CORRELATION OF STRENGTH WITH PHYSICAL PROPERTIES*

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Introduction

Most investigators have assumed that fracture of graphite occurs either at constant strain ($S \sim E$) or at constant strain-energy ($S^2 \sim E$), as per the Griffith equations (1-3). But both concepts assume that the material is brittle, isotropic, and without voids. To the contrary, manufactured graphites are deformable, extremely anisotropic on a microscopic scale, and seldom approach theoretical density.

Porosity of brittle solids can be treated "idealistically" in two ways: 1) The material may be visualized as a continuous solid, containing discrete pores (bubbles), or 2) It may be visualized as being a continuous void, containing particles which are bonded together at their points of contact.

Theory

MacKenzie (4) has derived the effect of porosity on elastic properties for the continuous-solid model, and Kerner (5) has treated the continuous-pore model. Both models yield a very large dependence of elastic properties on porosity, with the continuous-pore model predicting the larger effect.

Most brittle materials exhibit a dependency which is intermediate between the predictions of the two models. Euler (6) has shown how the two models can be combined to yield a better fit to experimental data.

Unfortunately, except for the treatment by Mrozowski (7), the dependency of strength on porosity has not received similar (or, at least, successful) attention. Although the model developed by Mrozowski leads to a considerable dependency of both strength and elastic moduli on porosity (as is observed), some of the finer details, such as relative dependence of the two properties (8), are not in agreement with theory. Considerable data has, however, been accumulated and empirical relationships have been developed for porous ceramics (9-11), as well as for graphites. In general, these relationships indicate that a 10% change in porosity will produce about 50% change in strength; this is the same "rule-of-thumb" which emanated from the pioneering work of Griggs (12) on the loss of strength during oxidation of graphite.

Assuming the empirical correlation: $(S/S_o) = (\rho/\rho_o)^{\alpha}$, where S = compressive strength, ρ = density, and the subscripted "o" indicates a reference state; the "rule-of-thumb" yields $\alpha = 6.58$. Assuming a similar relationship for elastic moduli: $(E/E_o) = (\rho/\rho_o)^{\beta}$, $(S/S_o) = (E/E_o)^{\gamma}$, where $\gamma = \alpha/\beta$. Euler's model gives a calculated change of $\sim$40% in elastic moduli between 80% (ρ = 1.81 Mg/m^3) and 70% (ρ = 1.58 Mg/m^3) of theoretical density; the exact calculations yield $\beta = 3.78$ and $\gamma = 1.74$.

Results With Unoxidized Samples

Six 3-inch diameter by 6-inch long samples were machined from different sections of a log of a high-density, high-strength graphite**. Density and elastic moduli [calculated from ultrasonic velocities, measured by the "pitch-catch" method (13)] were obtained and the samples were tested for compressive strength in accordance with ASTM Standard C-695 (14). The best "physically reasonable" correlations, with the Young's moduli (E_e) and shear moduli (E_s) measured parallel to the axis of the samples, are:

$$S = 0.3424\ \rho^{1.84} E_e^{1.87}, \text{ and}$$

$$S = 1.338\ \rho^{2.41} E_s^{1.74}, \text{ with}$$

S in megapascals, ρ in megagrams per cubic meter, and E in gigapascals.

For the moduli measured diametrically, the best correlations are:

$$S = 0.6109\ E_e^{1.69\sigma - 0.412}, \text{ and}$$

$$S = 3.875\ E_s^{1.67\sigma - 0.198}, \text{ where}$$

σ = Poisson's ratio.

The exponents for E are in excellent agreement with value, $\gamma = 1.74$, which was derived above. Moreover, the maximum difference between calculated and measured strength is 1.9% of measured strength (for the correlation of strength with density and shear modulus); the maximum difference for the other three correlations is 1.4%.

Results With Oxidized Samples

Nine samples, 3-inches in diameter and 8-inches long, were oxidized at varying rates in an atmosphere of 80% CO_2, 20% CO, to between 5 and 10% weight loss; oxidation profiles ranged from mostly surface to nearly homogeneous. After oxidation, 1 inch was removed from each end of the samples; density, ultrasonic velocity, and compressive strength were then measured. Original strengths were calculated, using the correlations determined for the unoxidized samples; change in strength was then correlated with change in ultrasonic velocity: $(S/S_o) = (v/v_o)^{\lambda}$, where v is the ultrasonic velocity (either of the shear wave or of the longitudinal wave), and $\lambda \simeq 2.3$.

The maximum difference between calculated and measured strength is 6.4% of measured strength (for the correlation of strength with Young's modulus and Poisson's ratio); the correlation of strength with density and Young's modulus yields a maximum difference of only 3.3%.

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** Stackpole Carbon Company, Grade 2020, log No. 89970 B-F880 #219; $\rho \simeq 1.8$ Mg/m^3, $S_o \simeq 86$ MPa for 1 inch-diameter samples (1 MPa = 145.04 psi).

Conclusions

- Relationships have been developed between strength and changes in ultrasonic velocity; which can be used to accurately and non-destructively determine the compressive strength of Stackpole Grade 2020 graphite.
- There is reason to believe that the general relationship between strength and elastic moduli may be applicable to other graphites and to porous ceramics.
- This is a promising area for both experimental and theoretical work.

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