DISCRETE-MATRIX MODEL FOR CARBON-Carbon COMPOSITES

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Carbon-carbon materials are characterized by high heat resistance and in a number of cases by relatively high resistance to thermal oxidation. However, their use for load-bearing applications presents certain difficulties. This is associated with the low degree of utilization of the strength of the reinforcement, the low shear strength, and the low elongation at break.

The chief performance-reducing factor is the lack of continuity of the carbon matrix. This is due to the fact that the synthetic organic resins used in carbon-carbon technology are characterized by a relatively low yield of solid products of pyrolysis, up to 25% of the volume of the starting resin. Moreover, these thermosets form solid products of pyrolysis with closed pores that cannot be filled during subsequent impregnation with organic resins or pyrolytic carbon precipitated from the gas phase.

Optical investigations of the structure using an electron microscope show that in the case of a resin with high shrinkage, defects in the form of cracks, closed pores, etc., are quite common [1, 2] (Fig. 1). Figure 1a shows defects in the zone between reinforcing elements; the distance between cracks, evidently due to chemical shrinkage, is 3-12 fiber diameters (i.e., up to 0.072 mm). The cracks in Fig. 1b are thermal cracks with an average spacing of up to 10 diameters. The defects in the interior of the matrix shown in Fig. 1c are also of chemical origin and illustrate the phenomenon of closed porosity.

In the light of these data it is possible to use the Rosen model with a fractional matrix (Fig. 2) as a model of the structure of the carbon-carbon composite. The presence of cracks or other local weakening of the matrix should lead to a sharp increase in the apparent length of the composite and hence to a loss of strength. In fact, in accordance with the Rosen model [3], if the deformation of the matrix is predominantly of the shear type, in the notation of Fig. 2 we should have

\[ \tau_s = \frac{G_b \alpha_s r_s^2 \sinh \eta z}{\eta E_a (r_a - r_f) (r_s^2 - r_f^2) \cosh \eta l} \]

where \( \tau_s \) is the shear stress in the matrix; \( z \) is the axial direction (see Fig. 2); \( l \) is the critical length of the composite with pore-free matrix; \( l_0 \) is the mean length of the continuous part of the matrix; and \( n \) is the number of matrix fractions on the length \( l_{eff} \). In expression (1),

\[ \eta^2 = \frac{2G_b}{E_b (r_a - r_f) r_f} \left[ 1 + \frac{E_f r_f^2}{E_a (r_s^2 - r_f^2)} \right] \]

and \( \eta \) is found from the expression

\[ l = 2r_f \left[ \left( \frac{1 - \frac{V_{b,5}}{V_{f,5}}}{V_{f,5}} \right) \frac{E_f}{G_b} \right]^{\frac{1}{5}} \left[ \arccosh \left( \frac{1 + (1 - \varphi)^2}{2 (1 - \varphi)} \right) \right]. \]

In expressions (2)-(4), \( G_b \) is the shear modulus of the matrix; \( E_a \) and \( E_f \) are the Young's moduli of the averaged composite and the reinforcement, respectively; \( r_{a,b,f} \) are the radii...
Fig. 1. Defects in the matrix of a carbon–carbon composite: a) cracks in the matrix between bundles of carbon fibers (magnification 325×); b) cracks in the matrix at a fiber (magnification 1600×); c) matrix defects in the zone between carbon fibers (magnification 4250×).