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THE INFLUENCE OF CREEP STRAIN ON THE ELASTIC MODULUS,
CRYSTALLOGRAPHIC ORIENTATION AND DENSITY OF A POCO GRAPHITE *

by

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ABSTRACT

POCO HPD-1 graphite is a very fine-grained, high-density, nearly isotropic graphite. However, it becomes less isotropic and less dense during high temperature creep deformation. Changes in crystallographic orientation, density, and modulus were measured as functions of creep strain. The modulus changes induced by creep seem to be related to the orientation and density changes. Modulus values were intermediate between calculated values based on the constant-stress model and those based on the constant-strain model.

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1. INTRODUCTION

POCO graphite, as represented by Grade HPD-1¹, reduces in cross-sectional area during high temperature creep, in contrast to other commercial polycrystalline manufactured graphites which show negligible reduction in area². Also, the decrease in density for a given increment of creep strain is less in POCO. Why should these be so? Since other graphites deform in creep through a crack-opening process^{3,4}, the possibility exists that POCO, like metals, and perhaps glassy carbon^{*5}, deforms by some additional, constant-volume process. This would be highly significant since dislocations with their Burgers vector partially out of the basal plane, twinning, kinking, or diffusional processes, for example, might greatly improve the plasticity of graphite.

Experiments were performed to determine the effect of high temperature creep on the elastic modulus, density, and orientation texture of Grade HPD-1 POCO graphite. High temperature deformation produces an orientation texture change in graphite⁶, and modulus and density data are available for POCO graphite⁷. Since the elastic modulus of bulk graphite is an "average" of highly anisotropic crystallites and voids, we wanted to determine if the changes in modulus could be accounted for by changes in density and degree of preferred orientation. Any new deformation modes should be expected to cause an additional change in modulus.

* Glassy carbon is similar to the POCO studied in that it shows a reduction in area and a small decrease in density during high temperature deformation.

2. EXPERIMENTAL TECHNIQUES

Tensile specimens were creep tested at 2400°C in an inert atmosphere. The procedures for creep testing have already been described many times, for example⁹ and will not be repeated here. After deformation, the gage lengths of the creep specimens were machined into right circular cylinders and their densities calculated from weight and size measurements. Elastic moduli were determined by a thin-rod sonic technique. Scanning electron micrographs were taken of polished and cathodically vacuum etched surfaces⁹ and preferred orientation measurements by x-ray diffraction techniques were made.

3. RESULTS

The orientation texture and the elastic modulus are shown as functions of creep strain in Figure 1, and for comparative purposes in Table I. The volume change is shown as a function of creep strain in Figure 2. The degree of preferred orientation, expressed either by the M-value^{*}, or by the Bacon anisotropy factor increases dramatically with increase of creep strain. After approximately 60% elongation, the POCO graphite has a fairly high degree of preferred orientation, as denoted by an M-value of 7.75. The degree of preferred orientation and the volume increase with the first increment of creep strain, in contrast to an initial decrease of elastic modulus, but additional strain results in a strongly increasing modulus change.

* The variation in the density of graphite basal plane poles, I , with the angle from some symmetry direction, ϕ , can be approximated by the expression, $I(\phi) = I(0^\circ) \sin^M \phi$. This M-value is thus, a measure of the degree of preferred orientation.

Scanning electron micrographs, Figure 3, shows representative microstructures after 10% (3a and 3c) and after 60% (3b and 3d) elongations. The pores elongate in the direction of the tensile axis (i.e., from the top to the bottom of the page). The matrix between pores does not show sufficient structural features to determine metallographically if crystallographic reorientation, or other changes, have taken place.

4. DISCUSSION

Creep deformation aligns the crystallites of POCO graphite thereby changing it from an isotropic to an anisotropic material. This effect is evident from the changes in crystallite preferred orientation as measured by x-ray techniques. The density also decreases with increasing creep strain. We now wish to determine if the modulus changes can be rationalized in terms of the orientation texture and density changes. We suggest that the initial decrease in modulus is due to the density decrease, and that the larger increase in modulus is due to the large increase in the preferred orientation texture.

Consider first the orientation texture change, for it appears that it has the most effect on modulus. Several models describing the effect of crystallographic orientation on elastic modulus have been proposed. The constant stress model by Reuss¹⁰ comes closest to fitting our data if partially pinned dislocations are assumed and the modulus calculations are based on an S_{44} value of $4.35 \times 10^{-11} \text{ cm}^2/\text{dyne}$ (which is applicable to many graphites) rather than on the value reported for highly annealed pyrolytic graphite with mobile dislocations (where $S_{44} = 4 \times 10^{-10} \text{ cm}^2/\text{dyne}$).

Calculations based on the Voight model¹¹, where strain is assumed to be constant, were also made. The constant-stress model gave values that were slightly high at low creep strains and significantly low at high strains; the constant-strain model gave values that were almost an order of magnitude higher than the experimental values. The real situation apparently lies somewhere between the constant-stress and the constant-strain models, but closer to the constant-stress model. The computed results based on constant stress are compared to the experimental values in Table I.

The effect on modulus of the density decreases that accompany creep strain are less severe than that of orientation texture changes, but the effect of density seems to dominate at small creep strains. Cost, Janowski and Rossi⁷ have discussed the effect of density on modulus for POCO graphites; new data which more nearly represents Grade HPD-1 POCO are also available¹². In either case, the results pertaining to the graphite in this study are the same. If the density changes brought on by creep strain were just as effective in reducing the modulus as were the density differences between various grades of POCO^{7,12}, then the modulus would decrease according to the dashed line in Figure 1. The initial rate of decrease of modulus determined experimentally is actually steeper. This is not at all surprising, as pore or crack shape and orientation must surely affect the rate of reduction of the apparent modulus. This has already been considered in relation to graphite by Hasselman¹³ and by Barrachin et al.¹⁴. Particle delamination type porosity and cracks are believed to be more effective in reducing modulus than is the more or less spherical voids. Surely, the

effect of slightly enlarging an interparticle pore or crack would not be as great as that of opening a new one. Since much of the creep strain, especially for large creep strains, is related to the enlargement of pre-existing interparticle cracks and pores, it is not surprising that the effect of decreased density on modulus becomes less pronounced with each additional increment of creep strain.

The dependence of modulus on creep strain seems to be entirely accounted for through the effects of orientation texture change and density change. New deformation modes unique to POCO, compared to other manufactured polycrystalline graphites, then, are not reflected in our results.

5. CONCLUSIONS

1. POCO graphite reorients crystallographically with creep strain.
2. The reorientation is accompanied by a reduction in density.
3. The modulus of elasticity is a function of both porosity and preferred crystallite orientation, with porosity effects predominating up to about 10% creep strain, and orientation effects predominating above 10% creep strain.
4. The modulus behavior suggests that at larger amounts of deformation, the material acts less like the Reuss constant stress model and more like the Voigt constant strain model.
5. No new deformation modes are suggested since the entire modulus-creep creep strain curve seems to be accounted for by density and orientation texture changes.

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TABLE I

The orientation texture expressed either as the M-value or Bacon Anisotropy Factor and the elastic modulus, as measured and calculated on the basis of the constant stress model (Reuss) for various high temperature creep strains.

Creep Strain pct.	M-value	Bacon Anisotropy Factor	Measured Modulus psi x 10 ⁶	Calculated Modulus psi x 10 ⁶
0	0	1.00	2.01	2.27
11.1	0.97	1.30	1.44	2.46
22.0	2.40	1.68	2.53	2.74
22.2	2.04	1.60	2.30	2.67
26.4	2.59	1.69	2.55	2.81
30.1	3.20	1.89	2.89	2.89
31.5	3.36	1.93	2.55	2.92
54.3	6.35	2.88	5.64	3.59

FIGURE CAPTIONS

- Figure 1. The change in elastic modulus, crystallographic orientation, and Bacon anisotropy factor as a function of creep strain.
- Figure 2. The volume change in the specimen gage section as a function of creep strain for several graphites and metals.
- Figure 3. Scanning electron micrographs of typical areas of POCO HPD-1 graphite after 10% creep strain (3a and 3c) and after approximately 60% creep strain (3b and 3d).

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