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DETERMINATION OF THE FRACTURE TOUGHNESS
OF EGCR-TYPE AGOT GRAPHITE

J. M. Corum

OAK RIDGE NATIONAL LABORATORY
operated by
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for the
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OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee
operated by
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DETERMINATION OF THE FRACTURE TOUGHNESS OF EGCR-TYPE AGOT GRAPHITE

J. M. Corum

Abstract

A first step was taken toward the application of fracture mechanics concepts to the design of graphite components to prevent brittle fracture. Tests were performed on notched bend specimens of EGCR-type AGOT graphite, and the results were used to determine values of G_c , the critical rate of strain-energy release. Relationships established both by the theory of elasticity and by experimental compliance testing were used. The specimens were beams with a single, lateral, artificial crack cut with a jeweler's saw.

The critical rate of strain-energy release for specimens oriented parallel to the axis of extrusion of the material was found to be approximately $0.39 \text{ in.-lb/in.}^2$, and for specimens oriented transverse to the axis of extrusion the value was approximately $0.29 \text{ in.-lb/in.}^2$. The G_c values based on the analytical and compliance analysis relationships were in good agreement. This agreement serves as a useful cross-check and adds confidence in the fracture-toughness values obtained. This initial study indicates that the concept of a critical strain-energy release rate being a condition for rapid crack propagation applies to graphite. However, the final proof can come only from the successful application of fracture mechanics to a component with a geometry and loading widely different from that of the laboratory specimen.

Introduction

Graphite is a brittle material at room temperature in that very little plastic deformation occurs prior to crack initiation in an unnotched member. Fracture generally occurs suddenly and propagates rapidly. Thus, the brittle fracture problem must be recognized and considered in the design of graphite components.

Several engineering approaches to prevention of brittle fracture have been proposed.¹ Those applicable to graphite can all be classified as stress analysis methods. They share a common objective, which is to determine through tests and analyses the applied loads at which rapid fracturing is either initiated or sustained.

In nearly all cases where low-stress brittle fracture is a possibility, it should be considered that flaws, defects, and other stress raisers have or will develop sharp crack-like characteristics. It has been stated (Ref. 1) that fracture mechanics is potentially the most useful stress analysis approach for dealing with such engineering situations. Briefly, fracture mechanics is the principle and practice of controlling brittle fracture by limiting the stress to a value that is compatible with defect size. The investigation described here is a first step toward the application of fracture mechanics concepts to the design of graphite components to prevent brittle fracture.

In 1920, Griffith² suggested that a brittle material, such as glass, contains tiny cracks or flaws of various dimensions. Centering interest on the largest of these, he reasoned that crack propagation would occur when the amount of strain energy released during a small increment of crack extension became greater than the surface energy associated with the newly formed crack increment. Thus, Griffith's instability criterion can be written as

$$\delta U \geq \delta \gamma , \quad (1)$$

where δU denotes the increment of elastic strain-energy release and $\delta \gamma$ denotes the increment of surface energy associated with the crack extension. Griffith measured the strain energy at incipient extension of cracks in glass, calculated the surface energy therefrom, and found that his values agreed well, within one order of magnitude, with values of surface energy determined from other experiments.

Although Griffith's theory worked well for glass, it gave completely erroneous results when applied to metals and plastics. Disagreement in surface energies was often several orders of magnitude. In 1948, Irwin³ and Orowan,⁴ working independently, pointed out that when plastic deformation occurs at the crack tip prior to fracture, the work necessary to extend a crack is much larger than a consideration of surface energy alone would indicate. In fact, the surface energy, $\delta \gamma$, is often negligible in comparison with the work, δW , of plastic deformation. Under such

conditions, the instability criterion can be written as

$$\delta U \geq \delta W . \quad (2)$$

Unlike surface energy, however, the work of plastic deformation cannot be easily estimated. The approach taken by Irwin was to ignore the micromechanisms that give rise to the energy absorbed during fracture and to construct, based on elastic theory, a new property, G_c , that gives a measure of just how sensitive a material is to crack extension. The resulting theory is usually referred to as the Griffith-Irwin crack theory and is the basis for fracture mechanics.^{5,6}

The basic premise of fracture mechanics can be illustrated by considering a body, such as a simple beam, that contains an initial crack. If a small increment of crack growth occurs, the elastic strain energy stored in the body is reduced by a small increment. Irwin defined the strain-energy release rate, G , by the equation

$$G \equiv \left(\frac{\partial U}{\partial A} \right)_{\delta} , \quad (3)$$

where A is the area of the crack surface, and the partial derivative is taken at constant deflection, δ , of the body. An increase in G occurs when the initial crack length is increased by slow crack growth or when the applied loads on the body are increased. According to the Griffith-Irwin concept, rapid crack propagation will commence from a stationary or slowly propagating crack when the strain-energy release rate, G , becomes equal to some critical value, G_c , which is called the critical rate of strain-energy release. Often G_c is alternately referred to as the fracture toughness or the crack extension force.

Irwin has regarded the strain-energy release rate, G , as both a measure of the intensity of the stresses surrounding the crack extension and as the driving force motivating crack extension. He has suggested that if two different loading systems produce the same stress environment near the leading edge of a crack, the influences on crack extension should be similar. Thus, the critical strain-energy release rate is considered to be a fundamental property of a material in that it is independent of the size,

shape, and type of loading of the specimen, provided the system can be described in terms of plane-strain conditions.

Fracture mechanics is applied, in principle, by the following steps:¹

1. Establish, based on the theory of elasticity or experimental compliance analysis, the appropriate relationship between applied load, specimen geometry, crack or flaw size, and strain-energy release rate for the laboratory test specimen to be used in determining G_c .

2. For this laboratory test specimen, measure the fracture strength under frangible* conditions, and from this fracture strength determine G_c by substituting in the relationship obtained in Step 1.

3. With either of the methods in Step 1, determine the relationship of load, crack size, and energy release rate for the specific engineering structure and the particular type of loading and type of flaw to be examined.

4. Based on G_c from Step 2 and the assumption that the largest undetectable crack or flaw exists in the worst possible location and with the worst possible orientation, calculate the fracture strength of the structure with the relationship obtained in Step 3. The allowable load should be less than this calculated fracture strength by a suitable safety factor.

The type of undetected flaw that might be considered in the design of a graphite component is illustrated in Fig. 1, which is a photograph of the fracture surface of a tensile specimen of RVD graphite. RVD is a fine-grained molded graphite with a high degree of uniformity. The flaw shown in the photograph is approximately 1/32 in. by 1/8 in. and was found after the specimen was tested.⁷

The investigation described here was concerned with applying the first two steps above to EGCR-type AGOT graphite. This graphite is an anisotropic material that is generally assumed to be isotropic in the plane perpendicular to the extrusion axis (i.e., it is transversely isotropic). Under this assumption there are three possible values of G_c to be considered.

*The behavior of a notched specimen is said to be frangible if no gross plastic flow occurs prior to fracture and the strength depends on the notch size.

Fig. 1. Photograph of Flaw Observed in the Fracture Surface of an RVD Graphite Tensile Specimen.

For a crack surface lying perpendicular to a uniaxial stress field, these three values are associated with the following sets of conditions:

1. A stress field in the direction of extrusion, with a crack propagating in a direction perpendicular to the direction of extrusion.
2. A stress field perpendicular to the direction of extrusion, with a crack propagating in a direction also perpendicular to the direction of extrusion.
3. A stress field perpendicular to the direction of extrusion, with a crack propagating in the direction of extrusion.

Four series of tests of notched bend specimens were used to examine these three situations, and the results were used to determine values of G_c for each of the three cases. Each beam had a single lateral crack cut in it with a jeweler's saw, and the specimens for each test series consisted of several sets of beams with the beams in each set having the same initial crack depth. All the specimens were tested by the two-point loading method, with the artificial crack placed on the tension side of the beam. Two series of beams were used in the first case, and values of G_c

were determined with the relationships of load, crack size, and energy release rate obtained both by a theory of elasticity analysis and by experimental compliance testing. In the second and third cases, only the theory of elasticity relationship was used, since the two different relationships yield essentially the same results in the first case.

The two methods of determining the relationships of load, crack size, and energy release rate for notched bend specimens are described in the next section, and in two subsequent sections the tests and test results are described and the G_c values are given. Several photographs that illustrate the progressive cracking of typical specimens and show typical fracture surfaces are presented and described. Finally, the last section contains a brief discussion of the results and suggestions for future work.

Methods for Determining Relationships of Load, Crack Size, and Energy Release Rate for Notched Bend Specimens

The strain-energy release rate, G , is defined as the change in elastic strain energy in a body per unit of area of new crack surface as an initial crack undergoes a virtual increment of growth. If the stress, or strain, distribution throughout the notched body can be calculated by the theory of elasticity, the strain-energy density throughout the body can be readily written, and the total strain energy, U , in the body can be determined by taking the integral of the strain-energy density over the entire volume.⁸ The strain-energy release rate is the partial derivative of U with respect to the crack depth.

Actually an elasticity analysis of a notched system is a difficult task, even for a notched beam. An experimental method called compliance analysis can also be used to determine strain-energy release rates for notched specimens. Both methods depend on the assumption, suggested by Irwin,⁹ that plastic deformation is confined to a relatively limited region near the crack tip, so the strain-energy release rate is determined almost entirely by the change of the elastic stress field outside this region of plastic flow.

Both the analytical method and the compliance analysis method of determining the relationship for strain-energy release rate in notched bend

specimens are described below. The two methods are discussed in Refs. 5, 6, 10, 11, and 12.

Analytical Method

The graphite notched bend specimen and the method of loading it are depicted in Fig. 2. The total depth of the beam is denoted by d ; the width of the beam, by b ; the crack depth, by c ; and the depth of the beam at the crack, by h . The total load applied to the specimen is denoted by P .

In the case of a thin semiinfinite plate with a shallow edge crack of depth c and with a uniform tensile stress σ applied normal to the plane of the crack, Griffith and others have shown that the strain-energy release rate is given by

$$G = \frac{\pi \sigma^2 c}{E}, \quad (4)$$

where E is the modulus of elasticity. For a thick plate, plane-strain conditions prevail, and E is replaced by $E/(1 - \nu^2)$, where ν is Poisson's ratio. Thus, Eq. (4) becomes

$$G = \frac{(1 - \nu^2)}{E} \pi \sigma^2 c. \quad (5)$$

For a beam with a shallow notch, where the crack depth, c , is small compared with the gross beam depth, d , it is reasonable to determine G

Fig. 2. Graphite Notched Bend Specimen.

from Eq. (5), with the maximum stress in the outer surface of the beam taken as the stress field σ . The maximum stress is

$$\sigma = \frac{6M}{bd^2} , \quad (6)$$

where M is the bending moment in the middle portion of the beam. If σ_n denotes the nominal bending stress at the root of the crack, then

$$\sigma = \frac{h^2}{d^2} \sigma_n . \quad (7)$$

Substituting this into Eq. (5) yields

$$G = \frac{(1 - \nu^2)}{E} \frac{\pi h^4 \sigma_n^2 c}{d^4} . \quad (8)$$

Winne and Wundt¹¹ have shown that Eq. (8) can be written as

$$G = \frac{(1 - \nu^2) \sigma_n^2 h}{E} f(c/d) , \quad (9)$$

where

$$f(c/d) = \frac{\pi c}{d} \left(1 - \frac{c}{d}\right)^3 . \quad (10)$$

Equation (10) holds only for c/d ratios of about 0.15 or less. For deeply notched beams, Winne and Wundt combined work done by Neuber¹³ and Irwin⁹ to obtain a relation for $f(c/d)$, and for intermediate notch depths they used a method developed by Bueckner¹⁴ to obtain values of $f(c/d)$. A plot of $f(c/d)$ as a function of c/d ratio is given in their paper.¹¹ This plot has been used in several investigations.

Recently, Gross and Srawley¹⁵ used a boundary-value-collocation procedure in conjunction with a stress function to determine values of the stress-intensity factor K for cracks of various depths in specimens subjected to pure bending. For plane-strain conditions, G is related to K

by

$$G = \frac{1 - \nu^2}{E} K^2 . \quad (11)$$

The stress-intensity factor, K , is a measure of the stress elevation relative to the unperturbed stress field caused by the presence of a crack. Since K is a linear function of load, the principle of superposition is applicable, and this makes the parameter K more attractive from an engineering viewpoint than the parameter G .

Gross and Srawley show that their calculations agree more closely with experimental measurements obtained by Lubahn¹⁶ than do the previously mentioned results used by Winne and Wundt. Consequently, the values of $f(c/d)$ used in the present investigation were determined from the results given by Gross and Srawley.

Figure 3 is a plot of $f(c/d)$ as a function of c/d as determined from the results of Gross and Srawley. If σ_n in Eq. (9) is written in terms of

Fig. 3. Values of $f(c/d)$ for Different c/d Ratios. (From Ref. 15)

the bending moment M in the midportion of the beam, the equation for G in terms of $f(c/d)$ can be rewritten as

$$G = \frac{1 - \nu^2}{E} \frac{36M^2}{b^2h^3} f(c/d) . \quad (12)$$

The critical value of G for each notched bend specimen is obtained by using, in the above relation, the value of the bending moment (which by Fig. 2 is equal to $1.5P$ in.-lb) that results in rapid propagation of the initial crack.

Compliance Analysis Method

The basis for compliance testing is the fact that the elastic strain energy in a notched bend specimen at any point during the elastic loading process is simply

$$U = \frac{1}{2} P\delta , \quad (13)$$

where δ is the deflection of the beam directly under the points of load application. Thus the elastic strain energy in a specimen can be easily determined through a simple test. In compliance testing, a series of notched specimens, with each specimen having a different crack depth and loaded entirely in the linear elastic region, provides strain-energy values as a function of crack depth. The strain-energy release rate, G , can be determined by graphically taking the derivative of the strain energy with respect to crack depth.

Since the load-deflection curve is linear within the range being considered, the curve can be represented by the relation

$$P = k\delta , \quad (14)$$

where k is the spring constant of the specimen corresponding to the crack length c . The spring constant is a decreasing function of the crack length c and may be measured as the initial slope of the load-deflection curves for beams with various initial crack lengths.

It is useful to recall that G is defined as the partial derivative of U with respect to crack area, with δ held constant. If δ is constant during a virtual extension of the crack, the ratio of P to k should remain approximately unchanged.¹⁷ For a very brittle material that has negligible plastic flow prior to fracture, this is obvious by considering Eq. (14). However, experiments on notched bars indicate that the constancy of P/k is not significantly altered by extensive plastic deformation confined to the vicinity of the crack.

The rate of strain-energy release is

$$G = \left(\frac{\partial U}{\partial A} \right)_{\delta} = \frac{\partial}{\partial A} \left(-\frac{1}{2} \frac{P^2}{k} \right), \quad (15)$$

where the strain energy is represented as a negative quantity so that the release rate, $\partial U/\partial A$, will be positive. Since, for P/k constant,

$$\left(\frac{\partial P}{\partial A} \right)_{\delta} = \frac{\partial}{\partial A} \left(k \frac{P}{k} \right) = \frac{P}{k} \frac{\partial k}{\partial A}, \quad (16)$$

the strain-energy release rate can be written as

$$\left(\frac{\partial U}{\partial A} \right)_{\delta} = -\frac{1}{2} \frac{\partial}{\partial A} \left(P \frac{P}{k} \right) = -\frac{1}{2} \left(\frac{P}{k} \right)^2 \frac{\partial k}{\partial A}. \quad (17)$$

The derivative $\frac{\partial k}{\partial A}$ can be expressed as

$$\frac{\partial k}{\partial A} = -k^2 \frac{\partial}{\partial A} \left(\frac{1}{k} \right), \quad (18)$$

so that Eq. (17) may be written as

$$G = \frac{1}{2} P^2 \frac{\partial}{\partial A} \left(\frac{1}{k} \right). \quad (19)$$

The crack area A is given by $A = bc$. Thus, the final expression for the strain-energy release rate is

$$G = \frac{1}{2bd} P^2 \frac{d}{d(c/d)} \left(\frac{1}{k} \right). \quad (20)$$

Experimentally, the procedure is to prepare a series of identical beams with initial cracks of various depths. The spring constant for each specimen is accurately measured with light loads, and the values of $1/k$, which is called the compliance, are then represented graphically as a function of c/d . The rate of change of $1/k$ with c/d can then be obtained from this plot so that G is known as a function of load. The critical strain-energy release rate for each specimen is obtained by substituting into the relation for G the value of the applied load that results in rapid propagation of the initial crack.

Tests of Notched Bend Specimens

Description of Material and Test Specimens

The specimens used in this investigation came from material manufactured for the graphite core columns of the Experimental Gas-Cooled Reactor.¹⁸ The graphite, designated EGCR-type AGOT, was manufactured by Union Carbide Corporation, Carbon Products Division, in the form of extrusions about 18 in. square by 20 ft long. Calcined Continental-Lake Charles petroleum coke, which has a needle-type particle structure, was used. The maximum particle size was limited to $1/32$ in., and a coal-tar pitch was used as the binder.

The orientation of the four series of notched bend specimens examined is depicted in Fig. 4 with respect to the direction of extrusion. The specimens in series 1 and 2 came from pieces removed in machining the fuel channels in one of the columns (designated file number 246). The graphitizing temperature used for this particular column was 2805°C , and the manufacturer's reported density of the column was 1.70 g/cm^3 . The specimens for series 3 and 4 came from an extra column (designated file number 325), which passed all acceptance tests but was not machined for use in the reactor. This latter column was graphitized at 2820°C , and the manufacturer's reported density was 1.69 g/cm^3 . The room-temperature mechanical properties of EGCR-type AGOT graphite have been extensively examined and are reported in Ref. 19.

Fig. 4. Orientation of Notched Bend Specimens with Respect to the Direction of Extrusion.

The arrangement for testing notched bend specimens is shown in Fig. 5. The single lateral artificial crack was placed in the specimen with a 0.0095-in.-wide jeweler's saw. All the specimens were tested by the two-point method with the artificial crack placed on the tensile side of the beam. The beams were loaded until complete fracture or rapid crack propagation occurred, and load and deflection data were recorded throughout each test.

Fig. 5. Arrangement for Testing Notched Bend Specimens.

One hundred and forty-six specimens were tested. In the first series of tests, all the beams were 1 ft long and 1 1/4 in. wide, and each had a depth h of 1 in. at the root of the crack. The total depth d was varied to produce seven different crack depth-to-beam depth ratios, including zero. Six specimens were tested for each of the seven sets, except one in which eight specimens were used.

In the second, third, and fourth series of tests, the beams were again 1 ft long and 1 1/4 in. wide, but the total depth was 1 1/4 in. in every case. The cracks penetrated the beams to various depths to produce six different crack depth-to-beam depth ratios for each series. As in the first series, six beams of each type were tested.

The compliance method of determining the relationship of load, crack depth, and energy release rate was not applicable to the first series of specimens, since the entire series of beams must have the same total depth. It was applicable to the second, third, and fourth series, and it was used in the second series. The results obtained with the strain-energy release rate relationship determined from compliance testing agreed closely with those obtained from the analytical relation. Consequently, only the analytical relation was used in series 3 and 4.

To make compliance measurements in series 2, deflections were recorded at both the midpoint of the beams and at a point directly under the points of load application. Only the midpoint deflections were recorded in the other series. The testing machine cross-head speed was approximately 0.01 in./min for all tests. A 120,000-lb Baldwin hydraulic testing machine was used. This is a very rigid machine for these tests.

Test Results

The mean load versus midpoint deflection curves for each of the seven sets of beams in the first series are shown in Fig. 6. All specimens in sets 1 and 2 broke into two pieces very suddenly with no forewarning. In the third and fourth sets, the beams cracked suddenly, again with no forewarning, but they did not break completely into two pieces. The cracks stopped short of the opposite sides of the beams. The tests were stopped when this sudden cracking occurred. Often, this kind of behavior is referred to as the "pop-in" phenomenon. In the first two sets, the initial

Fig. 6. Mean Load Versus Deflection Curves for Test Series 1 ($h = 1$ in.).

pop-in ran completely across the beams. In the third and fourth sets, the initial pop-in was large but did not run completely across the beams.

In the three remaining sets, 5, 6, and 7, there was no apparent sudden cracking. Instead, the fracture process probably consisted of many small pop-ins, so the cracks appeared to propagate very slowly across the beams as the load was applied. These tests were stopped soon after the load versus deflection curves began to bend downward, and rapid crack propagation was assumed to occur when the maximum load was reached.

The mean load versus midpoint deflection curves for the second test series are shown in Fig. 7. The curve for specimen set 4 is shown again in Fig. 7 because the results are applicable to both series 1 and 2. All specimens in sets 8, 9, and 10 broke suddenly into two pieces with no forewarning. These fractures thus consisted of a single pop-in that ran completely across the beams. In specimen sets 11 and 12, the beams never broke completely into two pieces, so their behavior was apparently the

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Fig. 7. Mean Load Versus Deflection Curves for Test Series 2
($d = 1 \frac{1}{4}$ in.).

result of many pop-ins. As the beams were deflected, the cracks propagated slowly across the specimens. Most of the midpoint deflections reached before the tests were stopped were at least twice the maximum deflections of the unnotched specimens. The test on one of the specimens in set 12 was continued past a deflection of 100 mils without complete separation. The behavior exhibited by the specimens in sets 11 and 12 was previously observed in tests of notched graphite specimens by Blakelock²⁰ in England. He believes that fracture is, in fact, complete but that the specimen is held together by the interlocking of grains at the fracture surface.

The mean load versus midpoint deflection curves for the third and fourth test series are shown in Figs. 8 and 9, respectively. The specimens in both of these series were taken with their long dimension perpendicular to the direction of extrusion, so they are transverse specimens,

Fig. 8. Mean Load Versus Deflection Curves for Test Series 3 ($d = 1 \frac{1}{4}$ in.).

Fig. 9. Mean Load Versus Deflection Curves for Test Series 4 ($d = 1 \frac{1}{4}$ in.).

while those in series 1 and 2 were parallel specimens. The only difference in series 3 and 4 is that in series 3 the crack propagated perpendicular to the grain, while in series 4 the crack propagated parallel to the grain (see Fig. 4).

The unnotched specimens in both series 3 and 4 broke suddenly into two pieces with no forewarning. In series 3 the specimens in sets 14 and 15 cracked suddenly, but they did not break completely into two pieces. However, the corresponding specimens in sets 20 and 21 of series 4 suddenly broke completely, except for three specimens in set 21. These three cracked suddenly but did not break.

All specimens in sets 16 and 17 of series 3 exhibited the behavior shown in Fig. 8. Apparently there were two distinct pop-ins in these

specimens. The corresponding specimens in sets 22 and 23 of series 4 did not exhibit these distinct pop-ins.

In summary, although the maximum loads reached in the corresponding specimen sets in series 3 and 4 were essentially the same, there was a noticeable difference in the fracturing process after rapid crack propagation had initiated. Apparently the propagating cracks encountered more resistance in the specimens of series 3 than in those of series 4. This is the kind of behavior that would be expected, based on the observation discussed later in this section that for this particular graphite the propagating cracks generally go around the particles or grains rather than through them. In series 3 the running cracks encountered particle boundaries more often than in series 4, since in the first case the cracks ran parallel to the small dimensions of the particles, while in the latter case they ran parallel to the large dimensions of the particles. This is depicted schematically in Fig. 10.

The average fracture loads, together with their coefficients of variation, are given in Table 1 for the four test series. Little can be said about the coefficients of variation of the fracture loads with increasing crack depth. The coefficients of variation for the transverse specimens were greater than for the parallel specimens. The modulus-of-rupture data show that the modulus for transverse specimens is about 64% of that for parallel specimens. This agrees closely with the findings reported in

Fig. 10. Schematic Representation of Crack Propagation in Test Series 3 and 4.

Table 1. Average Fracture Strengths for Notched Bend Specimens

Specimen Set	Crack Depth (in.)	c/d Ratio	Average Maximum Strength, P (lb)	Coefficient of Variation for Loads (%)
Test Series 1				
1	0	0	234 ^a	6.9
2	1/16	0.059	210	5.0
3	1/8	0.111	196	3.4
4	1/4	0.200	202	5.6
5	1/2	0.333	180	4.8
6	1	0.500	188	5.5
7	1 1/2	0.600	182	1.6
Test Series 2				
8	0	0	412 ^b	15.0
9	1/16	0.050	329	4.2
10	1/8	0.100	276	3.3
4	1/4	0.200	202	5.6
11	1/2	0.400	110	2.5
12	5/8	0.500	88	4.4
Test Series 3				
13	0	0	249 ^c	20.8
14	1/16	0.050	211	14.9
15	1/8	0.100	164	7.5
16	1/4	0.200	124	18.6
17	1/2	0.400	80	9.0
18	5/8	0.500	52	8.9
Test Series 4				
19	0	0	244 ^d	17.5
20	1/16	0.050	220	17.6
21	1/8	0.100	174	17.8
22	1/4	0.200	125	13.5
23	1/2	0.400	78	15.3
24	5/8	0.500	55	13.3

^aModulus of rupture = 1680 psi.

^bModulus of rupture = 1890 psi.

^cModulus of rupture = 1150 psi.

^dModulus of rupture = 1125 psi.

Ref. 19, where it is stated that the tensile fracture stress in the perpendicular direction is about 60% of that in the parallel direction for EGCR-type AGOT graphite.

Fracture Characteristics

The effects of the deflections that specimens in sets 11 and 12 of series 2 underwent without breaking completely into two pieces are depicted in the photographs of Fig. 11. The top picture shows one of the specimens in set 12 before any load was applied. The middle picture shows the same beam when it had a midpoint deflection of about 20 mils. The bottom picture, although not of the same beam as the first two, shows one of the other specimens in set 12 near the end of the test.

Movies were made of the progressive fracturing of several of the specimens. Three selected frames from the sequence made for one of the specimens in set 4 are shown in Fig. 12. The first picture shows the specimen at the beginning of the test before the load was applied. The second and third pictures were made from adjoining frames before and after the pop-in. The sequence was taken at 64 frames per second, and thus the second and third pictures indicate the suddenness of the pop-in. Actually, careful examination of the middle picture shows that the crack is faintly visible at the root of the saw cut. No crack was visible in the frame immediately preceding this one in the original sequence.

Four selected frames from the movie sequence made of one of the specimens in set 11 are reproduced in Fig. 13. The first picture shows the beam before loading; the second, at the first indication of crack growth, which is visible just to the left of the initial crack root; the third, during cracking; and the fourth, near the point where the test was discontinued. The original sequence was taken at 8 frames per second, in contrast to the 64 frames per second used for the specimen in set 4. The lack of a sudden change from frame to frame indicates the slowness of the crack growth.

"Before and after" photographs were made of the crack-root region of all the specimens tested in the second series. These photographs were made at a magnification of 10X and were taken of both sides of each as-machined specimen to indicate the paths the cracks followed through the material.

PHOTO 84904

Fig. 11. Progressive Cracking of Specimens in Set 12 ($5/8$ -in. Crack, $c/d = 0.500$).

Fig. 12. Progressive Cracking of Specimen in Set 4 (1/4-in. Crack, $c/d = 0.200$).

A typical set of photographs of one of the specimens in set 9 is shown in Fig. 14. Although these are poor photographs for the purpose, a comparison of the two indicates that the crack went through sizable voids and low-density areas while going around at least the larger particles or grains. These photographs indicate only what happened on the surface. However, the same kind of behavior was observed for all pairs of photographs.

Jenkins²¹ microscopically observed and photographed the sequence of events leading to fracture of a British reactor graphite strained slowly in tension. He found that the cracks which eventually led to fracture were formed in weak zones between the lamellae composing grains. These inter-lamellar cracks formed in large numbers, independently of each other, and none grew to large size. With increasing strain, however, enough were formed so that they began to join, and a fracture path eventually was established. Jenkins observed that the fracture path ran between lamellae until a set of lamellae was reached that was nearly perpendicular to the crack. In this case the cracks went around the set. The same thing happens at a grain boundary. Unless a lamella is present (on the new grain boundary) that is unfavorably oriented, the crack will propagate into the new grain. Thus the fracture is predominantly transgranular. Smith²² observed the

PHOTO 84906

Fig. 13. Progressive Cracking of Specimen in Set 11 (1/2-in. Crack,
 $c/d = 0.400$).

Fig. 14. Views of Specimen in Set 9 (1/16-in. Crack, $c/d = 0.050$) Before and After Cracking. 10X

same fracture process. In contrast, Tarpinian and Gazza²³ state that most failures occur through binder bridges between grains and speculate that preferential fracture is caused by high stress concentrations at such bridges that result from differential thermal contraction between the binder and grains. Apparently the fracture can be either transgranular or intergranular, depending on the graphite.

Jenkins concludes his paper by stating that crack nucleation in graphite is easy, whereas crack propagation is much more difficult. This is understandable in the light of recent work done in Britain by Sutton and Howard.²⁴ They found that cracks exist between the lamellae even before loading. With an electron microscope, they found that at room temperature a typical grain contained 6% by volume of this kind of crack, which is produced by anisotropic thermal contraction after graphitization. These many fine existing cracks begin to open upon load application.

The pattern and appearance of a fracture surface can often furnish information about the fracture itself. In addition to providing clues concerning the origin of the fracture and the direction of crack propagation,

the fracture surface tells the extent to which the strain-energy release rate, dU/dA , and the effective work rate, dW/dA , remained nearly equal as fracturing progressed.¹⁷ If dW/dA becomes and continues to be substantially less than dU/dA , the crack velocity increases, the fracture appearance changes, and repeated forking or shattering occurs. On the other hand, if the fracture surface is relatively smooth, with much less extensive branching, it can be concluded that a near equality of dU/dA and dW/dA existed all along.

Photographs of the fracture surfaces of specimens from sets 8 and 5 are shown in Figs. 15 and 16, respectively.* The specimen shown in Fig. 15 was unnotched, while the specimen of Fig. 16 had an initial crack depth of 1/2 in. The appearances of the two surfaces are quite different. In the unnotched specimen, fracture was apparently initiated at a single point near the middle of the outer tensile surface, which is at the top of Fig. 15. This observation is based on the presence of radial lines fanning out from this point and on the presence of several concentric circular arcs with this point as their center. The radial markings are called hackle marks, and they are caused by fractures on different surfaces that are joined by additional fractures. The circular marks are probably rib marks caused by momentary stopping of the crack and by the main crack front overtaking new cracks that have formed ahead of the main crack.

The fracture surface of the relatively deeply notched specimen shown in Fig. 16 does not exhibit large hackle and rib marks like the unnotched specimen. The surface irregularities in Fig. 16 are smaller and much more localized. Apparently the initial cut acted as a true crack, because fracture appears to have been initiated all along the root of the initial crack, as evidenced by the parallel hackle marks, which are perpendicular to the initial crack root and which are present all along the crack root. Although a few of the precracked specimens had a single point of fracture initiation, most of those examined were similar to the one shown in Fig. 16.

*The fracture surfaces shown in these photographs, together with several others, were examined briefly by V. D. Frechette, Professor of Ceramic Technology at Alfred University and fractography consultant to ORNL. The discussion here is based on his observations.

Fig. 15. Typical Fracture Surface of Unnotched Specimen (from Set 8).

Fig. 16. Typical Fracture Surface of Relatively Deeply Notched Specimen (from Set 5, 1/2-in. Crack, $c/d = 0.333$).

The appearance of the fracture surface of the unnotched specimen of Fig. 15 indicates that dW/dA probably became substantially less than dU/dA during the fracture process, which, it will be recalled, consisted of a single pop-in that broke the specimen into two pieces. The excess released energy went into the formation of additional crack surfaces around the main crack front.

In contrast, the fracture surface of the deeply notched specimen of Fig. 16 indicates that dW/dA and dU/dA were nearly equal throughout the fracture process. This is consistent with the previous observation that the fracture process probably consisted of many small pop-ins. The energy-release rate and the effective work should be equal at the beginning of each of the many pop-ins.

In this respect, Johnson⁶ states that although it is assumed that the critical strain-energy release rate, G_c , is a measure of dW/dA , it has not actually been demonstrated that

$$G_c = \frac{dW}{dA} .$$

This, according to Johnson, is a central question in fracture mechanics. Also, it should be emphasized that fracture mechanics and G_c values as considered in this investigation relate to conditions at the onset of fracture only, and therefore the G_c values reported in the following section are a measure of static fracture resistance. Although of less interest from a design viewpoint, it is also possible to obtain values of G_c in the presence of a running fracture that are a measure of dynamic fracture resistance.

Critical Strain-Energy Release Rates

The value of G_c determined for each set of beams by using the analytical relationship for load, crack depth, and energy release rate was calculated by using, in Eq. (12), the average maximum strength values given in Table 1 of the previous section. The appropriate values of $f(c/d)$ were determined from Fig. 3 on the assumption that the c/d ratios at the initiation of rapid crack propagation remained the same as they were initially. That

is, it was assumed that no slow crack growth occurred prior to rapid crack propagation.

The theory of elasticity analysis on which Eq. (12) and the function $f(c/d)$ are based was for an isotropic elastic material, whereas graphite is anisotropic. It was assumed, however, that Eq. (12) could still be used without appreciable error if the modulus of elasticity used was that for the direction parallel to the axis of the beam and the Poisson's ratio used was the negative of the ratio of the strain in the direction parallel to the crack root to the strain in the direction parallel to the axis of the beam with a stress applied in the latter direction. The appropriate elastic constants for each test series and their values are (refer to Fig. 4 for axis numbers, subscript notation refers to axes)

Test series 1 and 2:

$$E = E_3 = 1.8 \times 10^6 \text{ psi}$$

$$\nu = \nu_{32} = 0.09$$

Test series 3:

$$E = E_1 = 1.0 \times 10^6 \text{ psi}$$

$$\nu = \nu_{13} = 0.03$$

Test series 4:

$$E = E_2 = 1.0 \times 10^6 \text{ psi}$$

$$\nu = \nu_{21} = 0.08$$

These values were chosen from Ref. 19 as being the most appropriate for the specimens in this investigation. The validity of Eq. (12) for graphite specimens was verified by the agreement between the G_c values determined with this relationship and those based on compliance testing.

To determine the G_c values for the second test series by using the G relationship obtained by compliance testing, it was necessary to first plot $1/k$, the compliance, as a function of c/d . This plot is shown in

Fig. 17. Values for each individual specimen in each set are shown. The slopes required for use in Eq. (20) are also shown on the plot. The values of these slopes, together with the average maximum strength data given in Table 1, are sufficient to determine a G_c value for each set of specimens by using Eq. (20).

Values of G_c are given in Table 2 for each set of specimens in the four test series. For the second test series, two sets of values are given that are based on the two different G relationships.

The G_c values for the parallel specimens (series 1 and 2) are plotted as a function of c/d in Fig. 18. The values determined by the analytical

Fig. 17. Plot of Compliance ($1/k$) Versus Crack Depth-to-Beam Depth Ratio for Specimens of Series 2.

Table 2. G_c Values for Notched Bend Specimens

Specimen Set	Crack Depth (in.)	c/d Ratio	Value of G_c (in.-lb/in. ²)	
			Analytical	Compliance Testing
Test Series 1				
1	0	0		
2	1/16	0.059	0.21	
3	1/8	0.111	0.30	
4	1/4	0.200	0.42	
5	1/2	0.333	0.39	
6	1	0.500	0.43	
7	1 1/2	0.600	0.40	
Test Series 2				
8	0	0		
9	1/16	0.050	0.28	0.17
10	1/8	0.100	0.38	0.34
4	1/4	0.200	0.42	0.35
11	1/2	0.400	0.35	0.43
12	5/8	0.500	0.39	0.32
Test Series 3				
13	0	0		
14	1/16	0.050	0.21	
15	1/8	0.100	0.25	
16	1/4	0.200	0.29	
17	1/2	0.400	0.34	
18	5/8	0.500	0.24	
Test Series 4				
19	0	0		
20	1/16	0.050	0.23	
21	1/8	0.100	0.27	
22	1/4	0.200	0.29	
23	1/2	0.400	0.32	
24	5/8	0.500	0.27

Fig. 18. Critical Strain-Energy Release Rate Versus Crack Depth-to-Beam Depth Ratio for Parallel Specimens (Series 1 and 2).

and the compliance analysis relationships for G are in good agreement. However, both series of values tend to drop off for values of c/d below about 0.1. This is probably an indication of either the presence of slow crack growth prior to rapid crack propagation, a sizable zone of inelastic deformation at the crack tip, or preexisting cracks and flaws. Each of these factors can significantly affect the G_c values for small c/d ratios because they increase the effective depth of the initial crack slightly. This is discussed more fully in the following section.

The average value of G_c for the parallel specimens, based on only those values for c/d of 0.2 or greater, is 0.39 in.-lb/in.², with a coefficient of variation of 10%. If the G_c values for c/d ratios above 0.1 are considered, the average value becomes 0.38 in.-lb/in.².

The G_c values for the transverse specimens (series 3 and 4) are shown as a function of c/d in Fig. 19. The values for series 3, in which the crack ran transverse, and for series 4, in which the crack ran parallel, are essentially equal. Both series of values drop off slightly for low c/d values. However, the drop-off is not so significant as in series 1 and 2. As for the parallel specimens of series 1 and 2, only those values

Fig. 19. Critical Strain-Energy Release Rate Versus Crack Depth-to-Beam Depth Ratio for Transverse Specimens (Series 3 and 4).

for c/d of 0.2 or greater were considered in determining the average value of G_c for the transverse specimens. This value is 0.29 in.-lb/in.², with a coefficient of variation of 12%. If the G_c values for c/d ratios above 0.1 are considered, the average value becomes 0.28 in.-lb/in.². The critical strain-energy release rate for the transverse specimens is about 74% of that for the parallel specimens.

For comparative purposes, G_c for glass is about 0.06; for concrete, 0.1; for epoxy, 8; and for steels and aluminum alloys it ranges from below 100 to as high as 1000. Higher values, of course, indicate better resistance to fracture.

Figure 20 shows the effects of crack depth on the nominal bend strength of the specimens tested in each of the four series. The nominal bend strength is simply the stress at fracture at the crack tip calculated by the usual strength of materials formula. The experimental data are shown as plotted points with a dashed line drawn through them. The solid lines represent the behavior predicted with G_c values of 0.39 in.-lb/in.² and 0.29 in.-lb/in.² for series 1 and 2 and for series 3 and 4, respectively.

The bend strength dropped rapidly with increasing crack depth in all four series. It reached a minimum at a c/d ratio of about 0.4 in the first series and between 0.2 and 0.3 in the remaining series. The strength in the first series then remained constant or increased slightly. In the

Fig. 20. Predicted and Actual Effect of Initial Crack Depth on Nominal Bend Strength for Test Series 1, 2, 3, and 4.

remaining series, both the actual and the predicted strength increased significantly with further increases in crack depth.

This latter behavior was observed in tests of notched bend specimens of steels by Lubahn and Yukawa.²⁵ They state that the increase in bend strength beyond the minimum may be due either to the notch-sharpness effect or to a size effect. For a constant beam depth, d , and a constant root radius, r , an increase in crack depth, c , will result both in a decrease in size (defined as the beam depth, h , at the root of the crack) and a decrease in notch sharpness (defined as h/r). Both factors would contribute to increased strength, but apparently the effect here is due primarily to size, since fracture mechanics adequately predicts the increase. For a c/d ratio approaching one, Lubahn and Yukawa state that the strength would be expected to rise to a high value again from either size or notch-sharpness effects.

Discussion

The most significant finding of this investigation is that the critical rate of strain-energy release, G_c , is approximately 0.39 in.-lb/in.² for notched bend specimens oriented parallel to the direction of extrusion and approximately 0.29 in.-lb/in.² for specimens oriented perpendicular to the direction of extrusion. These values are averages of the values obtained from all sets of specimens with a crack depth-to-beam depth ratio, c/d , of 0.2 or larger. At a c/d ratio of about 0.1, the G_c values decreased with decreasing c/d ratio. This apparently is an indication of an increase in the effective crack depth prior to rapid crack propagation.

In the second test series, the G_c values were determined from relationships of load, crack size, and energy release rate based both on the theory of elasticity and on compliance analysis. The resulting G_c values were in good agreement. This agreement serves as a useful cross-check and also adds confidence in the fracture toughness values obtained.

Transverse specimens were used in both the third and fourth test series. However, the cracks ran transverse in the third series and parallel in the fourth series. There was essentially no difference in the G_c values in the

two series although there was a noticeable difference in the fracturing process after rapid crack propagation had been initiated.

The fracture process for the specimens used in this investigation consisted of a series of pop-ins. For shallow cracks, the initial pop-in was large enough to break the specimens into two pieces. For deep cracks, however, the initial pop-in was too small to be observed by eye. The results thus indicate that the deeper the initial crack, the smaller the initial pop-in.

For the same beam size, it was found that the maximum midpoint deflection a beam could withstand without breaking into two pieces decreased initially with increasing crack depth. However, the maximum deflections began to increase again at about the same c/d ratio at which the nominal bend strength began to increase again. A specimen with an initial crack that penetrates halfway through the beam depth can absorb at least twice the midpoint deflection that an uncracked specimen can.

Several obvious sources of error existed in this investigation, and, before fracture mechanics can be reliably applied to graphite bodies, these should be examined or shown to have a negligible effect. First, there are the problems of slow crack growth, significant inelastic deformation at the crack tip prior to rapid crack propagation, and/or the presence of small preexisting flaws and cracks that increase the effective depth of the initial crack. Each of these can have a significant effect for shallow cracks. Smith²⁶ has suggested that much of the inelastic deformation of graphite is due to the opening of existing interlamellar cracks. If this is true, slow crack growth and inelastic deformation at the crack tip are closely related. Both increase the effective length of the initial crack prior to rapid crack propagation. Consequently, computed G_c values based on the initial artificial crack length are low. For a given amount of slow crack growth or inelastic deformation at the crack tip or for a given increase in the effective crack depth caused by existing flaws, the error is much greater for shallow cracks than for deep ones. This may explain the drop-off in G_c values for small c/d ratios.

To further examine the magnitude of the increase in effective crack depth, it was assumed that the uncracked sets of beams in series 2, 3, and 4 actually had cracks in them at the instant of failure. Based on the

previously determined G_c values and the assumption that the cracks were of the same shape and orientation as the artificial cracks, the depths of these initial cracks were calculated from the average failure loads for each set. The effective crack depths were found to be 0.045, 0.053, and 0.061 in. for series 2, 3, and 4, respectively. Since the maximum grain size of EGCR-type AGOT graphite is approximately $1/32$ in. (0.031 in.), these initial flaws extend past or through one or two grains. If these crack depths are added to the initial artificial crack lengths for all the specimen sets and the G_c values are recalculated with these adjusted crack lengths, the values for small c/d ratios are increased to about the same values as those obtained for the deeper cracks.

A second source of error is the nonlinearity of the load versus deflection curves. This could be due to a combination of inelasticity, which graphite normally exhibits even at low strain levels, and slow crack growth. Although the load versus deflection curves shown in Figs. 6 through 9 do not deviate greatly from straight lines up to the point of maximum load, some error is undoubtedly introduced. Ideally, G_c measurements should come from tests in which the load versus deflection curves remain linear up to the point where complete fracture suddenly occurs.

The effect of specimen thickness is a third source of error. Specimen thickness is closely related to transverse constraint. The application of fracture mechanics is restricted in that it is assumed that the test specimen geometry is such that the conditions of transverse constraint are similar to those in the specific engineering structure that is to be examined. Fracture toughness is a minimum under plane-strain conditions. Furthermore, under plane-strain conditions the mode of fracture is generally a wedge-opening of the crack (referred to as mode I). The critical strain-energy release rate under these conditions is given the symbol G_{Ic} . Since it is the minimum possible value of G_c , the controlling parameter for design to avoid brittle fracture is generally G_{Ic} .

Only when systems can be described in terms of plane-strain conditions will the notch stresses be independent of the details of the various geometries.⁶ That is, a value of G_{Ic} can be measured in the laboratory and applied to a component even when the details of geometry and loads differ for the two cases.

To determine a value of G_{Ic} directly from a laboratory specimen, the constraint must be sufficient to assure plane-strain conditions in the notch vicinity. As the thickness of a notched bend specimen is increased, the constraint is increased and the G_c values decrease. For a sufficiently thick specimen the values approach G_{Ic} . The specimen thickness used in this investigation was intended to be large enough to give a good estimate of G_{Ic} . However, the required thickness varies with materials. The more inherent ductility a material has, the larger is the specimen thickness required to provide sufficient constraint to assure frangible conditions at fracture. Thus, when using a given specimen design on a material for the first time, several tests should be performed with specimen size as the variable parameter. Only in this way can it be verified that the calculated G_c values are actually a good approximation for G_{Ic} .

In addition to the factors discussed above that influence G_c measurements, the practical application of fracture mechanics to most graphites would have to account for the anisotropy in obtaining a relationship for G . This task is simplified somewhat because the principal stress axes usually coincide with the axes of anisotropy in most graphite structural elements. Anisotropy and nonlinear behavior are problems that arise in almost any structural investigation of graphite bodies, not just fracture mechanics.

Although this initial study indicates that the Griffith-Irwin concept of a critical strain-energy release rate being a condition for rapid crack propagation applies to graphite, further research is necessary before fracture mechanics can be reliably applied to the design of a graphite component with an assumed initial flaw. The final proof of the applicability can come only from the successful application of fracture mechanics to a realistic problem in which the component under consideration has a geometry and type of loading widely different from that of the laboratory specimen.

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