STRENGTH AND THERMAL STRAIN OF CARBON-FILLED COMPOSITE MATERIALS AT HIGH TEMPERATURES. COMMUNICATION 2. NATURE OF STRAIN AND WEAKENING OF MATERIALS WHEN HEATED FROM 290 TO 3300 K

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We have investigated the physicomechanical properties of carbon-filled composite materials. We have established that with an increase in temperature up to 770 K, some weakening of the materials occurs followed by their strengthening, with maximum values for the elasticity modulus $E$ at $T = 1270$ K and for the compressive breaking strength $\sigma_p$ at $T = 2270$ K. In this case, the $E$ values are about 5% greater than the original values, and the $\sigma_p$ values are more than double the original values. Further increase in temperature leads to a decrease in the strength characteristics under compression. In order to explain the reasons for weakening of composites upon heating, we have investigated the characteristic behavior of the thermal strain for carbon-filled composite materials, including in the processing stages of their fabrication. We have determined the characteristic behavior of the thermal strain for the original material: carbon-fiber reinforced plastic in a phenolformaldehyde matrix, carbonized carbon-fiber reinforced plastic, and carbon-filled composite materials densified with pyrolytic carbon. We have established that the shear stresses arising in the first annealing within carbon-fiber reinforced plastic (as a result of the action of shrinkage strain) are preserved over a broad temperature interval $570-1270$ K, and are the reason for weakening of carbon-filled composite materials in the same temperature range. We have carried out extensive microstructural investigations of carbon-filled composite materials, allowing us to explain the physical processes occurring in the composites under thermal and mechanical loads.

Using the technique outlined in Communication 1 [1], we have carried out a series of tests on samples of carbon-filled composite materials. The samples generally were cut from full-scale structural elements in the plane of reinforcement of the composite. With the goal of having the results of the investigations supplement each other, the strength ($\sigma_p$, $E$) and thermal strain ($\alpha$) characteristics were determined on the same carbon—carbon composite material, densified with pyrolytic carbon by chemical vapor deposition, under comparable conditions (heating rate, gaseous medium, pressure in the high-temperature chamber), taking into account the anisotropy of the composite.

For a deeper understanding of the processes involved in weakening of the composites upon heating, we present the results of investigation of the thermal strain and the structural changes in the material in the processing stages of fabrication of carbon—carbon composite from carbon-fiber reinforced plastic.

**Discussion of Experimental Results.** The stress—strain diagrams of the investigated samples of carbon-filled composite materials densified with pyrolytic carbon are shown in Fig. 1. As we see, the stress—strain diagram of the material in the temperature range $290-1770$ K is practically linear all the up to fracture; the ultimate strain in this case changes insignificantly; the section of nonlinearity is most pronounced at the temperature of $770$ K (Fig. 1a).

In the temperature range $290-2270$ K, fracture of the samples occurs along the planes of maximum tangential stresses (Fig. 2). However, in the temperature range $2770-3270$ K, the material is plastically deformed; the strain increases without an increase in load, but fracture does not occur (the dashed section on curves 2 and 3 in Fig. 1b). We should also note that
Fig. 1. Stress–strain diagrams for carbon-filled composite materials under compression along the weft in the temperature interval 290-1770 K: a) [(1) \( T = 290 \) K; (2) \( T = 770 \) K; (3) \( T = 1270 \) K; (4) \( T = 1770 \) K] and 2270-3270 K: b) [(1) \( T = 2270 \) K; (2) \( T = 2770 \) K; (3) \( T = 3270 \) K].

Fig. 2. Nature of fracture of samples of carbon-filled composite material at \( T = 290 \) K (a) and \( T = 2270 \) K (b).

For \( T = 3270 \) K, the stress corresponding to the inflection point \( K \) on the stress–strain diagram is above the breaking stress of the carbon-filled composite material in the original state (Fig. 1b). The point \( K \) on the stress–strain diagram corresponds to the moment the increase in the stresses of nondestructive deformation begin.

Photography of the samples of carbon-filled composite material in the original state and after compressive loading at a temperature of 3270 K are shown in Fig. 3.

The values of the porosity and density of the samples of carbon-filled composite materials not subjected to mechanical loading with an increase in temperature up to 3270 K differed by no more than 2-4\% from the values for the original state.