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SERIES A

THE BEHAVIOR OF GRAPHITE UNDER ALTERNATING STRESS

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ABSTRACT

The fatigue properties of grade AUF graphite were investigated at ambient and elevated temperatures. Specimens cut parallel to the axis of extrusion were stressed in reversed bending at room temperature and at 3550° F. The endurance limit of this graphite was found to increase from about 2500 lb/in.² at room temperature to about 4400 lb/in.² at 3550° F. The increase in endurance limit with temperature is correlative with the increase in short-time tensile strength with temperature observed in earlier studies of graphite.

This report is based on studies conducted for the Atomic Energy Commission under Contract AT-11-1-GEN-8.

I. INTRODUCTION

In view of the unique refractory characteristics exhibited by graphite in the course of experimental studies of its mechanical properties at elevated temperatures conducted at this laboratory,¹ graphite appeared promising as a possible structural material. The fact that its unrelaxed Young's modulus and short-time tensile strength increase with temperature makes graphite attractive for gas turbine application, for example. In such an application, however, it is necessary to know the fatigue properties of the material, and so a preliminary study of the behavior of graphite under alternating stress was undertaken.

II. PROCEDURE AND EQUIPMENT

It was known from earlier work² that the properties of extruded polycrystalline graphite varied considerably with position in the rod. A density profile of AUF graphite, for example, is presented in Fig. 1. In an effort to secure uniformity of the samples, all the specimens were cut from a 4 inch diameter core at the center of the extruded AUF rod. The length axes of the specimens were parallel to the direction of extrusion. Pertinent details of the specimens used in the fatigue testing are shown in Fig. 2.

In the testing, the specimen was stressed as a cantilever beam in reversed bending at a frequency of 1990 cycles per minute by means of a Krouse Testing Machine Company mechanical oscillator utilizing a cam with variable eccentricity to effect positive, constant-amplitude displacement of the specimen. As is shown in Fig. 3, a 6 inch length of 1/16 inch diameter steel wire served as a flexible linkage connecting the specimen and the oscillator. Failure of the specimen allowed the linkage (pivoted at the crosshead) to open a microswitch controlling the oscillator, automatically stopping the test.

Stresses in the specimens were calculated by individually calibrating each specimen; that is, the deflection of each specimen loaded under the cantilever conditions of the test was determined as a function of load. The deflections were measured with the use of a cathetometer. A typical load-deflection curve is shown in Fig. 4. The lack of the linearity which might be expected on the basis of the simple beam deflection formula²

$$\delta = \frac{P l^3}{3 E I} \quad \dots(1)$$

where

- δ = end deflection of a cantilever beam
- P = load applied at end of beam
- l = length of equivalent uniform beam
- I = cross sectional moment of inertia of equivalent uniform beam
- E = Young's modulus of material

is attributed to the nonlinear elasticity of graphite and does not represent any permanent deformation of the material. Knowledge of the amplitude of vibration (determined as a function of the cam eccentric setting) thus permitted calculation of the nominal maximum fiber stress in the specimen by means of the simple beam theory:

$$S = \frac{Mc}{I} \quad \dots(2)$$

where

- S = fiber stress
- M = applied moment at point in question
- I = cross sectional moment of inertia at point in question
- c = distance of extreme fiber from central axis of beam

The furnace used in the high-temperature testing is shown diagrammatically in Fig. 5. The specimen was heated by radiation from a surrounding graphite helix carrying a direct current. Temperatures at the central region of the specimen were determined by optical pyrometer measurements made through quartz windows. An inert atmosphere was maintained by a 16 ft³/min flow of helium entering at the top of the furnace and leaving through the linkage slot at the bottom. A view of the assembled equipment is shown in Fig. 6.

It seemed conceivable that an error in the high-temperature tests might arise as a result of the possible presence of residual moisture in the porous structure of the graphite. Any oxidation of the material when the specimen was heated to high temperatures could easily give rise to serious errors in the experimental results. In order to mitigate this possible difficulty, all specimens used in the high-temperature tests were dried at 300° F for 2 hours, cooled in a vacuum dessicator, and stored in the dessicator until used.

Calculation of the stresses in the high-temperature work was complicated by the change in the Young's modulus of the material with temperature. Due to the increased dynamic modulus observed in graphite at elevated temperatures,² any calculation based only upon the room-temperature load-deflection calibration of the specimens would necessarily underestimate the true stresses which prevail. As a first approximation, therefore, it was assumed on the basis of Eqs. (1) and (2) that for a given deflection the true stress at a given temperature would be in the same ratio to the nominal room-temperature stress as would the corresponding Young's moduli at the two temperature concerned:

$$\frac{S}{S_0} = \frac{E}{E_0} = f(T) \quad \dots(3)$$

This ratio as a function of temperature was calculated from Young's modulus data for center-cut AUF graphite presented in an earlier report³ and is given in Fig. 7.

In view of the nonlinear elasticity exhibited by graphite, the above assumption is of course valid only as a first approximation. In addition, another approximation was involved in considering the test temperature to be that observed at the middle of the specimen, the point of fracture. Since the great part of the deflection was due to strain concentrated in the narrow central region, however, and because of the slight thermal dependence of the elastic modulus of graphite, this approximation also appears reasonable. In view of the statistical and rather crude nature of a fatigue test, it was decided that more elaborate refinements in stress calculation* and control of

*Thermal expansion of the flexible linkage presumably effected a non-zero mean stress in the fatigue cycle even though a rough compensation for this effect was made when connecting the linkage.

the temperature distribution would not be justified for the present preliminary study. It should be emphasized that the above technique could not be used in the testing of metals because of the pronounced thermal dependence of their elastic properties.

III. RESULTS AND DISCUSSION

The results of two series of fatigue tests using AUF graphite specimens at room temperature and at 3550° F are presented in Fig. 8 in terms of the nominal maximum fiber stress vs. number of cycles to failure. It may be seen that the room temperature curve is similar in form to the "S-N" curves obtained with many metals, except that the horizontal portion of the curve (defining an endurance limit of 2500 lb/in.²) is reached after a considerably smaller number of cycles than is required in the case of most metals,⁴ and that the knee is not pronounced.

Fatigue tests on metals have indicated a definite proportionality between the endurance limit of a metal and its short-time tensile strength.⁴ Since the tensile strength of graphite had been found to increase with temperature,¹ it was believed that the endurance limit would exhibit a similar increase. The data of Fig. 8 show that AUF graphite possesses an endurance limit of about 4400 lb/in.² at 3550° F, an increase of about 75 per cent over its room-temperature value. Another effect of the elevated temperature revealed by Fig. 8 is that the apparently increased brittleness* of the graphite tended to eliminate the inclined portion of the S-N curve (which was poorly defined even at room temperature). Despite the scatter of the points (probably due to the unavoidable nonuniformity of the specimens), the data indicate that raising the temperature increases the tendency for the material to fail on the first half-cycle of any stress greater than the endurance limit. At high temperatures, accordingly, the high-frequency, creep-independent endurance limit should approach the short-time tensile strength. Preliminary tensile data on AUF graphite† seem to confirm this prediction.

*The resistance to long-time deformation by creep is reduced at high temperatures.¹ Measurements of the temperature dependence of the impact strength of graphite have not yet been made.

†Although grades ECA and AUF are nominally identical, the variations in the properties of commercial graphite within a given grade, batch, on piece are great enough to invalidate comparison of data unless careful control of the specimen material (usually on the basis of density) is maintained.

All the surfaces revealed by failure of the specimens at both high and low temperature were characteristic of brittle fracture, as had been all the fracture surfaces obtained in the earlier tensile testing.¹ A typical specimen broken at 3550° F is shown in Fig. 9. No evidence of the fatigue crack propagation encountered in metals was noted in any of the failures, which appeared to take place abruptly during a single-stress peak.

The tendency of fatigue failures of graphite at elevated temperatures to occur as "all-or-none" processes suggests that graphite behavior cannot be interpreted in terms of the theory of the fatigue of metals proposed by Orowan,⁵ which associates fatigue failure with the work hardening of plastic inhomogeneities within the specimen. During the early tensile testing of graphite specimens,¹ moreover, no evidence of work hardening as a result of plastic slip could be detected, and the permanent elongations realized are tentatively attributed to deformation by creep, which may be considered to be a diffusion mechanism involving no storage of strain energy. Although they cannot be regarded as completely conclusive, the graphite data encourage support for the contention of Freudenthal⁶ that plastic slip and strain hardening are not inseparable features of fatigue failures, and that the fatigue process may possibly be considered as "an essentially statistical effect of happenings on a submicroscopic scale".

IV. SUMMARY AND CONCLUSIONS

The fatigue behavior of AUF graphite specimens cut parallel to the axis of extrusion was investigated at room-temperature and at 3550° F. Well defined endurance limits were found in both cases, indicating the suitability of graphite for structural applications under conditions of alternating stress. Since the endurance limit (like the short-time tensile strength) was found to increase with temperature, it is concluded that creep characteristics and not fatigue behavior will determine the temperature limitations of graphite structures. Because of its unique strength and fatigue properties at elevated temperature, graphite appears attractive as a refractory material for gas turbine applications.

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Figure 1. A Typical Density Profile of Extruded AUF Rod.

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Figure 2. Details of Specimens Used in Fatigue Testing.

Figure 3. View of Oscillator, Flexible Linkage and Graphite Specimen.

Figure 4. Typical Load-Deflection Curve for a Fatigue Specimen of AUF Graphite.

Figure 5. Schematic View of Furnace Used in High Temperature Testing.

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Figure 6. Assembled Fatigue Test Equipment.

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Figure 7. Ratio of Unrelaxed Young's Modulus of AUF Graphite at a Given Temperature to Modulus at Room Temperature as a Function of Temperature.

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Figure 8. Fatigue Behavior of Center-Cut AUF Graphite

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Figure 9. Typical Specimen Broken at 3550° F.

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