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TEMPERATURE EFFECT ON THE PROCESS OF WEAR OF A FIBROUS COMPOSITE UNDER HIGH LOAD CONDITIONS

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Abstract. A model of the fibrous composite material friction and wear process is constructed taking into account the heating of the friction surface. The inhomogeneous temperature expansion of the composite components and the resulting fiber/matrix slippage near the friction surface and the friction surface profile change is considered. The influence of temperature on the distribution of stresses in the fiber and matrix and on the roughness of the friction surface of the composite is determined.

Keywords: composite mechanics, composite wear, composite friction, tribology

1. Introduction

Composite materials based on carbon are widely used in friction joints associated with high sliding velocities and surface forces, and hence temperature loads (primarily in aircraft braking systems). These materials demonstrate high thermal stability (which determines their choice), but at the same time show an unusual effect of temperature on the process of their friction and wear. According to the experimental studies [1-3] with an increase in the surface temperature carbon composites may show both decrease in wear rate and nonmonotonic wear rate behavior. The roughness of the worn surface and the size of wear debris typically have an inverse correlation with the wear rate. The theory of composite materials friction conditionally divides the process of their wear on two types: uniform wear and surface damage from chipping inclusions material. The first process has been studied rather well [4-6], but at high loads and surface friction energies, the second process begins to dominate. According to the theoretical model [7-9], decrease in surface unevenness of the composite and reduced wear debris size lead to improvement of wear resistance of the composite (which agrees well with the experimental results as described above), but the question of the relationship of these processes to the temperature and its effect on the microstructure of the material has been studied little [10]. In this paper, the effect of temperature on the process of friction and wear of fibrous composite material due to the uneven thermal expansion of the fiber and matrix material will be considered. To this end, the problem of heating the near-surface representative volume of composite material will be posed and solved, taking into account the process of its wear.

2. Problem formulation

Consider a fibrous unidirectional composite material with the direction of the fibers perpendicular to the friction surface (Fig. 1).

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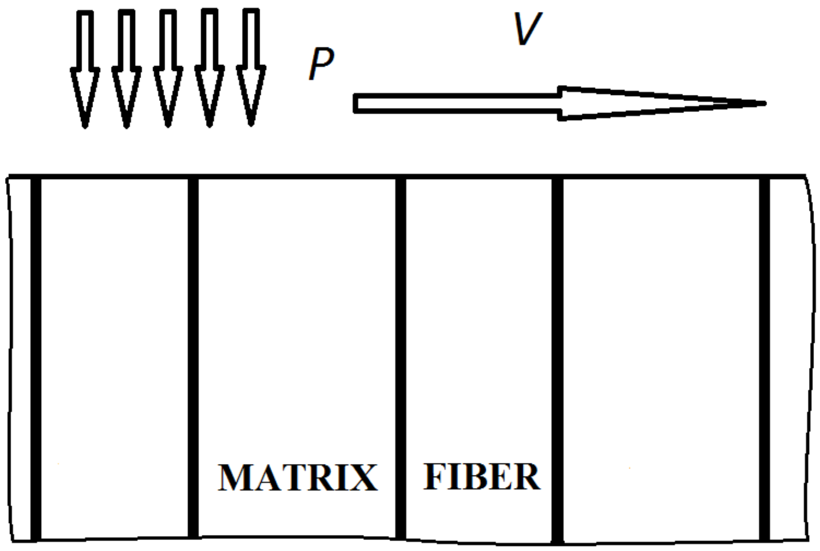

Fig. 1. Composite friction scheme

It interacts with the smooth hard counterbody with a specific load *P* and sliding speed *V*, whereby the friction surface is heated to a temperature *T*. As a result of wear, a redistribution of surface pressures occurs between the fiber and matrix regions on the friction surface, and the fiber slips with respect to the matrix within the depth *L*. The normal pressures on the surface of the fiber and matrix sections are assumed to be constant and equal σ_p^f and σ_p^m, respectively. As mentioned above, in the abrasive wear of composite material, the roughness of the friction surface caused by the uneven wear of its components has a determining effect on the wear rate. Also, the depth of fiber detachment from the matrix *L* is of great importance for fiber stability and the intensity of the process of breaking off its tips. To determine the influence of temperature on these quantities, we consider the representative volume of the composite material adjacent to the friction surface (Fig. 2).

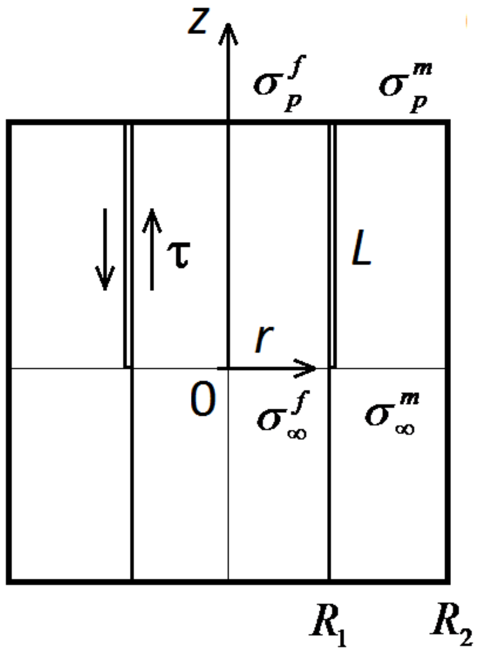

Fig. 2. The representative volume of composite

A representative volume is considered in the form of coaxial cylinders of length L, the inner one with radius R_1 represents the fiber, and the outer one with radius R_2 represents the region of the matrix adjacent to the fiber. On the boundary between the cylinders, the normal pressure q and the tangential force τ_S in the direction of the fiber axis 0z act. Cylinder coordinates connected with the cylinder axis are used.

3. Determination of stress distribution in fiber and matrix

Consider an arbitrary cross-section of the composite representative volume of small thickness (Fig. 3). Assuming that the stresses in the direction of the 0z axis depend only on z, one can use the solution of the cylinder and tube under pressure problem (assuming that the stresses σ_z^f, σ_z^m vary slowly along the 0z axis). Then we can neglect shear stresses and strains:

$$\tau_{rz}, \tau_{\theta z}, \tau_{r\theta} \approx 0, \quad \varepsilon_{rz}, \varepsilon_{\theta z}, \varepsilon_{r\theta} \approx 0. \tag{1}$$

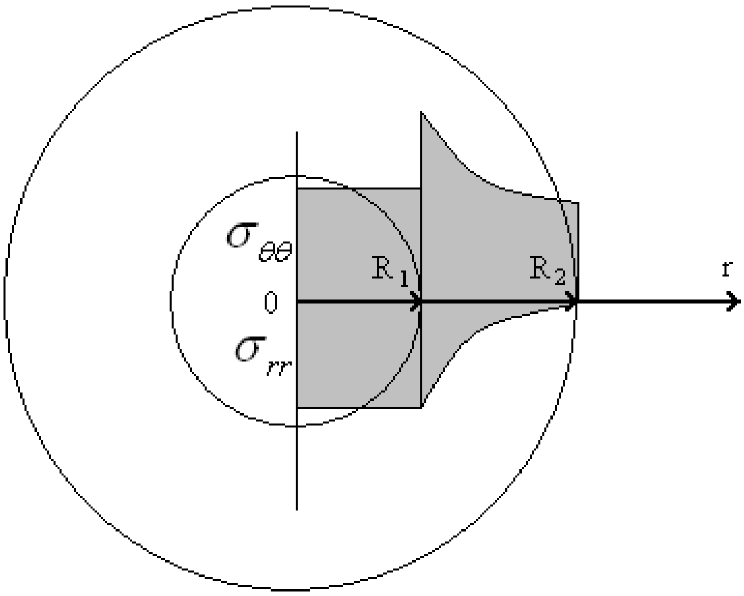

Fig. 3. The fiber cross-section in the cylindrical region of the matrix

From the solution of the cylinder and tube problem for the fiber region ($r<R_1$), the following distribution of stresses and strains is obtained:

$$\sigma_{rr}^f = \sigma_{\theta\theta}^f = A(z), \tag{2}$$

$$\varepsilon_{rr}^f = \varepsilon_{\theta\theta}^f = \frac{1}{E_f}\left(\sigma_{rr}^f - \upsilon_f(\sigma_{\theta\theta}^f + \sigma_z^f)\right) + \alpha_r^f T = \frac{(1-\upsilon_f)A(z) - \upsilon_f\sigma_z^f}{E_f} + \alpha_r^f T\ , \tag{3}$$

$$\varepsilon_{zz}^f = \frac{1}{E_f}\left(\sigma_z^f - \upsilon_f\left(\sigma_{rr}^f + \sigma_{\theta\theta}^f\right)\right) + \alpha_z^f T = \frac{\sigma_z^f - 2A(z)\upsilon_f}{E_f} + \alpha_z^f T\ , \tag{4}$$

$$u_r = r\varepsilon_{\theta\theta}^f = \left(\frac{1-\upsilon_f}{E_f}A(z) - \frac{\upsilon_f}{E_f}\sigma_z^f + \alpha_r^f T\right) r\ . \tag{5}$$

For the matrix region ($r>R_1$) we obtain:

$$\sigma_{rr}^m = \frac{B(z)}{r^2} + C(z); \quad \sigma_{\theta\theta}^m = -\frac{B(z)}{r^2} + C(z), \tag{6}$$

$$\varepsilon_{zz}^m = \frac{1}{E_m}\left(\sigma_z^m - \upsilon_m\left(\sigma_{rr}^m + \sigma_{\theta\theta}^m\right)\right) + \alpha_z^m T = \frac{1}{E_m}\left(\sigma_z^m - 2\upsilon_m C(z)\right) + \alpha_z^m T, \tag{7}$$

$$\varepsilon_{\theta\theta}^m = \frac{1}{E_m}\left(\sigma_{\theta\theta}^m - \upsilon_m(\sigma_{rr}^m + \sigma_z^m)\right) + \alpha_r^m T, \tag{8}$$

$$u_r = r\varepsilon_{\theta\theta} = -\frac{1+\upsilon_m}{E_m r}B(z) + \left(\frac{1-\upsilon_m}{E_m}C(z) - \frac{\upsilon_m}{E_m}\sigma_z^m + \alpha_r^m T\right)r, \tag{9}$$

where $E_{f,m}$ and $\upsilon_{f,m}$ are the elastic moduli and Poisson's ratios of fiber and matrix, respectively, $\alpha_r^{f,m}$ and $\alpha_z^{f,m}$ are the coefficients of thermal expansion of the fiber and matrix in the transverse and longitudinal directions, respectively. In this formulation, for simplicity, we neglect the anisotropy of the matrix and the fiber material in terms of the elastic properties, but we take into account the anisotropy of the thermal properties.

We obtain the following boundary conditions. On fiber/matrix interface ($r=R_1$):

$$u_{r+} - u_{r-} = u_0; \quad \sigma_{rr+} = \sigma_{rr-}, \tag{10}$$

where u_0 is the magnitude of the discrepancy between the fiber radius and the channel radius in the matrix as a result of the manufacturing process of the material.

For $r=R_2$ we obtain the following boundary conditions:

$$\sigma_{rr} = 0. \tag{11}$$

Equilibrium condition is:

$$S_f\sigma_z^f + (1-S_f)\sigma_z^m = -P, \tag{12}$$

where $S_f=R_1^2/R_2^2$ is the proportion of the volume of fiber in the volume of the composite.

From the boundary conditions (10, 11) we obtain the following system of linear equations for the unknowns A, B, C (as functions of variable z):

$$\begin{cases} A = \dfrac{B}{R_1^2} + C; \quad \dfrac{B}{R_2^2} + C = 0; \\ \left(\dfrac{\upsilon_f}{E_f}\sigma_z^f - \dfrac{1-\upsilon_f}{E_f}A + \alpha_r^f\Delta T\right)R_1 + \dfrac{1+\upsilon_m}{E_m R_1}B - \left(\dfrac{1-\upsilon_m}{E_m}C - \dfrac{\upsilon_m}{E_m}\sigma_z^m + \alpha_r^m\Delta T\right)R_1 = u_0. \end{cases} \tag{13}$$

By solving this system we obtain:

$$\begin{cases} B = \dfrac{A}{\dfrac{1}{R_1^2} + \dfrac{1}{R_2^2}}; \quad C = -\dfrac{A}{1/S_f - 1}; \\ A = -\dfrac{u_0/R_1 - \upsilon_m\sigma_z^m/E_m - \upsilon_f\sigma_z^f/E_f + \left(\alpha_r^f - \alpha_r^m\right)T}{-\dfrac{1-\upsilon_f}{E_f} + \dfrac{1+\upsilon_m}{E_m\left(1-R_1^2/R_2^2\right)} + \dfrac{1-\upsilon_m}{E_m\left(R_2^2/R_1^2 - 1\right)}}. \end{cases} \tag{14}$$

Hereby:

$$q(z) = -A(z) = \frac{u_0/R_1 - \upsilon_m\sigma_z^m(z)/E_m - \upsilon_f\sigma_z^f(z)/E_f + \left(\alpha_r^f - \alpha_r^m\right)T}{-\dfrac{1-\upsilon_f}{E_f} + \dfrac{1+\upsilon_m}{E_m\left(1-S_f\right)} + \dfrac{1-\upsilon_m}{E_m\left(1/S_f - 1\right)}}; \quad \tau_S(z) = \mu q(z), \tag{15}$$

where q is the normal force at the fiber/matrix interface, τ_S is the tangential force at the fiber/matrix interface, μ is the friction coefficient at the interface.

According to the «shear-lag» model of composite mechanics [11]:

$$\frac{d\sigma_z^f(z)}{dz} = sign(\sigma_p^f - \sigma_\infty^f)\frac{2}{R_1}\tau_S(z). \quad (16)$$

Whence follows:

$$\pm\frac{d\sigma_z^f(z)}{dz} = \frac{2}{R_1}\mu\frac{u_0/R_1 + \upsilon_m\left(P + S_f\sigma_z^f(z)\right)/E_m\left(1-S_f\right) - \upsilon_f\sigma_z^f(z)/E_f + \left(\alpha_r^f - \alpha_r^m\right)T}{-\frac{1-\upsilon_f}{E_f} + \frac{1+\upsilon_m}{E_m\left(1-S_f\right)} + \frac{1-\upsilon_m}{E_m\left(1/S_f - 1\right)}}. \quad (17)$$

Equation (17) is a first-order differential equation with respect to a function $\sigma_z^f(z)$ with boundary conditions:

$$\begin{cases} z = 0: & \sigma_z^f = \sigma_f^\infty \\ z = L: & \sigma_z^f = \sigma_p^f \end{cases}. \quad (18)$$

It can be solved analytically:

$$\sigma_z^f(z) = k\exp\left(\pm Q_1 z\right) - Q_2/Q_1, \quad (19)$$

where

$$k = \sigma_f^\infty + Q_2/Q_1, \quad (20)$$

$$L = \pm\frac{1}{Q_1}\ln\left(\frac{\sigma_p^f + Q_2/Q_1}{\sigma_f^\infty + Q_2/Q_1}\right), \quad (21)$$

$$Q_1 = \frac{2}{R_1}\mu\frac{\upsilon_m S_f/E_m\left(1-S_f\right) - \upsilon_f/E_f}{-\frac{1-\upsilon_f}{E_f} + \frac{1+\upsilon_m}{E_m\left(1-S_f\right)} + \frac{1-\upsilon_m}{E_m\left(1/S_f - 1\right)}},$$

$$Q_2 = \frac{2}{R_1}\mu\frac{u_0/R_1 + \upsilon_m P/E_m\left(1-S_f\right) + \left(\alpha_r^f - \alpha_r^m\right)T}{-\frac{1-\upsilon_f}{E_f} + \frac{1+\upsilon_m}{E_m\left(1-S_f\right)} + \frac{1-\upsilon_m}{E_m\left(1/S_f - 1\right)}}. \quad (22)$$

We consider the steady-state regime of wear process in which the wear rates of the composite components become equal. The boundary conditions on the friction surface ($z = L$) can be found from this condition [5]. If the wear law is taken in a power form:

$$W_f = K_f\left(\frac{\sigma_p^f}{\tilde{\sigma}}\right)^\alpha V, \quad W_m = K_m\left(\frac{\sigma_p^m}{\tilde{\sigma}}\right)^\alpha V, \quad (23)$$

where W_f and W_m are linear wear rates of fiber and matrix respectively; K_f and K_m are the wear coefficients of fiber and matrix materials respectively, coefficient α is considered to be equal for fiber and matrix, $\tilde{\sigma}$ is the dimension parameter, which is determined by the unit pressure, V is the sliding speed. From the condition of equal wear rates of fiber and matrix during the steady-state wear process ($W_f = W_m$) we can obtain:

$$\frac{\sigma_p^f}{\sigma_p^m} = \left(\frac{K_m}{K_f}\right)^{\frac{1}{\alpha}}. \quad (24)$$

From the equilibrium condition (12) it follows that:

$$S_f\sigma_p^f + (1-S_f)\sigma_p^m = -P. \quad (25)$$

Solving (24) and (25) as a linear system relatively to σ_p^f and σ_p^m we get:

$$\sigma_p^m = \frac{-P}{S_f\left(\left(\frac{K_m}{K_f}\right)^{\frac{1}{\alpha}} + \frac{1-S_f}{S_f}\right)}; \quad \sigma_p^f = \frac{-P}{S_f + \frac{1-S_f}{\left(\frac{K_m}{K_f}\right)^{\frac{1}{\alpha}}}}. \tag{26}$$

The boundary conditions based on the representative volume of the composite (z = 0) can be found from the condition of equal longitudinal deformations of fiber and matrix in the volume of the composite material. From (4) and (7) we obtain the equation:

$$\varepsilon_{zz}^f\Big|_{z=0} = \frac{\sigma_\infty^f - 2A(0)\upsilon_f}{E_f} + \alpha_z^f T = \varepsilon_{zz}^m\Big|_{z=0} = \frac{1}{E_m}\left(\sigma_\infty^m - 2\upsilon_m C(0)\right) + \alpha_z^m T . \tag{27}$$

Whence we obtain longitudinal stresses in the fiber for the composite, far from the friction surface:

$$\sigma_\infty^f = -\frac{\frac{P}{E_m\left(1-S_f\right)} + \frac{R_1 Q_2}{\mu}\left(\frac{\upsilon_f}{E_f} + \frac{\upsilon_m}{E_m\left(1/S_f - 1\right)}\right) + \left(\alpha_z^f - \alpha_z^m\right)T}{\frac{1}{E_f} + \frac{S_f}{E_m\left(1-S_f\right)} + \frac{R_1 Q_1}{\mu}\left(\frac{\upsilon_f}{E_f} + \frac{\upsilon_m}{E_m\left(1/S_f - 1\right)}\right)}. \tag{28}$$

Thus, we obtained the stress distribution in the fiber and matrix near the friction surface. The difference in the level between the fiber and the matrix when the load is removed (surface roughness) can be found from the formula:

$$u_\Delta = \int_0^L \left(\varepsilon_{zz}^f - \varepsilon_{zz}^m\right) dz . \tag{29}$$

4. Results and discussion

To simplify the consideration of the results, let us proceed to dimensionless quantities: $\overline{\sigma}_z^f = \frac{\sigma_z^f}{P}$; $\overline{\sigma}_z^m = \frac{\sigma_z^m}{P}$; $S_f \overline{\sigma}_z^f + (1-S_f)\overline{\sigma}_z^m = -1$; $\overline{E}_f = \frac{E_f}{P}$; $\overline{E}_m = \frac{E_m}{E_f}$;

$\overline{z} = \frac{z}{R_1}$; $\overline{u}_0 = \frac{u_0}{R_1}$; $\overline{L} = \frac{L}{R_1}$; $\overline{u}_\Delta = \frac{u_\Delta}{R_1}$.

The graph in Fig. 4 shows the dependence of the length of fiber and matrix slipping section length L on the temperature for various values of the coefficients of thermal expansion of fiber and matrix materials. With different combinations of these quantities, the length of the slippage can either grow or decrease or remain almost unchanged.

However, the greatest influence on the wear rate of carbon composite materials is due to the roughness of the friction surface caused by the uneven wear of the material components u_Δ [8]. The graph in Fig. 5 shows the dependence of this quantity on the temperature T.

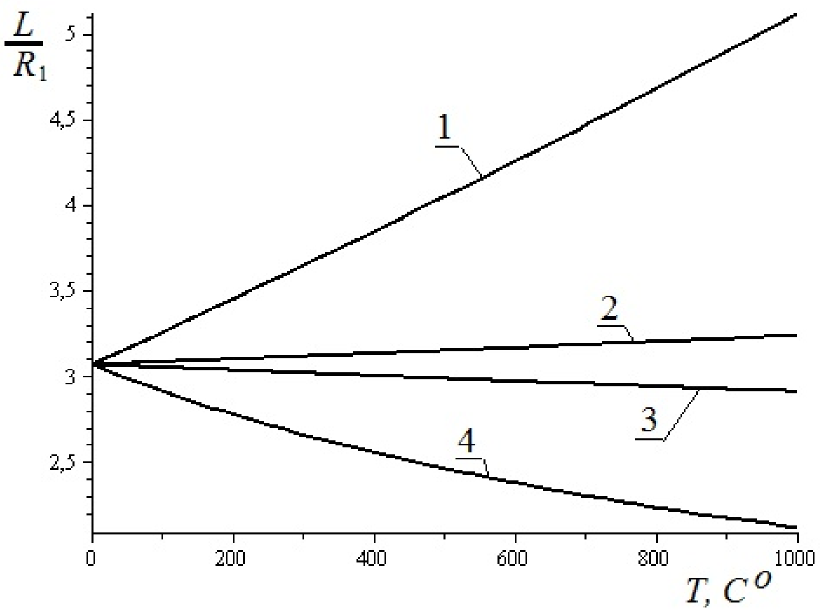

Fig. 4. Fiber/matrix slippage region length vs. temperature
1: $(\alpha_r^f - \alpha_r^m) = -10^{-6}$; $(\alpha_z^f - \alpha_z^m) = 10^{-5}$;
2: $(\alpha_r^f - \alpha_r^m) = -10^{-6}$; $(\alpha_z^f - \alpha_z^m) = -10^{-7}$;
3: $(\alpha_r^f - \alpha_r^m) = 10^{-6}$; $(\alpha_z^f - \alpha_z^m) = -10^{-8}$;
4: $(\alpha_r^f - \alpha_r^m) = 10^{-5}$; $(\alpha_z^f - \alpha_z^m) = 10^{-7}$

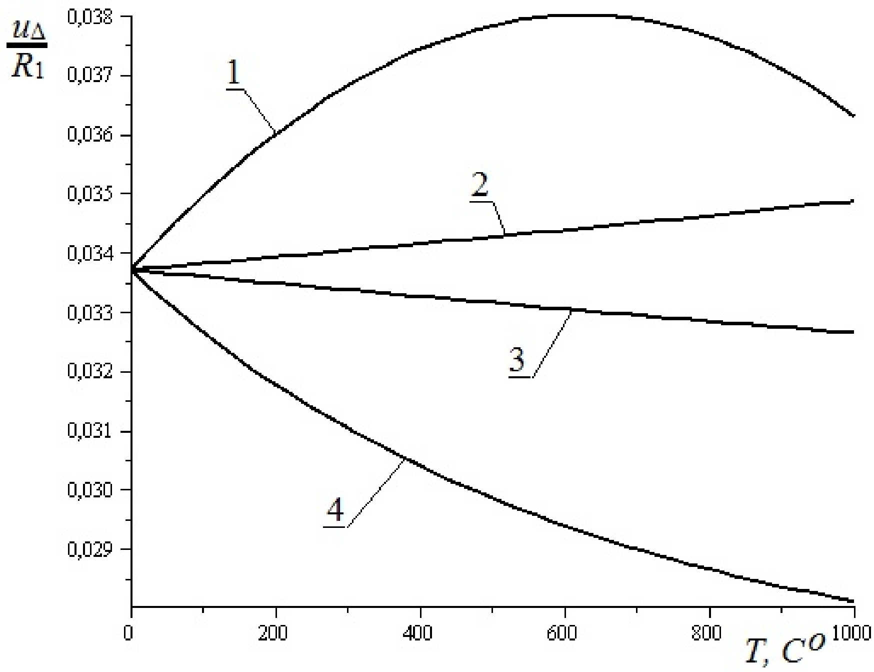

Fig. 5. Fiber/matrix level unevenness (surface roughness) vs. temperature.
1: $(\alpha_r^f - \alpha_r^m) = -10^{-6}$; $(\alpha_z^f - \alpha_z^m) = 10^{-5}$;
2: $(\alpha_r^f - \alpha_r^m) = -10^{-6}$; $(\alpha_z^f - \alpha_z^m) = -10^{-7}$;
3: $(\alpha_r^f - \alpha_r^m) = 10^{-6}$; $(\alpha_z^f - \alpha_z^m) = -10^{-8}$;
4: $(\alpha_r^f - \alpha_r^m) = 10^{-5}$; $(\alpha_z^f - \alpha_z^m) = 10^{-7}$

It should be noted that the friction model used in this work is insensitive to the value of u_Δ and hence to the temperature of the material because it considers only a uniform steady-state wear process. However, for a variety of real materials, as mentioned in the introduction, there is uneven wear with friction surface destruction, which is responsible for the majority of wear volume. In the first approximation, we can assume that the wear coefficient of the composite is proportional to the value u_Δ. Then curve 1 describes well the behavior of materials based on resin base matrix and unidirectional ex-PAN fibers [3]. Curve 4 describes well a composite based on a three-dimensional fibrous mat and a gas-deposited matrix [1]. Curve 3 describes the behavior of a material based on graphitized fiber and pitch based matrix [10]. Thus, the obtained model can be used to predict the effect of temperature on the wear resistance of carbon-carbon composites, provided that the constants used in it are correctly determined. Although the matrix material in such composites cannot be obtained in pure form, microindentation and atomic force microscopy [12-15] make it possible to determine the elastic and tribological properties of the composite components separately. The coefficients of thermal expansion of the matrix can be calculated from the macroscopic coefficients of thermal expansion of the composite at known fiber expansion coefficients.

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