OPERATIONAL ELASTIC PROPERTIES OF CHAOTICALLY REINFORCED TRIBOCOMPOSITES

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ABSTRACT

The problem of predicting the operational elastic properties of composites based on binders with a high content of epoxy groups (the grade of EPAF and its modification), chaotically reinforced with short polyimide (or glass) fibers with antifriction disperse additives of polytetrafluoroethylene was solved. Numerical model calculations of the effective elastic characteristics (Young's modulus and Poisson's ratio) of these tribocomposites were made taking into account changes in the concentrations of their components.

Keywords: transport engineering, modeling, tribocomposite, inclusion, epoxy binder, effective elastic moduli.

Background. Composites on a polymer basis, consisting of discrete inclusions and the surrounding solid matrix (binder) find wide practical application in transport engineering, for example, in friction and conjugation nodes. Reinforcement of these materials is often made by inclusions of non-isometric shape (fibers, disks, etc.) by the composite specially oriented in the space. Since the technologies for their creation are quite expensive, there is a need to develop methods for modeling the structure, selecting components and predicting their effect on the operational physical and mechanical properties of the materials being designed [1–4].

To obtain high-strength and heat-resistant polymeric tribocomposites, epoxy resins with a high content of epoxy groups – from 28 to 54 % (this is 1,5–2,5 times higher than for the most commonly used in the industry domestic resin brand ED-20 or its American counterpart DER-330) [5]. In the same article, the results of studies of strength and thermophysical parameters of epoxy binders based on triglycidylparaminaminophenol resins of the grades of EPAF and EPAF-m (EPAP-m resin modified with diglycidyl ether of DL-camphoric acid in a ratio of 60: 40) are presented. The content of epoxy groups in EPAP is 38 %, and in EPAP-m – 30 %. It was also shown in [5] that cured polymers on the basis of the investigated resins reach the maximum values of physico-mechanical parameters for epoxy materials of this class described in the literature.

Objective. The objective of the authors is to consider operational elastic properties of chaotically reinforced tribocomposites.

Methods. The authors use general scientific and engineering methods, mathematical calculations, comparative analysis.

Results.

Statement of the problem and construction of the model

In this paper, the problem of predicting the operational elastic properties of tribocomposites based on epoxy resins with a high content of epoxy groups with antifriction dispersed additives and chaotically distributed in the space material by chopped short fibers is solved. The solution of this problem is based on the calculation of their effective (operational) elastic properties [2, 4, 6]. These properties are determined by means of the fourth-rank tensor c^* («*» here and further indicates that the effective characteristics of the composites are considered), which connects the mean values of the stresses $\langle\sigma_{ij}(r)\rangle$ and the deformations $\langle\varepsilon_{kl}(r)\rangle$ in the material:

$$\langle\sigma_{ij}(r)\rangle = (c^*)_{ijkl}\,\langle\varepsilon_{kl}(r)\rangle,\ i, j, k, l = 1, 2, 3, \qquad (1)$$

where r – radius vector of the random point of the medium, the angle brackets here and below determine the averaging procedure. We note that for a multicomponent composite, if the ergodicity condition is satisfied, averaging over the volume (for each component of it) can be used [6]. Then the averaging operation over the entire volume of the material for some random variable a(r) reduces to summation:

$$\langle\sigma a(r)\rangle = \sum_s V_s\,\langle a_s(r)\rangle, \qquad (2)$$

where V_s – volume concentration of the s-th type component, and $a_s(r)$ – random variable corresponding to the specified component,

$$\sum_s V_s = 1.$$

To carry out a correct analysis of effective elastic properties of composites, allowing for interaction of elements of heterogeneity, composition, shape, orientation and concentration of components, it is necessary to solve the equilibrium equations for an elastic inhomogeneous medium. However, in general case it is not possible to obtain a relation for numerical calculations of the tensor of the effective elastic moduli c^*. Therefore, various approximations are used to calculate it. One of these approximations, taking into account the factors enumerated above, is the generalized singular approximation of the theory of random fields [6]. It uses only the singular component of the Green's tensor of equilibrium equations, depending only on the Dirac delta function, and also introduces a homogeneous comparison body which material constants enter the final expression for computing c^*. The physical meaning of the generalized singular approximation is the assumption that the fields of stress and strains are homogeneous within the element of inhomogeneity. In this case, the expression for c^* in (1) has the following form (the indices are omitted) [6]:

$$c^* = \langle c(r)(I - g(r)c''(r))^{-1}\rangle\,\langle(I - g(r)c''(r))^{-1}\rangle^{-1}, \qquad (3)$$

where I – unit tensor of the fourth rank; c(r) – elastic modulus tensor; two dashes denote the

Table 1

Physico-mechanical properties of tribocomposite components [1, 5, 7–10]

Type of component	Material of component	E, GPa		ρ, g/cm^3
1	PTFE	0,15	0,33	2,20
2	ARIMID AFG	120,0 76,2	0,36 0,22	1,45 2,54
3	EPAF EPAF-m ED-20	5,4 4,6 3,8	0,46 0,42 0,39	1,30 1,24 1,18

difference $c''(r) = c(r) - c^c$ between the corresponding parameters of inhomogeneous medium and homogeneous comparison body (characteristics of the comparison body are denoted below by the superscript «c»); g(r) – integral of the singular component of the second derivative of the Green's tensor of the equilibrium equations, which is a fourth-rank tensor. To calculate the components g_{ijkl} of the tensor g(r), it is first necessary to perform calculations of the components a_{iklj} of the fourth-rank tensor A, and then perform a symmetrization operation in a_{iklj} with respect to two pairs of indices (i, j and k, l) [6]. The components a_{iklj} of the tensor A are calculated using the following relation:

$$a_{iklj} = -\frac{1}{4\pi}\int n_k n_j (t^{-1})_{il}\, d\Omega , \qquad (4)$$

where $d\Omega = \sin\theta d\theta d\varphi$ – solid angle element in the spherical coordinate system, $(t^{-1})_{il}$ – elements of the matrix inverse to the matrix T with elements $t_{il} = (c^c)_{iklj}\, n_k\, n_j$, a n_k and n_j (k, j = 1, 2, 3) – components of the exterior normal vector to the inclusion surface. For ellipsoidal inclusions with principal semiaxes l_1, l_2 and l_3, the components of the normal vector are determined by the relations $n_1 = (l_1)^{-1} \sin\theta \cos\varphi$, $n_2 = (l_2)^{-1} \sin\theta \sin\varphi$, $n_3 = (l_3)^{-1} \cos\theta$.

Equation (3) can be used to calculate the effective characteristics of statistically homogeneous matrix composites with ellipsoidal inclusions oriented relative to each other [2].

Carrying out model calculations

Composites with inclusions of two types are then considered. The first type includes dispersed inclusions of polytetrafluoroethylene (PTFE), evenly distributed in the space of the composite and performing an antifriction role. The second type includes chopped short fibers randomly distributed in the space of the composite and performing the function of hardening it. Separate study is carried out for composites filled with: a) high-heat-resistant polyimide fibers (ARIMID brand, TU2272–034–17277875–2003, manufactured by LLC LIRSOT, Mytischi); b) fibers of alkali-free glass (AFG). As a matrix – a component of the third type – epoxy binders of EPAF, EPAF-m and ED-20 are considered. The binder ED-20 is considered for carrying out a comparative analysis of the operational elastic characteristics of tribocomposites based on it and on the basis of EPAP and EPAF-m resins. The physical and mechanical properties of tribocomposite components are given in Table 1 (E – Young's modulus for compression, ν – Poisson's ratio, ρ – density).

When constructing a model for predicting the effective elastic properties of the materials in question, we will base our analysis on the representation of their structure in the form of statistically homogeneous matrix composites. Reinforcement of composites is made by inclusions in the form of spheres of the same radius R and in the form of elongated ellipsoids of revolution (l_1, l_2 and l_3 – semi-axes of these ellipsoids, the largest of which is of length L). In this case, the ellipsoids are oriented with their larger semiaxis in the space of the composite in seven different directions (relative to the laboratory coordinate system). Namely, parallel to the coordinate axes (three directions) and parallel to the straight lines, forming equal angles with all coordinate axes (four directions). In addition, we will assume that the model composites consist of isotropic components with volume concentrations V_1, V_2 and V_3, where the index «1» refers to PTFE, the index «2» refers to fibers (ARIMID or AFG), and «3» refers to binding agent (EPAF, EPAF-m or ED-20).

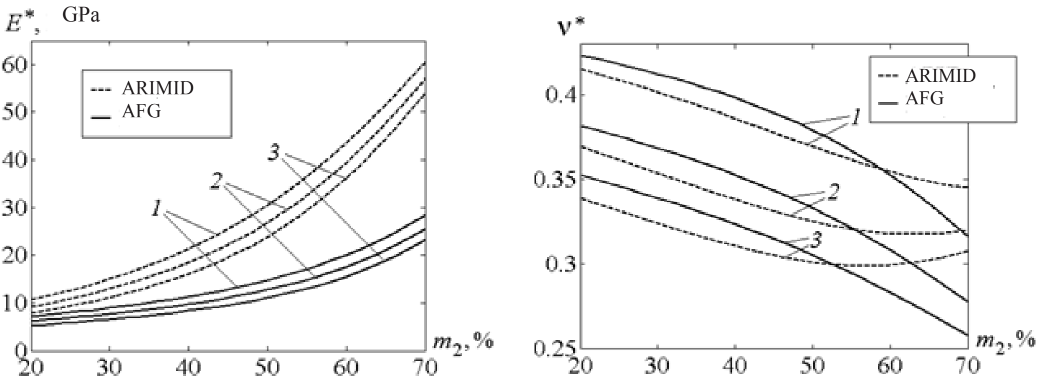
Taking into account (2), the calculated relation (3) for the elastic modulus tensor c^* takes the following form:

$$c^* = \left(\sum_s V_s c_s \left(I - g_s\left(c_s - c^c\right)\right)^{-1}\right) \cdot \left(\sum_s V_s \left(I - g_s\left(c_s - c^c\right)\right)^{-1}\right)^{-1}. \qquad (5)$$

In formula (5), c_s and c^c are the elastic moduli tensors of the s-th component of the composite and the homogeneous reference body, respectively; g_s is the tensor g(r) of the s-th component of the composite, calculated from the relation (4). In this case, g_1 corresponds to spherical inclusions ($l_1 = l_2 = l_3 = R = 1$); g_2 corresponds to ellipsoidal inclusions (fibers) oriented with respect to the coordinate axes along the seven directions indicated above, with the main semiaxis L = 50 and the remaining semiaxes equal to 1; g_3 refers to the binder (in calculating g_3 it was assumed that $l_1 = l_2 = l_3 = 1$). We will also assume that the volмume contents of the ellipsoidal inclusions in each of the seven indicated directions are the same and are equal to $V_2/7$.

To carry out model calculations in operations on tensors the matrix form of their recording was used [6]. The nonzero elements c_{ij} (i, j = 1, 2, ..., 6) of the symmetric matrix of the elastic modulus tensor c for an isotropic material are expressed in terms of the Young's modulus E and Poisson's ratio ν as follows:

$$c_{11} = c_{22} = c_{33} = \frac{E(1-\nu)}{(1+\nu)(1-2\nu)} \;;$$



a *b*

Pic. 1. Change in operational elastic properties of tribocomposites with an increase in the percentage of m_2 fibers (ARIMID or AFG) and fixed concentration m_1 = 10 % PTFE: 1 – EPAF, 2 – EPAF-m, 3 – ED-20.

$$c_{44} = c_{55} = c_{66} = \frac{E}{2(1+\nu)};$$

$$c_{12} = c_{21} = c_{13} = \frac{E\nu}{(1+\nu)(1-2\nu)}.$$

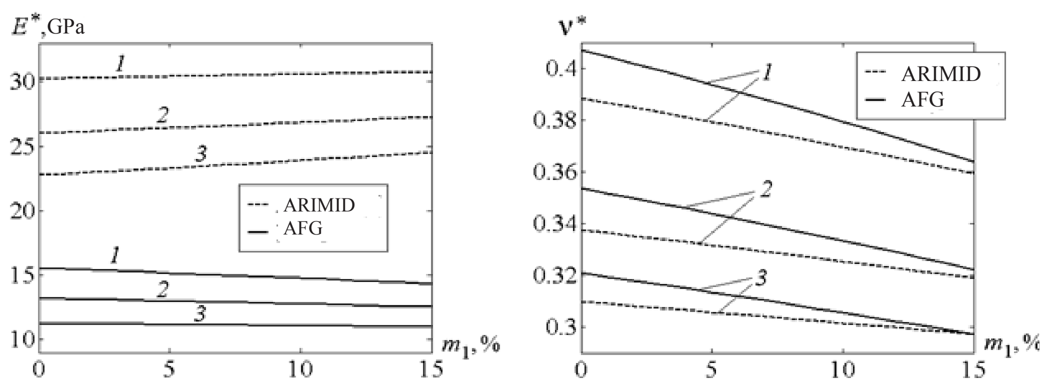
In calculating the elastic characteristics of a homogeneous comparison body, the self-consistency method was used [6; 11]. To this end, an iterative procedure was organized in which the values of the elastic modulus tensor (in the matrix form of recording) obtained at the previous step of the iteration were taken as parameters c^c of the comparison body. As initial values of the parameters of the comparison body, the elastic characteristics obtained in the Hill approximation were taken, i.e. arithmetic mean values obtained in the Reuss and Voigt approximations [6; 11]. The exit from the iterative procedure was performed when the maximum difference between the c^c modules was less than 0,01.

The results of all model calculations are given below with respect to the percentage concentrations m_s (s = 1, 2, 3) of the heterogeneity elements according to mass, associated with the volume concentrations and densities of the composite components using formula

$$m_s = \frac{V_s \rho_s}{\sum_i V_i \rho_i} \cdot 100 \text{, mas. \%.}$$

Numerical simulation based on the relation (5) for different values of the inclusions concentrations has shown that the composites considered in this work have an isotropy of effective elastic properties [6]. Thus, the calculations of the tensor of the effective moduli of elasticity c^* fully confirmed those assumptions that could be advanced, starting from the structure of the materials under consideration.

Pic. 1 and 2 show the results of numerical calculations of the values of the operational elastic characteristics – the Young's modulus E^* and the Poisson's ratio ν^* – model tribocomposites from changes in the percentage contents of the fibers (ARIMID or AFG) and dispersed PTFE inclusions.



a *b*

Pic. 2. Change in operational elastic properties of tribocomposites with increasing percentage of m_1 of PTFE and fixed concentration m_2 = 50 % of fibers (ARIMID or AFG): 1 – EPAF, 2 – EPAF-m, 3 – ED-20.

The operational elastic characteristics E^* and ν^* were calculated through the elements of the matrix c^* using the following formulas [6]:

$$E^* = \frac{c_{44}^*(3c_{12}^* + 2c_{44}^*)}{c_{12}^* + c_{44}^*};$$

$$\nu^* = \frac{c_{12}^*}{2(c_{12}^* + c_{44}^*)}.$$

Conclusion. *On the basis of the conducted researches it is possible to conclude the following.*

1. Application of resins with a high content of epoxy groups as binders leads to a significant improvement in operational elastic properties of tribocomposites in comparison with materials based on other polymer binders (see Pic. 1, 2 and [4]).

2. An increase in concentration of fibers at a fixed content of PTFE inclusions leads to an increase in the E^* values, while the character of the dependence is nonlinear (Pic. 1a). An increase in the concentration of dispersed inclusions of PTFE at a fixed fiber content can lead to both a slight growth (when using ARIMID fibers) and to a slight decrease in the E^* values (using AFG fibers). The character of the dependence is close to nonlinear (Pic. 2a).

3. An increase in concentration of ARIMID fibers with a fixed content of PTFE inclusions leads to a nonmonotonic change in the values of the Poisson's ratio ν^* (Pic. 1b). An increase in the percentage content of disperse antifriction additives of PTFE at a fixed concentration of ARIMID fibers leads to a slight decrease in the values of ν^* according to a law close to linear (Pic. 2b).

4. An increase in concentration of both AFG fibers and dispersed antifriction additives of PTFE leads to a monotonous decrease in the values of the Poisson's ratio ν^* (Pic. 1b, 2b).

5. Since the variation in the percentage of fibers (ARIMID or AFG) results in a more significant change in operational elastic characteristics of tribocomposites than the variation in the concentration of PTFE inclusions, additional experimental and theoretical studies are needed to optimize the concentration of both PTFE and fibers in order to maximize the tribocharacteristics of the composites under consideration without significant deterioration of their elastic-strength indicators. This is especially important for tribocomposites operating in heavily loaded friction nodes.

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