## Effects of Weak Interfaces on Thermal Expansion of 3D Carbon-Carbon Composites

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Interfaces between the constituents of carbon-carbon composites usually are weak. Therefore, transfer of stress from one constituent to another can require relatively long "shear lag" distances because the interface fails and, instead of efficient elastic stress transfer, only friction and mechanical-interlock forces are available. Detrimental effects on tensile strength have been identified (1,2). This paper shows that weak interfaces also affect the measurement of thermal expansion of 3D carbon-carbons.

Thermal expansion usually is measured by observing the change in length of a uniformly heated bar. For materials of a microstructural dimension small enough to be considered homogeneous on the scale of the specimen, the length change is a direct measure of the thermal expansion of the bulk material. However, for 3D composites, the diametral dimension of the yarns is in the order of 1 mm, which is not very small compared to typical specimens. As the composite's thermal expansion depends on stress interactions among the variously oriented yarns, and as these stresses are affected by free surfaces at the boundaries of the specimen, the change in length is not necessarily a direct measure of the thermal expansion of the bulk composite.

For this analysis, the 3D composite is taken to consist of two phases: "yarn", comprising the primary bundles that are oriented axially (parallel to the bar's length), and "matrix" comprising the other yarn bundles and the matrix pockets. Differences in the thermal expansions of the two phases give rise to stresses when the bar is heated. Generally, the "yarn" will be in axial tension while the "matrix" will be in axial compression; transverse to the axis, the interface will be in compression (3). At the end of the bar, in the absence of externally applied forces, the axial stresses in yarn and matrix will be zero. Thus, near the end, the axial stresses vary, implying shear at the yarn-matrix interface.

Specifically, we consider simple square bars as are commonly used. The symmetry of the situation allows us to study half the length of such a specimen, considering a single yarn and its surrounding matrix (Fig. 1). Because of shear lag, the matrix will displace axially more than the yarn, giving rise to a wavy surface at the specimen end (Fig. 2). In the region that remains bonded, the shear stress can be predicted from an elastic shear lag analysis. If the interface shear stress exceeds the interface strength, debonding will occur. In the debonded region, a frictional shear stress can exist, which we assume

is the sum of two factors: the product of a and the transverse عمر friction coefficient compressive stress  $\mathbf{s}_{\mathbf{c}}^{\mathbf{c}}$  acting across the interface, and a constant  $\tau'$  representing resistance by other effects, such as mechanical interlocking between rough interface surfaces. The compressive stress,  $\sigma_c$  , arises from the minimechanical interactions between the transverse yarns and the rest of the composite (which) includes our primary axial yarn). Because shear lag phenomena apply also to the transverse yarns, the compression will vary with distance from a transverse free surface. At a transverse surface, the compressive stress on the primary yarn will approach zero. Toward the center of a large enough body, the compressive stress will approach a maximum value. Thus, we may consider two extremes, one applying to the corner of a specimen and the other applying to the centerline (Fig. 3).



Fig. 1. Idealization of 3D composite for analysis.



Fig. 2. Deformation of end surface on heating,

From these considerations, it is clear that the thermal strain measured in an expansion test will depend on whether the test technique reads the length change of the "matrix" phase or of the "yarn" phase, and will also depend on whether the measurement includes the corners of the specimen or just the centerline. Thus, various types of specimen ends used in dilatometer tests (Fig. 4) may give different data.

Numerical examples have been calculated, based on input properties intended to represent 3D composites made with T-300 fibers, densified with pitch to more than 1.8 g/cm<sup>3</sup>, and heat-treated to temperatures above 2200 C. Fig. 5 shows the predicted length changes (divided by specimen length) for 50 mm long bars with 21 percent of the volume occupied by axial yarn bundles that are 1.6 mm square. Three curves are shown: (A) "matrix" phase response at corner of specimen, (B) "matrix" phase response at centerline of specimen, and (C) "yarn" phase response at centerline. The predicted yarn response at the corner is essentially the same as (C). The data points are from Lander (4): squares were measured on flat-ended specimens in a way that includes the "matrix" response; crosses were measured on a specimen with protruding yarns, so they represent "yarn" response. There is respectable agreement between data and analysis. Both show that substantial differences can occur between the two types of measurement. Analysis shows that the yarn response is very close to the theoretical expansion of the composite. Therefore, we may conclude that dilatometry on flat-ended specimens can produce substantial overestimates of the true expansion of the composite. Increasing the ratio of specimen length to yarn diameter, and increasing the volume fraction of yarn, will tend to decrease the errors.

On the basis of the findings, the use of flat-ended specimens in dilatometers should be discouraged. The use of spherical-end specimens is preferable to flat-end specimens; however, significant error may be experienced due to surface roughening. Pin-ended specimens should be quite accurate if the pin rests on the end of a yarn and is of a diameter smaller than the yarn cross-section; otherwise, data from pinned specimens may be influenced by roughening at the base of the pin. Of the ends shown in Fig. 4, the most accurate appear to be the protruding-yarn specimens (Fig. 4c/d) first used by Lander (4)

Many of the properties that are inputs to the analysis are not well known. Research should be directed toward measuring transverse properties of yarn bundles, accounting for pre-existing microcracks, and measuring yarn interface strengths and friction coefficients, all as functions of temperature. Also, the analysis now does not treat creep/relaxation effects, which are undoubtably important at temperatures above 2000 C; extension of the analysis, and acquisition of relevant creep data would be worthwhile.

## Acknowledgments

Sponsored by the Office of Naval Research. Thanks to Mr. L. L. Lander for stimulating discussions.











Fig. 5. Effects of end type on thermal strain data: analytical predictions and Lander's data.

## References

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