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EVALUATION OF FRACTURE STRENGTH BY SONIC TESTING*

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ABSTRACT

The Griffith-Irwin equation is used to describe the fracture characteristics of graphite. The material constants, Young's modulus and mean flaw size, are measured sonically from velocity and attenuation measurements. The effects of steam oxidation and neutron irradiation on fracture strength are shown to be predictable assuming a constant strain-energy release rate.

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The concepts of fracture mechanics have been fairly successful in explaining mechanical properties of graphite and their relationships to microstructure.^{1,2,3,4} While studies using fracture mechanics are extremely helpful in relating fabrication variables to the eventual product strength, it is equally important to understand the relevant influences of oxidation and nuclear irradiation on the fracture characteristics of graphite. In the past, fracture mechanics studies generally used large fracture-toughness specimens, which in many cases are impractical because of size and geometric limitations. This is especially true for oxidation and irradiation studies, where specimen sizes are limited and many specimens are required to meaningfully evaluate the various parameters. The purpose of this study was to describe a methodology for estimating the flaw size independently by use of ultrasonic attenuation measurements. Thus, simple mechanical property tests compatible with geometric restrictions can be made to confirm initial assumptions describing the fracture characteristics of graphites. It should be noted that not only are insights in understanding the effects of structural alterations of fracture improved, but the methodology also offers potential procedures for nondestructively estimating product quality.

The Griffith-Irwin theory for elastic materials has been shown^{3,4} to form the basis for fracture mechanics studies in graphite,

$$\sigma_f = (EG_{IC}/2\pi a)^{1/2} = K_{IC}/(2\pi a)^{1/2} \quad (1)$$

where

- σ_f = fracture stress,
- G_{IC} = strain energy release rate,
- E = Young's modulus,
- a = radius of critical flaw size,
- K_{IC} = fracture toughness = $(EG_{IC})^{1/2}$.

Generally, the fracture toughness, K_{IC} , and fracture strength are evaluated and the critical flaw size is estimated by Eq. (1). Obviously, this requires not only a statistically significant number of strength tests but an almost equal number of fracture toughness tests to evaluate each parameter. If, however, both Young's modulus, E , and the inherent defect size, a , could be measured nondestructively by ultrasonics then G_{IC} could be evaluated by simple fracture tests. If, as might be expected, G_{IC} is constant or only mildly affected for a graphite grade, the ultrasonic measurements could furnish nondestructive estimates of strength. Our purpose is to illustrate how scatterers of sonic waves appear to be voids within the graphite that make the critical defect.

Ultrasonic attenuation can be summarized in terms of the attenuation coefficient α , the scattering domain size, S , frequency f , and wave length λ .^{5,6,7} Generally scattering contributes a large part of the overall attenuation, and the functional dependence can be tabulated as in Table 1.

Table 1. Functional dependence of scattering

λ/S	Type of Scattering	Functional Relationship
$\gg 1$	Rayleigh	$S^3 f^4$
~ 1	Stochastic	$S f^2$
< 1	Diffusive	$1/S$

The frequency dependence for most materials falls between the second power and the fourth power, decreasing obviously with higher frequencies. It is important to realize the linearity or proportionality of scattering with S in the stochastic range. Therefore, the highest practical frequency should be used in making attenuation measurements.

There are several established procedures for measuring the absolute values of the attenuation coefficients. However, most of these techniques require special specimens and equipment, again reducing the applicability of the test and eliminating subsize or irregular specimens, such as irradiation and brittle ring specimens. We have also found inconsistencies in the above techniques from uncertain coupling losses between transducers and specimens with and without buffer rods. These inconsistencies cast doubts on the capability of the techniques to actually yield absolute attenuation measurements. It is enough to admit that the directly coupled 2.25-MHz wide-band transducers used in making transmission measurements provide only relative values. These measurements have geometric and coupling factors that are unique to each test sensor, and data from different sample geometries should not be interrelated.

The proportionality of the attenuation to flaw size was demonstrated by several methods. The first was to perform conventional fracture toughness tests on a series of experimental graphites and compare the calculated critical flaw size with the attenuation measurements. The results of this series showed excellent agreement and proportionality over a range of defect sizes. In this case, the strain energy release rate varied slightly because of sulfur content in the filler coke.

A second series compared the attenuation coefficient of a carefully fabricated series of graphites made with controlled particle sizes to the same density from the same filler coke. The pore sizes were measured from the microstructure and found to be equal in length to

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the particle size and about one-half in diameter. Again the proportionality was observed. Since these graphites were made from the same filler through the same fabrication process, G_{IC} would be expected to be constant. Therefore, from Eq. (1), the fracture strength should show the proportionality

$$\sigma_f \propto (E/\alpha)^{1/2} \quad (2)$$

The agreement of the data was observed over a wide range in fracture stresses.

Attenuation measurements have been made on irradiation specimens that eventually were fracture tested. The results show the expected decrease in defect size with the normal densification by irradiation. However, as the graphite begins to expand after maximum densification due to irradiation, the increase in defect size is greater than would be expected from a simple increase in porosity. Again, if we examine the proportionality of Eq. (2), we can confirm that G_{IC} is again constant and unaffected by irradiation. This comparison can be made in Fig. 1 by examining the effect of irradiation on the fracture strength relative to values predicted with and without the attenuation results. As noted, without considering the attenuation estimates are low initially and, of more importance, are too high at the higher fluences.

Fig. 1. The effect of irradiation on fracture strength.

The mechanical properties as affected by steam oxidation can also be examined by the use of attenuation measurements. It is well-established that the reduction of strength by oxidation is considerably greater than can be expected from a simple loss in mass. The reduction in Young's modulus is not adequate to explain the loss without a reduction in the strain energy release rate, a significant increase in the defect size, or both. The consistency of the strain energy release rate can again be confirmed by the proportionality of Eq. (2). Shown in Fig. 2 are compressive strength test results of steam-oxidized 2020 grade graphite as a function of $(E/\alpha)^{1/2}$. The proportionality and goodness of fit are obvious. Again, we conclude that G_{IC} remains unaffected by oxidation. This affords an excellent nondestructive measurement yielding greater insight into the development of pore structure of various graphites by oxidation under various conditions.

Fig. 2. Compressive strength of oxidized Grade 2020 graphite as a function of the parameter $(\text{Young's modulus/attenuation})^{1/2}$.

Conclusions

This paper is primarily directed to illustrating the significance of sonic attenuation measurements in graphite. In this process, however, we have reasonably demonstrated that graphites made from the same filler but with different particle size have the same strain energy release rate. We have also demonstrated that G_{IC} is also either constant or only mildly altered by oxidation and nuclear irradiation. Thus, under controlled conditions sonic measurements should yield highly reliable estimates of fracture strength.

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