Prediction of Strength for Graphite with Density Gradient

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Abstract Tensile and compressive strengths were predicted for polycrystalline graphite with density gradient caused by non-uniform oxidation on the basis of the results obtained for uniform oxidation studied previously. The prediction is based on an assumption that fracture initially occurs at the surface and progressively extends toward the interior region of specimen. The tensile and compressive strengths could be predicted reasonably well, if their density profiles were known.

Introduction

Degradation of mechanical properties of nuclear graphite caused by thermal oxidation is one of the most serious problems for safety analysis and design of high temperature gas cooled reactors(HTGR's). In general, the oxidation behavior of graphite varies with reaction temperature and/or atmosphere. Depending on the condition, graphite is oxidized uniformly or non-uniformly. In non-uniform oxidation, density gradient appears within a graphite material. The material in HTGR's is to be oxidized by either impurity gases in helium coolant during normal operation or air intruded due to depressurization of helium coolant in an emergency.[1] In both cases the graphite components are believed to be oxidized at various temperatures corresponding to their locations in the reactor. It is believed that non-uniform oxidation of graphite usually occurs in HTGR's.[2]

Recently, Yoda et al. have investigated the effects of oxidation on tensile and compressive deformation behaviors for a nuclear-grade isotropic graphite.[3,4] They have found an emprical formula for stress-strain relationship by comparing flow stress for the uniformly oxidized with that for the unoxidized specimen. This formula could reproduce stress-strain relationship reasonably well for graphite specimen with density gradient, if its density profile is known.

In the present work, tensile and compressive strengths of graphite specimens with density gradient were predicted on the basis of the results obtained for uniform oxidation. The theoretical results were compared with the experimental ones.

Experimental

Material Graphite used was an isotropic fine-grained purified IG-11 manufactured by Toyo Tanso Co., Ltd. Some properties of the graphite are described in references.[5,6]

Specimen and oxidation Oxidation was carried out in stagnant air using an electrical furnace for dog bone type specimens for tensile tests with dimensions of 10 mm dia. by 30 mm long at the gage section, and for cylindrical specimens for compressive tests with dimensions of 20 mm dia. by 30 mm long. To minimize the end effect, quartz plates were contacted to both ends of each specimen. The oxidation temperature was determined to be 973 K on the basis of previous studies.[7] Burn off level and density change were calculated from the weight loss and dimensional changes.

Tensile and compressive tests These tests were carried out using an Instron type testing machine at a strain rate of $3x\ 10^{-4}\ sec^{-1}$. Strains were measured using a differential transducer and a pair of foil strain gages.

Density profile measurement Layers about 0.4 mm thick were cut incrementally from the exterior surface using a lath. For each cut, the apparent density of the region removed from the exterior surface was calculated from the weight loss and volume of the layer. A specimen was chosen among the specimens oxidized in the same condition in order to measure its density profile.

Results and discussion

Theory Strength of cylindrical specimens with an density gradient(Fig. 1) was predicted. When external load P is applied to the cross section of the specimen, the displacement along the loading axis is believed to be uniform within the cross section. However, the stress exerted perpendicular to the cross section varies depending on the location of the cross section. According to the results obtained for uniformly oxidized graphite, the strength decreases with decreasing density ρ, being expressed as

$$\sigma_f/\sigma_{f0} = (\rho/\rho_0)^n \qquad (1)$$

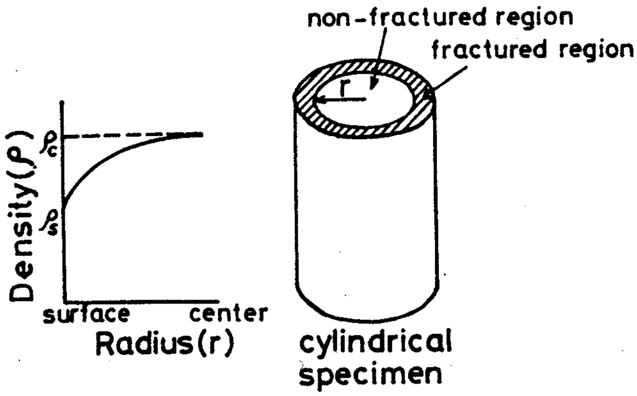


Fig. 1. A schematic of a cylindrical specimen with such a density gradient as shown in the left side. Fracture extends from the surface to the interior of the specimen.

where, σ_f and σ_{f0} are the strengths of the uniformly oxidized and unoxidized specimens, ρ_0 and ρ the densities before and after oxidation, and n the constant, respectively.[3,4] Accordingly, fracture strength at the exterior of the specimen having such a density gradient is always smaller than that of the interior portion adjacent to the exterior.[3,4]

Now, we consider the infinitesimal layer with density ρ and strength σ_f adjacent to the region at radius r to which the partial fracture has already extended, and assume that the fracture strain of the exterior is always smaller than that of the interior (Fig. 1.). Whether or not the partial fracture of the layer extends toward the interior region is determind by the following relationship; where P is applied load.

$$P/\pi r^2 \lesseqgtr \sigma_f \qquad (2)$$

The left side in eq. (2) means the average stress σ applied to the non-fractured region with radius r. If σ exceeds the local fracture strength σ_f of the infinitesimal exterior layer at radius r, that is $\sigma>\sigma_f$, the local (partial) fracture must occur at the layer and extend toward the interior. When $\sigma<\sigma_f$, the fracture must be restricted. Thus the following relationship must be satisfied to extend local fracture of the layer toward the interior of the remaining body.

$$P/\pi r^2 > \sigma_f \qquad (3)$$

Taking account of that the infinitesimal layer at radius r has the uniform density ρ, eq. (3) can be rewritten using eq. (1), as

$$P/\pi r^2 > \sigma_{f0}\ (\rho/\rho_0)^n \qquad (4)$$

Here, if we could express a density profile of the specimen (Fig. 1.) as $\rho = f(r)$ (5), eq. (4) can be expressed as a function of radius r by

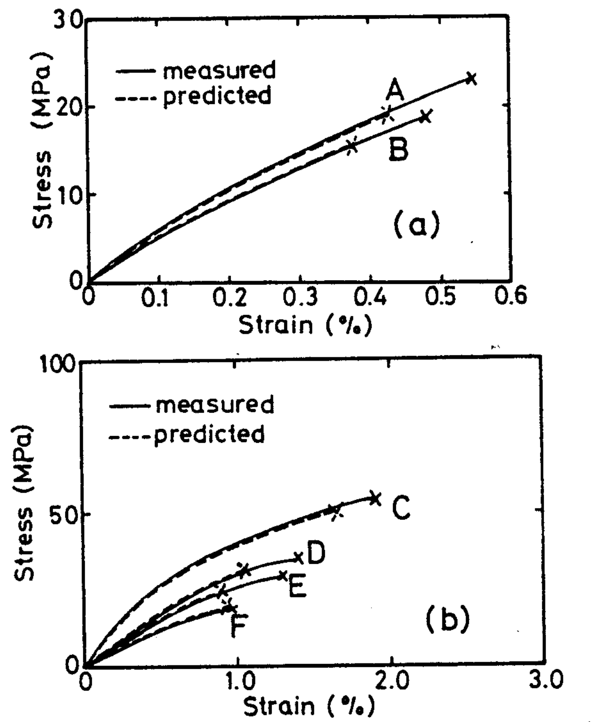
$$P > \sigma_{f0}\pi r^2 (f(r)/\rho_0)^n \equiv Q(r) \qquad (6)$$

where, σ_{f0}, ρ and n are material constants being able to be experimentally determined. Consequently, the strength of the specimen can be predicted by finding the maximum Q(r) value of eq. (6) with variable r.

Calculation of strength The stress-strain relationship was predicted in previous studies.[3,4] An example of the calculation will be given for tensile strength of specimen A. Substituting the f(r) for density profile, n=6.24, σ_{f0}=28 MPa, and ρ_0=1.76 g/cm^3 into eq. (6), 1442.7 N was obtained as the maximum Q(r) value. Dividing this value by the area of the cross section, we obtain the strength 18.5 MPa. The results are summerized in Table 1 for both tensile and compressive tests. Measured and predicted stress-strain curves of tensile and compressive tests are shown in Figs. 2. (a) and (b), respectively.

Table 1. Measured and predicted strengths for tensile (A and B) and compressive (C,D,E, and F) tests

Specimen	Total Burn off (%)	Measured Strength σ_m (MPa)	Predicted Strength σ_p (MPa)	σ_m/σ_p
A	4.6	23.0	18.0	0.78
B	9.7	18.5	14.9	0.81
C	4.8	54.0	50.2	0.93
D	12.2	35.3	30.8	0.87
E	19.5	30.7	24.4	0.80
F	29.5	19.7	19.7	1.00



Figs.2 (a),(b) Measured and predicted stress-strain curves. Cross marks indicate fractured. (a) Tensile tests (b) Compressive tests

Conclusion

The tensile and compressive strengths of non-uniformly oxidized graphite specimens were predicted. Predicted and measured strengths are agreed fairly well.

References

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