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LETTER TO THE EDITOR

The effect of oxidation on the flexural strength of graphite

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The fact that oxidation decreases the fracture stress (strength) of polycrystalline graphite has been well documented[1–5]. However, in terms of the classical Griffith eqn (6) applied to catastrophic failure in brittle materials:

$$\sigma_f = K_{Ic}c^{-1/2}Y, \tag{1}$$

where σ_f is the fracture stress (strength), K_{Ic} is the fracture toughness, c is the flaw size, and Y is a geometrical constant ($\approx \pi^{-1/2}$), the oxidation-strength studies only yield quantitative data on changes in σ_f. As is evident from eqn (1), these strength decreases may be from one of two sources, either a decrease in the fracture toughness, K_{Ic}, and/or an increase in the flaw size, c. It is apparent that to fully understand the effects of oxidation on the strength of graphite, at least two of the parameters (σ_f, K_{Ic} and c) from the equation must be measured independently for identical graphites. For polycrystalline graphites, opaque materials with small microscopic flaws, only measurements of σ_f and K_{Ic} are practical. This note compares σ_f and K_{Ic} measurements for four commercial polycrystalline graphites, oxidized to total weight losses of approx. 5, 10 and 20%.

Material preparation, oxidation, characterization and fracture toughness measurements of the four graphites have been previously discussed[7, 8].

The filler in grades 580, 3499 and KK-16 was petroleum coke; the filler in grade 4029 was lampblack mixed with coal tar pitch, then carbonized and ground. Coal tar pitch was the binder for each grade.

The bend or flexural strengths of the as-received and oxidized specimens (6 mm × 6 mm × 36 mm) were measured at room temperature in three point flexure at a crosshead speed of 8.5×10^{-5} m/s. Fracture toughness and strength data (mean and 95% confidence limits) are listed in Table 1. Fracture stress (strength) is plotted as a function of fracture toughness in Fig. 1.

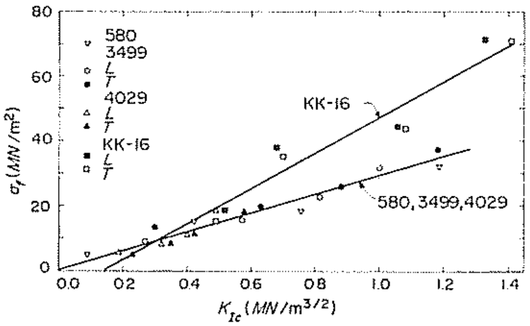

Fig. 1. Flexural strength vs fracture toughness for the as-received and oxidized graphites.

For all four of these graphites, σ_f and K_{Ic} consistently decrease with increasing oxidation. The linear form of these strength-fracture toughness results (combined data for grades 580, 3499 and 4029; but, individual data for grade KK-16) suggests an analysis of the effects of oxidation on the graphites' strengths through eqn (1) recast in the form of:

$$y = a_0 + a_1 x,$$

or

$$\sigma_f = 0 + (Yc^{-1/2})K_{Ic} \tag{2}$$

where the term $(Yc^{-1/2})$ is then the slope of the linear strength-fracture toughness plot with a zero intercept. Linear regression parameters for these graphites' flexural strength-fracture toughness data are listed along with their 95% confidence limits in Table 2.

For the combined data of grades 580, 3499 and 4029, linearity

Table 1. Fracture toughnesses, $K_{Ic}(MN/m^{3/2})$, and fracture stresses $\sigma_f(MN/m^2)$, of the as-received and oxidized graphites

GRAPHITE GRADE/ORIENTATION	AS-RECEIVED		~5% TOTAL BURNOFF		~10% TOTAL BURNOFF		~20% TOTAL BURNOFF	
	K_{Ic} (8)	σ_f	K_{Ic} (8)	σ_f	K_{Ic} (8)	σ_f	K_{Ic} (8)	σ_f
580/LONGITUDINAL	1.19	32.5±1.8	0.76	18.1±0.3	0.43	15.6±0.4	0.09	5.2±0.8
3499/LONGITUDINAL	1.00	31.2±0.7	0.81	22.6±0.2	0.57	15.7±0.3	0.27	8.8±0.8
TRANSVERSE	1.18	37.3±0.7	0.88	25.7±0.2	0.63	19.2±0.2	0.30	13.5±1.2
KK-16/LONGITUDINAL	1.33	71.1±2.5	1.06	44.4±2.3	0.68	37.7±0.3	0.52	18.4±1.5
TRANSVERSE	1.41	71.5±2.6	1.08	43.7±2.5	0.70	35.1±1.2	0.49	15.3±2.2
4029/LONGITUDINAL	0.50	17.9±0.4	0.40	11.3±0.8	0.32	8.5±0.03	0.19	4.9±0.02
TRANSVERSE	0.58	18.4±0.5	0.42	11.3±0.6	0.35	8.4±0.2	0.23	5.0±0.4

Table 2. Regression analysis of the strength–fracture toughness data for the graphites

GRAPHITE GRADES	(580, 3499, 4029)	(KK-16)
Linear Regression Parameter		
Slope ($m^{-1/2}$)	28.5±3.4	55.9±16.3
Intercept (MN/m^2)	0.76±2.2	-8.6±15.8

and a very nearly-zero intercept clearly indicates the applicability of eqn (2). The slope of $28.5 \pm 3.4\ m^{-1/2}$ is equal to the $(Yc^{-1/2})$ of eqn (2). For the data of grade KK-16, a linear relationship with a slope of $55.9 \pm 16.3\ m^{-1/2}$ is obtained. Due to the limited data for this grade of graphite, wider confidence limits exist; however, the origin is included well within the intercept's limits.

The strength-fracture toughness data for these as-received and oxidized graphites leads to two primary conclusions. For the four graphites examined, the linear flexural strength-fracture toughness data indicates that the flaw size (c) does not change appreciably during oxidation. The decreases in strength with oxidation are primarily due to corresponding decreases in the fracture toughness of the graphite from the oxidation process.

Second, the strength-fracture toughness data for three of the four graphites can be consolidated into a single linear relationship (slope = $Yc^{-1/2}$). For the fourth graphite, the same linear type of relationship, but with an increased slope is observed. Estimation of the flaw sizes for the combined flexural strength-fracture toughness data of the three grades 580, 3499 and 4029 and also for grade KK-16 result in approximate values of 390 and 100 μ respectively. That is, at catastrophic failure, the critical flaw in grade KK-16 is only about one fourth of that for the other three graphites examined. This is consistent with their filler particle sizes; for grade KK-16's maximum filler size is only $\approx 20\ \mu m$ compared to the other grades, 100–200 μm. For the four graphites examined, the critical flaw sizes appear to scale with the microstructure, specifically the filler particle sizes.

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