Fracture Toughness of Anisotropic Graphites*

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Abstract. Fracture toughness measurements have been made at 0, 30, 45, 60, and 90 degrees from the extrusion axis on a reasonably anisotropic graphite, grade AGOT. It was found that the fracture toughness did not vary appreciably with orientation. An observed variation in strength was found to be the result of defect orientation.

Introduction

The strength of most grades of graphite tends to be anisotropic. The strength in the preferred *c*-axis direction is fairly weak compared to the preferred *a*-axis direction. The strength differences in the preferred directions are generally assumed to be a result of the much higher Young's modulus in the *a*-axis compared to the *c*-axis direction. The Griffith-Irwin expression for fracture,

$$\sigma_f = (G_{IC}E/2\pi c)^{1/2} = K_{IC}/(2\pi c)^{1/2} , \quad (1)$$

is used to correlate the properties, where

- σ_f = fracture stress,
- G_{IC} = strain energy release rate,
- E = Young's modulus,
- c = radius of the critical defect,
- K_{IC} = fracture toughness.

Procedure

The results of fracture toughness testing of some fairly anisotropic electrode grades indicated that the toughness was essentially isotropic. To investigate this phenomenon further, a series of short-rod fracture-toughness specimens was machined from a block of AGOT graphite with the specimen axis at 0, 30, 45, and 90° to the extrusion axis. Some of the properties previously obtained from this block (Table 1) demonstrate the degree of anisotropy. The specimens were made with a geometry to force the crack to propagate in either the direction normal to the theta vector or normal to the cross product of the axial and theta vector.

The velocity of sonic longitudinal and shear waves were used to calculate the elastic constants for each specimen. The electrical resistivity was also measured using eddy-current techniques. The results of these evaluations assure the consistency of the preferred orientation in the specimens before evaluation.

Table 1. Properties of AGOT Graphite.

	With grain	Against grain
Flexural strength (MPa)	12.3	7.8
Young's modulus (GPa)	13.0	6.7
Coefficient of thermal expansion ($^\circ C^{-1} \times 10^{-6}$)	1.5	2.5
Electrical resistivity ($\mu\Omega$-m)	5.0	9.1

Results and Discussion

The results of this test series are similar to those of E. P. Kennedy, given in this conference, in that the fracture toughness was also essentially isotropic. Our results (shown in Fig. 1) actually indicate a slight reduction in the fracture toughness in the strongest direction. The calculated values of the strain-energy release rate, G_{IC}, are given in Fig. 2. As would be expected, G_{IC} decreased significantly with increasing deviation from the extrusion axis for those specimens oriented with the crack normal to the cross product of the axial and theta vectors. These results are in sharp conflict with the initial assumption that the strength differences are related to the differences in Young's modulus. It is readily apparent that the fracture strength is not controlled by Young's modulus. It seems apparent from Eq. (1) that if the fracture toughness of this material is isotropic, the sole factor controlling the fracture strength is the defect size.

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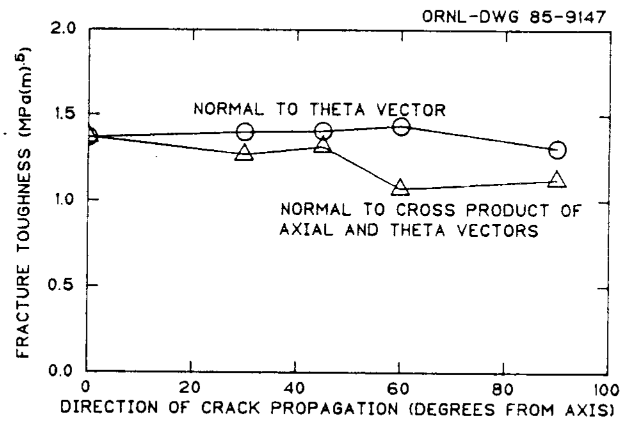

Figure 1. The effect of orientation on the fracture toughness of grade AGOT graphite.

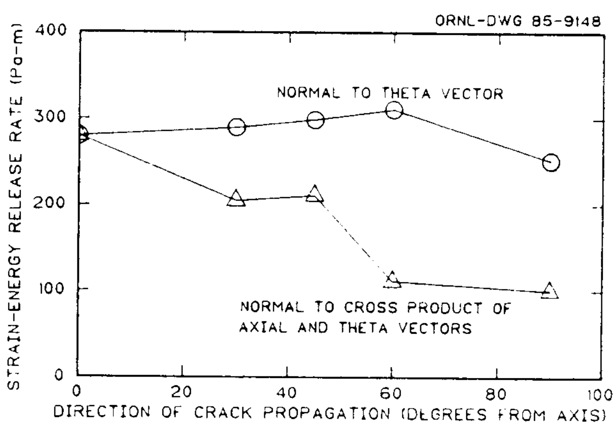

Figure 2. The effect of orientation on the strain-energy release rate of grade AGOT graphite.

The defect size can be measured independently by sonic attenuation as the proportionality has previously been demonstrated. The results of sonic attenuation measurements as a function of angle are given in Fig. 3. The change in defect size is a natural result of the projection of the filler particles with a high shape factor used to make grade AGOT. The ratio in strength can then be calculated using the square root of the ratio in defect size from Fig. 3. The calculated value is 1.56

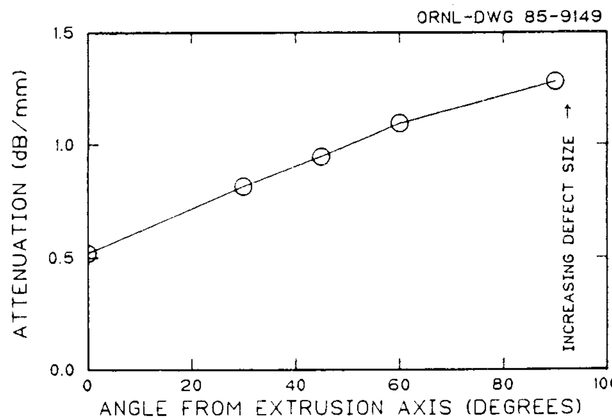

Figure 3. The effect of orientation on the sonic attenuation in grade AGOT graphite.

compared to a ratio of 1.57 from Table 1. The results from Fig. 2 also support the earlier hypothesis by E. P. Kennedy that crack branching has a greater effect on fracture energy than does the tortuosity of the crack path. The increase in energy by the tortuosity factor is a result of forcing the crack to move up and around filler particles misaligned for cleavage. Crack branching increases the energy required for fracture by reducing the stress intensity at the crack tip and by the actual increase in the number of fracture faces created by the branching. In the case where the crack is propagating normal to the aligned particle, the increased tortuosity of the crack path would dominate as the energy-absorbing mechanism. In the case where the crack is propagating parallel to the aligned particles, crack branching would dominate as the energy-absorbing mechanism. It seems evident that crack branching requires a much higher energy for fracture than does tortuosity.

Conclusions

These results are significant in that they show clearly that it is the defect size that controls the anisotropy in strength of graphite. This is in contrast to the past assumptions that variations in Young's modulus controlled fracture. It also seems apparent from these studies that crack branching is the most significant factor in increasing the energy required for fracture.