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The strength and stiffness of graphitized 3D carbon-carbon composites, when loaded mechanically along a direction parallel to a set of yarns, appear to be dominated by the properties of that set of yarn bundles because the continuity of load through transversely-oriented yarn bundles and matrix material is interrupted by the open crack pattern (described in [1] [2]). Thus, it is not surprising that good linear correlations have been observed between tensile strength (and stiffness) and the fiber areafraction in the direction of loading. Shear behavior however, depends upon the transfer of force from one set of yarns to another. Given the crack pattern, two orthogonal sets of yarns communicate mechanically only through load paths that are of limited area and somewhat tortuous. As the temperature is raised, and the cracks close to the extent that frictional load transfer can take place across them, the shear stiffness of the composite should increase. That such an effect does take place is illustrated by measurements of shear modulus at several temperatures up to 2500°C [1].

Shear behavior is closely related to tensile or compressive behavior in directions other than the principal yarn directions. Such "off-axis" tensile or compressive tests can be used to rigorously derive the shear modulus and to infer a good approximation to the shear stress-strain behavior [3] [4]. For example, uniaxial compression in the 45-degree offaxis direction (bisecting the 90° angle between two yarn sets) may be resolved into "on-axis" shear plus biaxial compression (Figure 1). As the shear deformations in typical orthogonal carbon-carbons will be large relative to the compressional strains, such tests offer a convenient way of studying shear behavior. Figure 2 shows schematically some of the essential features of the stress-strain response of 3D carbon-carbons tested in 45-degree off-axis compression at room temperature:

- a) the strains attained are much higher than strains-to-failure in on-axis tests;
- b) the stress-strain curves are smoothly non-linear and much of the non-linear strain is recovered on unloading. (Non-linearity frequently occurs in on-axis tests, but is usually accompanied by jogs in the curve that are attributed to progressive cracking of filaments, and other irreversible effects).

A technique has been developed to obtain replicas of specimen surfaces while the specimens are under load in a mechanical-test machine. Replicas were made from a 45° off-axis compression specimen of one of the materials (D) described by Seibold [5]. These replicas were then processed for viewing in the electron microscope, and photographs were taken in a scanning electron microscope. The replica is essentially a "negative" of the specimen surfaces; thus cracks and pores appear as protrusions in the photos. Figure 3 shows the development of a crack within a yarn bundle at strains of about 5 percent. No other type of damage is readily apparent at this magnification. On a much finer scale, at about 5000X magnification, there appears to be an opening of very fine cracks in the matrix between filaments within a yarn bundle. The high strains measured in such specimens appear to be accommodated by distortions of existing cracks, extension of cracks surrounding yarn bundles. None of these processes appear to involve breakage of filaments.

These are preliminary results. Encouragement may be derived from the success of the observational technique: there appears to be much more information to be gleaned from more detailed photography and from taking replicas at other load conditions (including zero load after unloading).

The smooth non-linear loading/unloading stressstrain curve in off-axis compression is qualitatively similar in essential features to the stress-strain response of bulk graphite in uniaxial compression. In studies of prooftesting graphite [6] [7], it was found that annealing after loading would restore the original dimensions of the specimen (erase the residual strain) and also restore the virgin stress-strain response. The mechanisms underlying this phenomenon are not well understood. Some controversy surrounds the question whether polycrystalline graphite deforms non-linearly by means of classical dislocation-motion plasticity or by means of crack opening or by both mechanisms. It would be of interest to discover whether the carbon-carbon system also responds to annealing in the same way as does graphite.

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Figure 1. Off-axis compression test of 3D carboncarbon composite.



Figure 2. Typical stress-strain response.



Figure 3. Replicas of the same region at two loads during an off-axis compression test of a 3D carbon-carbon (Material D):

Top: at zero load

Bottom: at 5500 psi stress and approx. 5 percent strain

Note extension of cracks around yarn bundle at center of photo and occurrence of new crack through the bundle.