnitude with values of surface energy determined from other experiments.

To determine the strain energy released during a small crack extension, Griffith's theory employs an analytical solution to the stress field about the crack tip. This method is accurate, provided that the size of the plastic zone at the tip of the crack is small compared to the size of the crack, and the gross stress on the system is in the elastic range. However, the fracture of an amorphous brittle material, such as glass, is considerably different from that of less brittle, polycrystal. A major difference is the amount of plastic deformation at the crack tip prior to fracture. Plastic deformation in glass at room temperature is negligible. Thus, only the energy necessary to create two new surfaces at the tip of the crack is required for crack propagation. However, for crack propagation in polycrystalline materials, such as metals, additional energy is needed to plastically deform the grains surrounding the tip of the crack. In fact, the surface energy is often negligible in comparison with the work of plastic deformation. Unlike surface energy, the work of plastic deformation is very difficult to calculate.

The application of Griffith's crack theory to materials that deform plastically at the crack tip was not feasible until Irwin demonstrated that plastic deformation could be included in Griffith's theory while retaining the linear elastic concepts. This approach, referred to as the Griffith-Irwin crack theory⁽²⁾, assumes that rapid crack propagation will begin from a stationary or slowly propagating crack whenever a small extension of the crack releases as much stored elastic strain energy as the total energy, both plastic deformation and surface, required to form the new crack increment. The elastic strain energy release is G , measured in units of in.-lb/in.^2 . At the point of instability, i.e., where the crack propagates rapidly without an increase in stress, G becomes G_c (G "critical") the fracture toughness. Under conditions of plane strain at the crack tip G is denoted G_I and is related to the plane strain stress field

parameter, K_I , by the following relationship

$$K_I = \sqrt{\frac{EG_I}{1-\nu^2}}$$

where E is the elastic modulus and ν is Poisson's ratio. K_I , measured in units of $\sqrt{\text{in.-lb/in.}^2}$, is a measure of the stress elevation relative to the undisturbed stress field caused by the presence of a crack. G_{Ic} and K_{Ic} are the parameters for fracture toughness generally discussed in the literature.

Plane strain fracture toughness appears to be a basic material property that is independent of size, shape and type of loading of the specimen. It does depend on composition, microstructure, temperature, and rate of loading.

THE DCB SPECIMEN AND ITS CALCULATION

The Griffith-Irwin crack theory can be applied to nuclear graphite for design purposes or fundamental investigations. For such application the fracture toughness of nuclear graphite must be measured. The following sections describe the development of a method for such measurements.

A variety of specimen shapes can be used for determining the fracture toughness of nuclear graphite. These include a center or surface cracked panel, single edge notched panel, notched round bar and a double cantilever beam. The latter has been investigated at this laboratory for fracture toughness tests on nuclear graphite.

The double cantilever beam (DCB) specimen has been used for surface energy studies of various materials by a number of investigators⁽³⁻⁷⁾. Berry⁽⁸⁾ and Gilman⁽⁹⁾ have extensively analyzed the mechanics of the specimen. In addition, the DCB specimen has been successfully used in determining the plane strain fracture toughness of various metals here at BNW⁽¹⁰⁾.

When the DCB specimen is stressed, a crack propagates down its length in jumps. Approximately 30 separate fracture toughness tests are obtained per sample of nuclear graphite. The fact that a single specimen of small size produces many data points is a distinct advantage, especially in radiation effects studies, where small specimens are used.

The DCB specimen design is shown in Figure 1. The dimensions for the width and depth of the beams of the DCB specimen represent a compromise. There must be enough mass to be representative of the graphite and provide restraint against plastic bending but minimum mass is desirable for irradiation effects studies.

Five specimens of varying section width, 0.066 - 0.300 in. (the distance between the grooves or the width of the plane of fracture) were prepared for calibration. Specimens 1, 2, 3, 4, and 5 will be identified in the following calibration procedure with section widths of 0.066, 0.130, 0.196, 0.262, and 0.300 in. respectively. These specimens were taken from the center portion of a 4 1/4 x 4 1/4 in. bar of SGBF nuclear graphite. Texas coke and Barrett Medium No. 30 pitch binder were used in this extruded graphite which was graphitized at 2450°C. SGBF's density is 1.64 g/cm³ and the transverse-to-parallel ratio of coefficients of thermal expansion is approximately 1.75. Since the length of the DCB specimens was parallel to the direction of extrusion, the tip of the crack extended parallel to the direction of extrusion. All tests were performed at room temperature.

The calibration of the DCB specimens determines the compliances, or the bending constants, of the beams of the specimens at known crack lengths. The compliance (ϕ) at a known crack length is the slope of the deflection-load curve.

$$\phi = y/f \quad (1)$$

where y is the deflection of the beams and f is the applied force.

Hoagland⁽¹⁰⁾ reports compliances found by measuring the length of the crack, loading the specimen until crack propagation occurred, measuring the new crack length and repeating the process until the crack had traveled the full length of the specimen. Unfortunately the porosity of graphite prevented positive identification of the crack tip position. Thus, a different approach was taken. A 0.010 in. saw was used to extend the crack down the length of the specimen in approximately 0.25-in. increments. At each increment the crack length was measured to an accuracy of ± 0.001 in. The specimen then was loaded to an amount necessary to define the slope of the deflection-load curve, but not enough to propagate the crack.

Twenty-two values of compliance at known crack lengths were determined for each specimen, thereby providing a statistical basis for determining the relationship between ϕ and c .

Figure 2 shows the relationship between the compliance, ϕ , and crack length, c , for the five specimens. The crack length is measured from the center of the holes in the specimen through which the loading pins pass. In all cases the relationship between ϕ and c could be represented by the empirical equation

$$\phi = Bc^n \quad (2)$$

where B and n are parameters whose values were estimated through a nonlinear regression analyses of the data for each specimen. This equation fits the data well for all of the specimens except (because of end effects) for data, shown by the unfilled circles in Figure 2, obtained on very short and very long cracks relative to the specimen length. These points were not used in the calculation of B and n given in Table I, below.

TABLE I

Results of Fit to Equation $\phi = Bc^n$

Specimen	Section Width, in.	$B \times 10^{-4}$	n
1	0.066	$3.590 \pm 0.315^*$	$2.616 \pm 0.0541^*$
2	0.130	2.817 ± 0.197	2.681 ± 0.0430
3	0.196	2.603 ± 0.148	2.669 ± 0.0349
4	0.262	2.654 ± 0.165	2.652 ± 0.0384
5	0.300	2.294 ± 0.184	2.734 ± 0.0491

* $\pm$ values are for 95% confidence limits.

APPLICATION OF THE DCB SPECIMEN TO FRACTURE TOUGHNESS TESTING

With the relationship of compliance and crack length for the DCB specimen known, the plane strain fracture toughness of SGBF graphite can be determined. The elastic strain energy developed in the arms of the DCB specimen is given by

$$U = 1/2 f y \quad (3)$$

The strain energy release rate, G, is given by

$$G = -\left(\frac{\delta U}{\delta A}\right)_y \quad (4)$$

where δA is the incremental increase in crack area.

$$\left(\frac{\delta U}{\delta A}\right)_y = \left(\frac{\delta U}{\delta c}\right)_y \frac{1}{W} \quad (W \text{ is the section width}) \quad (5)$$

From Equations 1-5 one obtains an equation for G which was used for this study

$$G = \frac{n y^2}{2 w B} \left(\frac{B f}{y}\right) \frac{n+1}{n} \quad (6)$$

G may then be converted to K, for plane strain conditions, using

$$K_I = \sqrt{\frac{E G}{1-\nu}} \quad (7)$$

where E is the elastic modulus, 1.61×10^6 psi in the direction parallel to extrusion for SGBF graphite, and ν is Poisson's ratio, 0.1 for SGBF graphite.

When fracture occurs, the results can be described in terms of G_c or K_c or their plane-strain counterparts G_{Ic} or K_{Ic} . In plane strain fracture there is negligible deformation parallel to the crack front prior to fracture. This condition is achieved by having a thickness (section width) large enough to prevent deformation in this direction. In the case of the DCB specimen, the sharply pointed grooves provide a highly triaxial stress state. Therefore, one goal of this study was to determine if the five specimens studied would exhibit plane strain fracture.

Duplicates of the five specimens were tested at room temperature. These specimens were loaded in the Instron, a tensile testing machine, as shown in Figure 3, and the initial crack was extended down the length of the specimen in jumps. This crack-propagation produced the recording seen in Figure 4. From this recording one can determine the coordinates of the points of crack initiation and crack arrest.

Examining the recording, one can see two nonlinear portions of the deflection-load curve prior to crack initiation. The nonlinear portion in the low Y region shows that the system is not perfectly "stiff." The nonlinear portion in the upper Y region resulted from inelastic behavior of the specimen due to slow crack growth and plastic bending of the arms. This plastic bending is shown in Figure 5. The distance, d , varied from 0.001 in., for the specimen of 0.066 in. section width, to 0.009 in., for the specimen of 0.300 in. section width.

Because the determination of fracture toughness using the DCB specimen assumes a linear deflection-load curve, a correction was required for the nonlinear portions. A line was drawn tangent to the linear portion, as shown in Figure 4, and its intercept with the Y axis was designated Y_0 . This line intersects the vertical line through the point of crack initiations at point Y_c' .

The deflection, Y_p , between this intercept, Y_c' , and Y_c , the deflection at crack initiation, represents the inelastic behavior of the specimen. The gap between Y_0 and the actual intercept of the deflection-load curve with the Y axis, represents the "slop" in the system. Thus the deflection used for this crack propagation would be $Y_c' - Y_0$. The second crack propagation shown in the recording was not used because its inelastic behavior could not be confidently estimated.

A computer program is used to calculate fracture toughness values for each crack propagation. The results are shown in Table II. G_{Ic} and K_{Ic} are the average fracture toughness values at crack initiation and G_{Ia} and K_{Ia} are the average values at crack arrest. The difference between G_{Ic} and G_{Ia} or K_{Ic} and K_{Ia} is a measure of a material's ability to arrest a propagating crack. Generally a smaller difference denotes greater crack arrest capability.

TABLE II
Results of Fracture Toughness Tests

<u>Section width, in.</u>	<u>G_{Ic} lb-in./in.²</u>	<u>G_{Ia} lb-in./in.²</u>	<u>K_{Ic} lb-√in./in.²</u>	<u>K_{Ia} lb-√in./in.²</u>
0.066	1.26	1.15	1430	1368
0.130	1.34	1.28	1474	1438
0.196	1.18	1.15	1386	1366
0.262	1.29	1.24	1446	1419
0.300	1.19	1.14	1388	1362

EFFECT OF SECTION WIDTH

Figure 6 shows the effect of section width on K_{Ic} . For each section width the measured range of K_{Ic} and average K_{Ic} are shown. Examination of these results indicates that K_{Ic} is essentially constant, i.e., plane-strain conditions exist.

for the range of section widths studied. This is to be expected since graphite is brittle and the sharply pointed grooves on the sides of the DCB specimen provide a highly triaxial stress state. For future fracture toughness testing the DCB specimen of section width, 0.196 in. is recommended. This size gives enough width for suitable representation of graphite but not too much width for excessive plastic bending. In addition, it had the lowest K_{Ic} value and the smallest sample variance as seen in Table III.

TABLE III

Effect of Section Width on Sample Variance

Section width, in.	Sample Variance
0.066	5204
0.130	10671
0.196	750
0.262	1661
0.300	4437

EFFECT OF CRACK LENGTH ON K_{Ic}

Figure 7 shows the effect of crack length on K_{Ic} for the specimen having the 0.196 in. section width. As was typical for other specimens the results indicate no noticeable effect of crack length on K_{Ic} .

WORK OF FRACTURE

G_{Ic} is equivalent to the work of fracture for an infinitesimally small crack extension at the instant rapid crack propagation begins. The average value of G_{Ic} for the specimen with 0.196 in. section width was 2.1×10^5 ergs/cm². Using the areas under the deflection-load curves to estimate the work for complete fracture of this same specimen, the average work of fracture was found to be

2.6×10^5 ergs/cm². These are the same order of magnitude as values for work of fracture of other graphites found by other methods.

DISCUSSION

The DCB specimen has been found to be a very useful tool to study the fracture characteristics of nuclear graphite. The specimen can be used to determine the fracture toughness of nuclear graphite and also it provides information on the ability of a material to arrest a moving crack.

The calibration of DCB specimens for future studies with SGBF Graphite is unnecessary provided they are identical with any of the specimens used in this study. However, calibration would be necessary for crack propagation transverse to the extrusion direction or for specimens with different dimensions than those used in this study. Also, if a different grade of nuclear graphite was used in future studies, calibration would be necessary.

The results of this study have provided a method for performing fundamental and engineering studies on the fracture of nuclear graphite. Of interest would be studies oriented toward the determination of the effects of temperature, irradiation, humidity and composition on the fracture characteristics of nuclear graphite.

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REFERENCES

- 1 A. A. Griffith. "The Phenomena of Rupture and Flow in Solids," Phil. Trans. Roy. Soc., 221: 163-198 (1921).
- 2 G. R. Irwin. "Fracture Mechanics," Structural Mechanics, J. N. Goodier and N. J. Hoff, editors, pp. 557-594, Pergamon Press, New York, 1960.
- 3 J. P. Berry. "Determination of Fracture Surface Energies by the Cleavage Technique," J. Appl. Phys., 34: 62-68 (1963).
- 4 J. J. Gilman. "Direct Measurements of the Surface Energies of Crystals," J. Appl. Phys., 31: 2208-2218 (1960).
- 5 J. J. Benbow and F. C. Roesler. "Experiments on Controlled Fractures," Proc. Phys. Soc. (London), Series B, 70: 201-211 (1957).
- 6 E. J. Ripling, S. Mostovoy and R. L. Patrick. "Measuring Fracture Toughness of Adhesive Joints," Materials Research and Standards, 4: 129-134 (March, 1964).
- 7 J. W. Obreimoff. "The Splitting Strength of Mica," Proc. Roy. Soc. (London) Series A, 127: 290-297 (1930).
- 8 J. P. Berry. "Some Kinetic Considerations of the Griffith Criterion for Fracture - I Equations of Motion at Constant Force," J. Mech. Phys. Solids, 8: 194-206 (1960).
- 9 J. J. Gilman and P. P. Gillis. "Double-Cantilever Cleavage Mode of Crack Propagation," J. Appl. Phys., 35: 647-658 (1964).
- 10 R. G. Hoagland. A Double Cantilever Beam Specimen for Determining the Plane Straine Fracture Toughness of Metals, BNWL-168, Battelle-Northwest; Richland, Washington. December, 1965.

*For Compliance Tests: $Co = 1''$

For Fracture Toughness Tests: $Co = 2''$ for Specimens 1-3

$Co = 2.25''$ for Specimens 4-5

FIGURE 1

DCB Specimen Design

FIGURE 2
Compliance Test Results on Specimens
Number 1, 2, 3, 4, and 5

FIGURE 3

DCB Specimen Loading Arrangement

FIGURE 4

Crack Propagation Recording

FIGURE 5

Plastic Bending of the DCB Specimen

FIGURE 6

Effect of Section Width on Fracture Toughness

FIGURE 7

Fracture Toughness as a Function
of Crack Length for Specimen
with 0.296 in. Section Width