The Influence of Grain Size Distribution on a Fracture Criterion for Graphites

T. D. Burchell,+ B. McEnaney,+ A. P. G. Rose,* and M. O. Tucker*.

+School of Materials Science, University of Bath, Bath, BA2 7AY, U.K.

*Central Electricity Generating Board, Berkeley Nuclear Laboratories, Berkeley, Glos., U.K.

Introduction

A model of graphite fracture in tension[1] has been developed further, to describe fracture in the non-uniform stress conditions of three-and four-point bend and combined tension and bending[2]. The model assumes the graphite to consist of a regular array of single-sized, cubic particles. Each particle contains a plane of weakness, parallel to the basal planes, which will cleave when the resolved stress on the plane exceeds a certain value. The cleavage stress is obtained from the onset of acoustic emission[3], observed at approximately 20-50% of the final failure stress, depending on graphite texture[4].

Once a crack has initiated, that is the most favourably orientated particle in a position of high stress has cleaved, crack propagation may occur by cleavage of adjacent particles. Pores are modelled as particles having zero cleavage stress. The model then considers the probability of an initiating particle being surrounded by other cleaved particles. Once a contiguous array of cleaved particles attains the critical crack size, as given by Linear Elastic Fracture Mechanics, the specimen is assumed to fail.

Although good agreement between predicted and experimental mean stress at failure has been obtained in all cases considered, the model tends to underpredict the number of failures at low applied stress. This is due, at least in part, to the over-simplified microstructural input used. To overcome this limitation work is being done to obtain data on distributions of (i) grain size, (ii) pore size and (iii) cleavage stress. The present paper describes a method of particle size determination, the insertion of the improved information into the fracture model, and the resultant predictions of the distributions of stress at failure in four-point bend.

Experimental

Two needle-coke filler, pitch binder graphites currently used for British C.A.G.R. fuel sleeves, and denoted here as graphite A and B were examined. Grain sizes were obtained from polished specimens using a graduated eye piece lens and a moving stage, on a Zeiss IM-35 inverted stage microscope with polarized light.

The experimental failure probability data were obtained from a series of four point bend tests on specimens of graphite A cut perpendicular to the extrusion direction. Experimental strength data are not yet available for graphite B.

Results and Discussion

Measurement of grain sizes.

Grain size distribution obtained by repeated sets of 100 observations were not significantly different at the 95% confidence level for a given orientation of the graphites. The grain sizes perpendicular to the extrusion direction were significantly smaller than those parallel to the extrusion direction reflecting the anisotropy of the graphites. The grain size distributions obtained from 200 observations parallel to the extrusion direction are in Figs. 1 and 2. The range of grain sizes was from 0.1 to 1.4 mm, the lower limit being set by the difficulty in distinguishing between small grains and similarly-sized isochromatic domains in the binder phase. For graphite B grain sizes are represented well by a normal distribution. For graphite A the fit to a normal distribution is less good, with evidence for some skew towards small grain sizes. However, for convenience, both sets of grain sizes are assumed to be normally distributed as indicated in Figs. 1 and 2.

Development of the Model

All particles at a stress greater than the cleavage stress are considered potential initiation sites. Therefore the model requires the number of (cubic) particles present in the specimen. For a single particle size this quantity is readily determined, but for a normal distribution $f(x)$, there are $f(x)dx$ particles of size between x and $x + dx$. Thus the mean volume $\bar{V}$ of the particles is given by

$$\bar{V} = \int_0^\infty x^3 f(x)\,dx \Big/ \int_0^\infty f(x)\,dx$$

The solution of this equation is

$$\bar{V} = \bar{x}\ (\bar{x}^2+3\sigma^2) + \frac{2(2/\pi)^{1/2}\sigma(\bar{x}^2+\sigma^2)\exp(-\bar{x}^2/2\sigma^2)}{[1 + 2\mathrm{erf}(\bar{x}/\sigma 2^{1/2})\ \pi^{1/2}]}$$

where $\bar{x}$ and σ are the mean and standard deviation of the grain size distribution. Substituting the values of $\bar{x}$ and σ (Figs. 1 and 2), the effective particle size ($= \bar{V}^{1/3}$) is 0.71mm for graphite A and 0.76mm for graphite B. Thus the model for grains as cubic particles gives an effective particle size which is greater than the mean of the experimental grain size distribution ($\bar{x}$ = 0.57 and 0.66 mm for graphites A and B respectively). In the model, the size of all potential initiation sites is chosen from the respective normal distribution determined for each graphite.

Application of the Model

The experimental probability data for graphite A are compared with the probability curve calculated using the model incorporating the grain size distribution in Fig. 3. Also included in Fig. 3 is the probability curve for graphite A calculated using a single grain size. Compared to the latter curve, the model incorporating the distribution of grain sizes better represents the experimental distribution of failure stress probability, particularly at low failure probabilities. In order to correctly predict the mean failure stress the input parameter K_{IC} has been arbitrarily increased from the experimental value of 1.2 $MPam^{1/2}$ to 1.4 $MPam^{1/2}$. It is possible that the incorporation of distributions of pore size and cleavage stress may make the arbitrary increase in K_{IC} unnecessary.

Figs. 3 also includes the calculated failure probability of graphite B obtained using the distribution of grain sizes for this graphite, Fig. 2. The lower predicted mean stress for graphite B is in qualitative agreement with the relative strength of the two graphites determined in three point bend loading.

Quantitative image analysis of these two graphites is in progress to improve the modelling of the porosity distribution using an approach similar to that adopted here for grain sizes. It is possible that acoustic emission studies of different graphites may provide a model for the distribution of cleavage stress[4].

Conclusions

Using a measured distribution of grain sizes an improved representation of the probability of failure in four point bend tests has been obtained for graphite A. Predictions for the mean failure strength of graphites A and B are in qualitative agreement with experimental results obtained from three point bend tests.

Acknowledgements

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References

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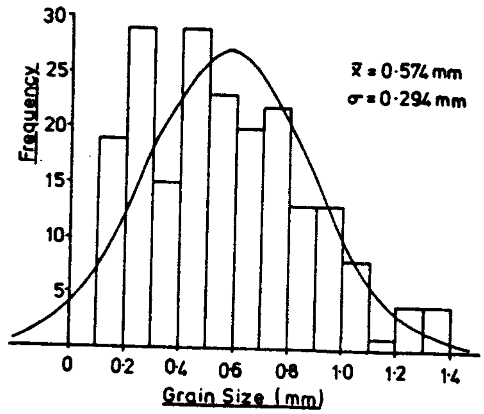

Fig. 1. Grain size distribution for graphite A

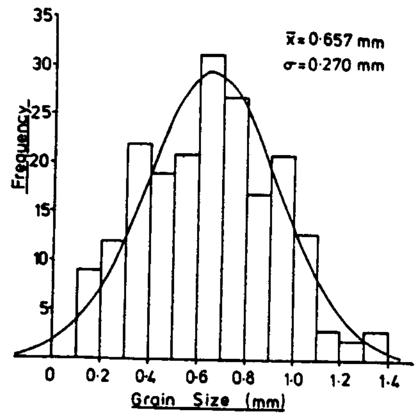

Fig. 2. Grain size distribution for graphite B

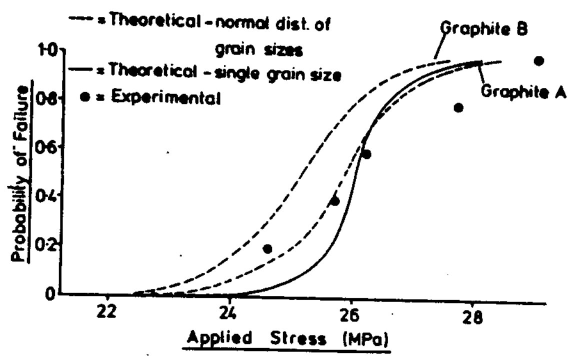

Fig. 3. Comparison of experimental and predicted failure probabilities in four point bend.