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MASTER

RESIDUAL STRESSES IN EXTRUDED GRAPHITE TUBES

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RESIDUAL STRESSES IN EXTRUDED GRAPHITE TUBES

Summary

Extruded graphite tubes contain a strong crystalline texture which results in highly anisotropic thermal expansion coefficients in the tube wall. This could lead to high residual stresses in material cooled from the heat treatment temperature, and experiments involving cutting a longitudinal slit in a length of tubing and measuring the opening or closure of the gap do indeed reveal the presence of residual tangential stresses. This deflection method gives no details of the stress distribution, and the magnitude of the stress computed depends on arbitrary assumptions made about the stress distribution.

A complete analysis of the residual stresses in a tube can be made by the Sachs boring-out technique, where changes of length at the outer surface are recorded by resistance strain gauges as the inside is progressively machined away. This method was applied to a section from General Atomic extruded tube No. 2380-58.

The results showed that both tangential and longitudinal stresses of maximum value about 300 psi were present. The tangential stress pattern consisted of a small region of compressive stress at the inner surface, a larger zone of tensile stress, then a compressive zone near the outside surface. This pattern is qualitatively consistent with the "cooling stresses" expected from the texture of the tube. The longitudinal stress pattern was different at two positions 90° apart, consisting of tensile stress at the inside and compressive stress at the outside in one case, and the reverse situation at the other position. This distribution may be associated with bending stresses introduced into the extruded material by uneven flow between the top and bottom of the horizontal extrusion dies.

One-shot deflection tests for tangential and longitudinal stresses gave about the right value for the maximum tangential stress, but estimates of the maximum longitudinal stresses were inconsistent with the values obtained by the boring out technique.

INTRODUCTION

Preferred orientation measurements on General Atomic extruded graphite tube stock⁽¹⁾ show a pronounced texture in the tube wall with the basal planes predominantly oriented tangentially to the wall surface (Fig. 1). The edges of the basal planes are well aligned along the length of the tube, but only roughly aligned circumferentially, apart from a better-oriented "skin" that may be present at the inner and outer surfaces. As a result of the texture, the thermal expansion coefficients in the radial, tangential and longitudinal directions are different - typical values at 400°C are 8.8, 4.0 and $1.7 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$ respectively. The anisotropic contraction rates could result in residual internal stresses which might reach an important fraction of the ultimate tensile strength.

The "snap-ring" test (involving the measurement of the change in outside diameter of a section of tube when it is slit longitudinally) gives an estimate of the sum of the bending moments of the tangential internal stresses integrated across the tube wall. It gives no information about the distribution of stresses, and it is necessary to assume an arbitrary stress distribution in order to calculate a value for the maximum stress present. It is usually assumed that the stress distribution is the same as in an elastically bent beam.

A complete analysis of the internal stresses can be made by the Sachs boring-out method^(2,3), where the longitudinal and tangential strains at the outside surface of the tube are measured as the inside is progressively machined away. This method was applied to a section cut from extruded tube No. 2380-58, made from GP 38 graphite and Barrett No. 30 pitch and baked out at 900°C. This tube was made at an early stage in the extrusion development program and does not represent optimum process conditions.

Measurements

A piece of graphite tube 9" long was used; the outside diameter was 3.5" and the inside diameter 2.75". Two resistance strain gauges, each capable of measuring strain in two mutually perpendicular directions, were cemented to the outside of the tube at its mid point in two positions 90° apart. The tube was set up on a vertical milling machine and the strain gauges connected to a resistance measuring unit, using a dummy strain gauge as one half of a two-arm bridge in each case. The strain measurements were reproducible to within 5×10^{-6} inches per inch. A boring bar was used to remove material from the inside of the tube. Strain measurements were made as the wall thickness was reduced in steps of about .025", the clamping bolts holding the sample being slackened off before readings were taken. The final measurements were made when the wall thickness was reduced to .040".

(A) POLE FIGURE SHOWING THE RELATIVE DENSITY OF "c" AXES.

(B) THE "LIE" OF THE BASAL PLANES (SCHEMATIC)

Figure 1. Texture in the wall of an extruded graphite tube.

The internal stresses were calculated from the formulae⁽³⁾:

$$\sigma_L = \frac{E}{1-\nu^2} \left[(A_o - A) \frac{d\Lambda}{dA} - \Lambda \right]$$

$$\sigma_T = \frac{E}{1-\nu^2} \left[(A_o - A) \frac{d\theta}{dA} - \frac{A_o + A}{2A} \theta \right]$$

$$\sigma_R = \frac{E}{1-\nu^2} \left[\frac{A_o - A}{2A} \theta \right]$$

$$\Lambda = e_L + \nu e_T$$

$$\theta = e_T + \nu e_L$$

where σ_L , σ_T , and σ_R are the longitudinal, tangential, and radial stresses respectively.

e_L and e_T are the measured longitudinal and tangential strains.

E is Young's Modulus

ν is Poisson's Ratio

A_o is $\frac{\pi}{4} \times (\text{outside diameter})^2$

A is $\frac{\pi}{4} \times (\text{internal diameter})^2$

E was measured from a bend test, and ν from a compression test, on specimens cut from the same tube. In both cases strains were measured by resistance strain gauges. The measurements were 1.3×10^{-6} psi and 0.195 respectively. No allowance was made for the different elastic properties of the material in different directions. These differences are probably small, since Young's Modulus is relatively insensitive to preferred orientation.⁽⁴⁾

Figure 2 shows the surface strains at the two positions 90° apart (A and B), plotted as a function of the amount of material bored from the inside of the tube. The corresponding internal stresses are given in Figs. 3 and 4. No data are available on the stresses within .040" of the outer surface because this was the amount of material remaining after the last cut. It can be seen that maximum stresses of about 300 psi are present in both the longitudinal and tangential directions. Radial stresses are very small.

Figure 2. Surface strains at positions A and B as inside of tube is bored out.

The tangential stress distributions are qualitatively similar for strain gauges A and B, but the longitudinal distributions are mutually inverted between the two positions, suggesting the presence of a locked-in flexural stress.

Deflection methods for residual stress measurement

Tangential stresses may be estimated by measuring the opening or closing of a longitudinal cut in a section of the tube. On the assumption that the stress distribution is linear, the maximum stress σ_t is given by⁽³⁾:

$$\sigma_t = \frac{E t a}{\pi D^2 (1-\nu^2)}$$

where t is the wall thickness, D the outside diameter, and a the opening or closure of the cut.

In the same way, a long thin longitudinal tongue cut in the tube wall will deflect inwards or outwards if asymmetrical longitudinal stresses are present. Again assuming a linear stress distribution, the maximum stress σ_ℓ is given by⁽³⁾:

$$\sigma_\ell = \frac{E t b}{L^2 (1-\nu^2)}$$

where b is the deflection at the free end of the tongue and L is its length.

Both deflection tests were applied to the tube whose stress patterns are shown in Figs. 3 and 4. The calculated maximum stresses were:

$$\sigma_t - 340 \text{ psi (closure of cut)}$$

$$\sigma_\ell \text{ in line with gauge A} - 119 \text{ psi (inward deflection of tongue)}$$

$$\sigma_\ell \text{ in line with gauge B} - 54 \text{ psi (inward deflection of tongue)}$$

As already pointed out, these values assume a linear stress distribution. With complex stress distributions such as those observed, the calculated stresses represent the maximum stress in the linear stress distribution that would produce the same bending moment about the neutral axis as the actual stress distribution. The calculated maximum stress thus represents a stress which in general is of the same order of magnitude as the true maximum stress, but can be either an underestimate or an overestimate depending on the details of the stress distribution.

Figure 3. Residual stresses in tube wall at position A.

Figure 4. Residual stresses in tube wall at position B (90° from A).

In the present case the stress calculated from the "snap-ring" tests is about the same as the measured maximum tangential stress, and the direction of deflection (i. e. closure of the cut) is the same as expected, since the stress is predominantly tensile on the inside and compressive on the outside. However, the maximum longitudinal stresses calculated from the tongue deflection are considerably lower than those measured in the boring-out experiment, and in addition the direction of deflection of the tongue in line with gauge A is opposite to that expected. This may be because the two measurements sampled the stress at different points along the length of the bar, and the residual flexural stress may vary considerably over short distances. Also the formulae used for calculating stresses in the boring-out experiment assume a cylindrically-symmetrical stress distribution, and therefore do not rigorously apply to the present case.

Discussion

Tangential stresses: Both A and B strain gauges reveal the presence of a small region of compressive stress near the inner surface, then a larger zone of tensile stress, and finally a compressive region near the outer surface. This pattern can be qualitatively explained in terms of the thermal expansion coefficients in various directions in the tube wall, assuming the body is stress-free at its heat treatment temperature and the stresses develop on cooling. Consider a segment of the tube wall subtending a fixed angle at the center (Fig. 5a). Since the radial expansion coefficient is higher than the circumferential coefficient, the inner and outer arcs try to contract very little on cooling while the radial width of the segment decreases much faster. This would result in the situation shown in Fig. 5b. In actual fact the segment is constrained to stay the same shape on cooling, resulting in a compressive stress at the outside and a tensile stress on the inside (Fig. 5c).

This simple stress pattern is modified by the presence of the more highly oriented inner and outer "skins", in which the anisotropy of the thermal expansion coefficients is higher than in the bulk of the wall material. The unrestrained length changes on cooling in the three layers are shown schematically in Figs. 5d and 5e. Since the three layers actually remain joined together during cooling, a stress pattern of the type shown in Fig. 5f is produced. If this "skin effect" stress pattern is superimposed upon the pattern expected in the anisotropic wall without oriented "skins" (Fig. 5c), the result (Fig. 5g) is qualitatively similar to the one observed. It therefore seems probable that the tangential residual stresses are due to differential contractions on cooling.

A-C DEVELOPMENT OF RESIDUAL STRESS DUE TO UNEQUAL RADIAL AND CIRCUMFERENTIAL CONTRACTION RATES

D-F: DEVELOPMENT OF RESIDUAL STRESS DUE TO HIGHLY ORIENTED INNER AND OUTER "SKINS"

G: FINAL STRESS DISTRIBUTION IN TUBE WALL, TAKING "SKIN EFFECT" INTO ACCOUNT (PATTERN C PLUS PATTERN F)

Figure 5. Schematic illustration of the formation of residual stresses in the wall of an extruded graphite tube.

Longitudinal stresses: The observed difference in longitudinal stress pattern between the two positions A and B cannot be explained by preferred orientation effects. The stress pattern (Figs. 3 and 4) suggests internal stresses of a flexural nature. It is significant that extruded green-stock normally exhibits a considerable bow, possibly connected with uneven flow from top to bottom of the horizontal extrusion dies⁽⁵⁾ or slight misalignment between the die and the receiving rollers. The localized flow associated with the bowing could lead to residual flexural stresses in the extruded tube.

The longitudinal residual stresses could be more troublesome than tangential stresses in contributing to failure in HTGR fuel elements because the most important stresses developed in service are flexural stresses.

CONCLUSIONS

1. The extruded graphite tube examined contained tangential and longitudinal residual stresses. In both cases the maximum stress was about 300 psi.
2. The distribution of tangential stress is consistent with the cooling stress pattern expected from the anisotropic texture of the tube.
3. The longitudinal stresses probably result from uneven flow around the extrusion dies, which produces a bowing effect.
4. Deflection methods give no information about the distribution of the stress, and may give misleading values for the maximum stress. In the present case the "snap-ring" test gave approximately the right value for the maximum tangential stress, but the "tongue deflection" test did not give the correct maximum longitudinal stresses, possibly because the residual flexural stress has local variations along the tube.

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