Fracture Mechanics Analysis of Extruded Graphite

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Introduction

The concepts of fracture mechanics applied to graphite have provided acceptable explanations of the fracture process in many diverse applications. These concepts can also be applied to bulk graphites when conventional flexural strength testing does not provide necessary data required to fully characterize fracture parameters. To demonstrate this, fracture toughness tests were performed on a medium grain, extruded graphite. Fracture toughness results were compared to processing and raw material changes as well as the conventionally measured physical properties. The results show fracture toughness to be independent of test orientation, and that fracture toughness correlates with microstructural and fractographic observations.

Material and Tests

A medium grain, extruded graphite was selected for this study. The test material was obtained from bodies produced by four different extrusion reduction ratios. The graphites were further identified by needle filler coke. Although the source of coke was the same, the cokes are uniquely identified by different process lots. One lot was extruded as a calcined coke (Type A) and as a graphitized coke (Type A') and the second lot was processed as a graphitized coke only (Type B'). Lastly, the basic heat treatment process is identified as either a conventional process (Type I) or a conventional process with an additional heat treatment step (Type II). A list of the test materials and their associated physical properties are shown in Table I.

The fracture toughness (K_{IC}) tests were performed at Oak Ridge National Laboratory using a short rod specimen with a chevron notch [1]. The specimen diameter is 25.4mm. Specimens were oriented with the normal to the fracture plane in the longitudinal direction (extrusion direction) and the crack propagating in the radial direction (L-R orientation). A second set of specimens from the graphites extruded with the standard reduction ratio were oriented with the normal to the fracture plane in the transverse directions and the crack propagating in the longitudinal direction (R-L direction).

Table I. Physical Properties

Reduction Ratio	Heat Treatment Type	Coke Type	Apparent Density (g/cm³)	Electrical Resistivity (μΩ·m)		Flexural Strength (MPa)		Sonic Elastic Modulus (GPa)	
				L	T	L	T	L	T
1.6 x Std.	1	A	1.78	4.48	8.63	20.9	11.1	13.3	5.9
1.4 x Std.	I	B'	1.78	4.64	9.69	19.1	11.4	14.9	4.8
1.2 x Std.	I	B'	1.78	4.12	9.22	21.4	11.8	15.8	4.9
Std.	I	A'	1.77	4.46	8.61	20.5	12.9	14.4	6.5
Std.	II	A'	1.76	4.56	8.34	18.9	12.0	12.9	5.8

Measured K_{IC} (stress-intensity factor at failure) data is used to calculate the strain-energy release rate (G_{IC} or the energy required to create new surface) and the critical defect size ($2a_c$) using the equations

$$G_{IC} = \frac{K_{IC}^2}{E} \quad (1)$$

and

$$2a_c = \frac{2}{\pi}\left(\frac{K_{IC}}{\sigma_f}\right)^2 \quad (2)$$

where E = elastic modulus
σ_f = flexure strength

Results

The conventional flexure strength test data in Table I indicate that the resistance to failure for all graphites are essentially equal, and discernable differences due to processing or raw material changes can only be observed by measuring other physical properties. As shown by Table I, Type II heat treatment generally yields reduced properties when compared to Type I heat treatment. Although the effects of extrusion reduction ratio changes are not explicitly demonstrated from the data, a higher apparent density is measured for the larger reduction ratio. Finally it is evident that significant differences do exist between the different coke types as can be measured by the electrical resistivity, and elastic modulus.

The fracture toughness results in Table II clearly demonstrate differences between the graphites' resistance to failure. While flexure strength did not distinguish raw material differences, fracture toughness data effectively contrasts the graphites made using the type A' and B' cokes. Similar differences, although slight, can also be seen between the two heat treatment processes.

Another noteworthy observation is

Table II. Fracture Mechanics Data

Reduction Ratio	Treatment Type	Coke Type	Sample Orientation	K_{IC} (MPa$\sqrt{m}$)	$2a_c$ (mm)	G_{IC} (Pa·m)
1.6 x Std.	I	A	L-R	1.31	2.50	129
1.4 x Std.	I	B'	L-R	1.01	1.78	68
1.2 x Std.	I	B'	L-R	1.07	1.59	72
Std.	I	A'	L-R	1.41	3.01	138
Std.	I	A'	R-L	1.41	7.61	306
Std.	II	A'	L-R	1.28	2.92	127
Std.	II	A'	R-L	1.25	6.91	269

independence of fracture toughness to the preferred orientation, in contrast to the anisotropy of flexural strength. Even more remarkable is the greater energy (G_{IC}) required to propagate a crack in the longitudinal direction (R-L) than to propagate a crack in the transverse direction (L-R). This seemingly contradictory notion that with-grain fracture may be more difficult to propagate than across-grain fracture is explained by a better understanding of fracture toughness results and the graphite's microstructure.

Discussion

The approach used here to calculate the fracture toughness parameters of graphite assumes linear elastic conditions. This simplification neglects graphite's actual non-linear stress-strain behavior. By neglecting this non-linearity, the calculated G_{IC} overestimates the true plane strain energy fracture toughness by an amount equal to the plastic work energy component[2]. This plastic deformation term is associated with preexisting microcracks, acting as a psuedo-plastic zone at stress concentration points. It is the orientation and density of the microcracking that determines the extent of the graphite's stress relief mechanism.

The higher G_{IC} values calculated for the with-grain fracture (R-L orientation) imply that a higher density of microcracks are oriented in the longitudinal direction. When the fracture toughness specimen is loaded, the applied external energy is essentially consumed by the process of opening these preexisting microcracks. This process effectively relieves the stresses at the crack tip. The stress relief mechanism continues until coincidental alignment of these microcracks advances the crack to its critical crack length, where failure occurs.

On the other hand, fracture in the transverse direction (L-R orientation) does not benefit from this stress relief system due to the preferred orientation of the microcracks. Here the crack front propagates by a tortuous intergranular path due to misoriented grains. Failure occurs only after sufficient energy has been absorbed at the crack tip to advance the crack either around or through the grain. As expected from these two different fracture processes, the critical crack length is larger in the orientation that can accommodate the greater energy consumption.

As might be expected, G_{IC} and the fracture toughness of the graphites extruded using the Type A' and B' cokes (same source) should essentially be equal, all other conditions being the same. However, the graphites made using the B' type coke deviate from the expected results by as much as 50%. This large deviation is apparently affected by large defects observed within the microstructure. Inspection of the L-R oriented short rod specimen fracture surface reveals a relatively smooth surface with many cleaved facets, in contrast to the irregular fracture surface of the tougher graphites with the same fracture orientation. With the presence of these defects and without the preferred orientation of the microcrack stress relief mechanism, the low energy fracture is to be expected.

Conclusion

This study has shown that fracture mechanics principles provide a simple method to evaluate a graphite's resistance to failure when conventional flexure tests do not. Although the true plane strain fracture toughness is not calculated, the total fracture energy, calculated for two different orientations, show the importance of the microcrack stress relief mechanisms in the fracture process. Finally, unexpected differences in the fracture toughness are explained with microstructural and fractographic observations.

References

1. L. M. Barker, "K_{IC} Measurements Using Short Rod Specimens - The Elastic Plastic Case," TR 77-91R, Terratek Systems, Salt Lake City, Utah, (1977).
2. M. Sakai, K. Urashima, M. Inagaki, "Energy Principles of Elastic-Plastic Fracture and Its Application to the Fracture Mechanics of a Polycrystalline Graphite," Journal of the American Ceramic Society, 66 (12) pp. 868-873, Dec. 1983.