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Substantiation of conditions of effective working capacity of tribocouples of the details made of polymeric composite materials with high-modulus fillers

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Abstract

This work is devoted to the study of the conditions of effective performance of triad couplings of parts made of polymeric composite materials. The stress state of the material is associated with the characteristics of the accumulation of dislocations, the energy of activation of their movement. The average stress, friction stress is determined. Based on this, expressions for estimating critical stresses and loads on tribocouple parts are obtained. The distribution of the force on the tribocoupling of parts is determined taking into account the quality characteristics of the friction surfaces, modulus of elasticity and Poisson's constant of the components of the polymer composite material. This problem is considered for tribocouples of parts of various kinds.

Expressions for calculation of nominal pressures at different types of contact of material of details of tribocoupling are received, and also the equations on which it is possible to estimate in them values of nominal critical pressure are resulted.

The conditions for efficient operation of tribocoupling of parts made of polymer composite materials are clarified. It is determined that a significant increase in the nominal critical pressure on the tribocoupling is possible with the use of high-modulus fillers, the modulus of elasticity of which is greater than the modulus of elasticity of the polymer matrix.

Key words: polymer composite material, macroheterophase material, high modulus filler, tribocoupling of parts, matrix, filler, stress field, elastic contact, critical pressure, nominal pressure

Introduction

The efficiency of using tribocouples of parts made of macroheterophase polymer composite materials depends on the content of the filler, its size, shape, nature and tribological properties of the structural components of the composite material and the strength of the bond between them.

Today there is no single theory of reliability and efficiency of tribotechnical polymer composites and methods of substantiation of their optimal composition and structure. Existing methods for predicting the composition and structure of composites cover some cases due to practical application, but they do not take into account different types of contacts, the presence of an elastic component, which is achieved during the correct running of parts and critical pressure on the triad. There is also no criterion by which it is possible to assess a degree of efficiency of the triad couplings of systems and units of machines, parts of which are made of polymeric composite materials with high-modulus fillers.

Literature review

The use of tribocoupling of parts made of polymeric composite materials (PCM) has shown their effectiveness in increasing the durability of systems and units of machines [1-3]. However, there is a problem of optimizing the composition of polymer composites from the content of fillers, the distribution of stress fields in the polymer matrix, the geometric shape and concentration of the filler and the development of methods for evaluating the efficiency and reliability of such tribocouples [4,5].

Specific features of the work of PCM with a macroheterogeneous structure necessitate the analysis of the stress-strain state (SSS), which occurs under load conditions during operation [6-8] by friction forces. There is a need to take into account different types of triangular parts and different types of contacts of their work surfaces. The same amount of deformation of the components of PCM can lead to brittle destruction of one component, to viscous – the second component and tired – the third component [7]. The strength characteristics of each of the components of the PCM are decisive. Research on SSS of surface layers reinforced with PCM [8] revealed the need to take into account the interaction of neighboring contour and actual contacts in the process of sliding friction. In the scientific literature, this issue is insufficiently studied and not all types of wear in the conjugation of machine parts are considered [9,10]. PCM chipping and exfoliation processes should also be considered. Note that in the implementation of such performance properties of materials as their wear resistance, the task is complicated by the significant dependence of stresses on the volume ratio of components, their size, shape, as well as design features of conjugate parts and properties of working (technological) environment.

The authors of [11-14] the main cause of destructive processes in the surface layers of PCM is SSS, which occurs as a result of contact stresses and deformations under the influence of loads on the tribocoupling of parts. This leads to a detailed study of the features in the surface layers of the materials of the tribocouples of parts. The study of the peculiarities of PCM in the process of functioning of three-part couplings allows to approach unsolved problems from a single position. The use of physical and mathematical models [7,8] is appropriate, and VAT estimates are carried out by load distribution in different types of contact by polarization-optical and other methods [9]. Attempts to compare the wear resistance and SSS of the surface layers of PCM made in [11]. According to research conducted in [15], there is a need for relaxation of local maximum stresses in the surface layers of tribocouple parts. It was found that with increasing volumetric content and filler size, the intensity of wear of parts decreases. However, the influence of these factors on the value of the maximum tangential stresses in the PCM is not sufficiently clarified [4,16].

The connection between the wear process of PCM and their mechanical properties is given in [6, 17]. The results of wear resistance studies of PCM with homogeneous and heterogeneous structure show that in the first case it is lower than in the second due to faster equalization of contact pressure. The phenomenon of spontaneous installation and maintenance of the stationary mode of wear of PCM is also revealed. This is due to the existence of feedback. Based on the ideal conditions of sliding contact, in [5] with the help of friction surface models, tribotechnical characteristics of PCM with different structure and different composition were calculated.

The current results of research [4-6] do not allow to fully assess the effectiveness of the triad coupling of parts and the nature and amount of wear. There is a need to connect them with the types of contacts and the conditions of contact.

It was found that in the operation of tribocouples of parts, elastic and plastic deformation of their materials are the main processes that initiate the emergence and development of physical, chemical and mechanical processes in the surface layers of PCM [17]. It is shown that in the PCM the main part of the load is received by the filler. Reinforcing fillers prevent the movement of dislocations in the matrix, which is subject to plastic deformation, limiting it [3]. Strengthening of PCM is carried out by increasing the content of the filler and reducing the distance between its particles. In [9] it was found that depending on the structural state of the PCM, the magnitude of the accumulated plastic deformation is not the same, which causes a different course of relaxation processes. The type and dispersion of filler particles (carbides, borides, oxides, intermetallics) in the polymer matrix, which are barriers to plastic deformation, significantly affect the inhibition of the relaxation process, but it is not known how the degree of dispersion of the filler affects the properties of PCM, filler – for stress relaxation, wear process and efficiency of triboconjugation of parts in general.

Purpose

The aim of this work is to identify the conditions for the effective operation of various truboconjugations of parts made of macroheterophase polymer composite materials with high modulus filler, taking into account different types of contact.

Results

Using different combinations of PCM, regarding the variation of high-modulus fillers in the polymer matrix, it is possible from a macroscopic point of view to ensure the predominant presence on the friction surfaces of parts of one or another type of contacts. Analytical methods for estimating the optimal structure of such PCM have not yet been developed. To determine the allowable force in heavy-duty tribocouples of parts made of macroheterophase PCM, one of the efficiency indicators can be the critical pressure, the value of which is estimated at the beginning of plastic deformation, brittle fracture or setting of friction surfaces. This uses the fact that in macroheterophase PCM the nature of deformation and fracture is similar to the nature of deformation and fracture of single-phase materials.

It is quite clear. that in tribocouples of parts made of materials of macroheterophase structure, the contacts of the two surfaces of polymeric materials are the least effective. These materials should be used in reinforced form and provide such structures and composition that the share of space occupied by the contacts of two plastic materials was minimal, and with high-modulus fillers – maximum.

The quantitative efficiency of different types of contacts can be assessed by assuming that the main mechanism of setting of PCM materials is the formation of a common degree on the surface of physical contact. In this case, the stress created by the accumulation of dislocations in the area of the sources of dislocations, which is located beyond the contact boundary at a distance l, is:

$$\sigma_l = \sigma_f + \frac{1}{2}(\sigma - \sigma_f)(l_s / l_d), \tag{1}$$

where σ_f – friction stress; l_s – length of the sliding strip; l_d – distance to the cluster of dislocations.

If with increasing current voltage the value σ reaches the value σ_l at which the source of dislocations begins to work, we can assume that $\sigma_l = \bar{\sigma}$, $\sigma = \sigma_{cr}$, where $\bar{\sigma}$ is the average voltage; σ_{cr} – critical value of voltage. In this case, the value of the critical voltage is equal to:

$$\sigma_{cr} = 2\bar{\sigma}\left(\frac{l_d}{l_s}\right)^{1/2} + \sigma_f\left(1 - 2\left(\frac{l_d}{l_s}\right)\right)^{1/2}, \tag{2}$$

where $\sigma_f < \bar{\sigma}$; $l_d << l_s$.

The value of the average voltage can be determined from the equation:

$$\bar{\sigma} = \left(\frac{3b_d \dot{\varepsilon} k_b T}{V}\right)^{1/2} \exp(U_0 / 3k_b T), \tag{3}$$

where b_d – constant, characterizing the degree of deformation, 0.2%, of this material; $\dot{\varepsilon}$ – the rate of relative deformation of the material; V – activation volume; k_b – became Boltzmann; T – absolute temperature; U_0 – dislocation motion activation energy.

Similar to equation (3), the amount of friction stress is determined:

$$\sigma_f = \left(\frac{3b_d^f \dot{\varepsilon} k_b T}{V^f}\right)^{1/2} \exp(U_0^f / 3k_b T). \tag{4}$$

Given expressions (3) and (4) in equation (2), we obtain:

$$\sigma_{\kappa p} = 2\left(\frac{l_d}{l_s}\right)^{1/2}\left(\frac{3b_d \dot{\varepsilon} k_b T}{V}\right)^{1/2} \exp(U_0 / 3k_b T) + \left(1 - 2\left(\frac{l_d}{l_s}\right)\right)^{1/2}\left(\frac{3b_d^f \dot{\varepsilon} k_b T}{V^f}\right)^{1/2} \exp(U_0^f / 3k_b T), \tag{5}$$

Taking the critical load P_{cr} proportional σ_{cr}, we have:

$$P_{cr} = C_u \sigma_{cr} = C_u \left\{ 2\left(\frac{l_d}{l_s}\right)^{1/2}\left(\frac{3b_d \dot{\varepsilon} k_b T}{V}\right)^{1/2} \exp(U_0 / 3k_b T) + \left(1 - 2\left(\frac{l_d}{l_s}\right)\right)^{1/2}\left(\frac{3b_d^f \dot{\varepsilon} k_b T}{V^f}\right)^{1/2} \exp(U_0^f / 3k_b T) \right\}, \tag{6}$$

where C_u – is the coefficient that takes into account the shape and size of the contact irregularities of the working surfaces of the parts.

The lack of data on the values of C_u, l_d, b_d, b_d^f, U_0, U_0^f does not allow to determine the specific value of the critical load P_{cr} for a given triad of parts. From equation (16) it follows that the value P_{cr} of is greater the greater the energy of motion of dislocations U_0 and U_0^f.

Analysis of the influence of the structure and phase composition of PCM on the quality parameters of friction surfaces showed that when contacting tribocouples of parts made of macroheterophase composites, it is possible to provide the required share of friction surface area. In this case, you should use the laws of contact established for tribocoupling of the first kind, when single-phase material is in contact with single-phase. At the same time, the presence on the friction surface of areas with different composition of contact materials leads to a redistribution of contact pressures between contacts of different types. This causes a change in the critical load on the triad coupling of parts, and hence the coefficient of friction and wear resistance.

It is found that while ensuring the process of minimal wear and stabilization of the friction force, it is necessary to create such conditions when in the process of operation of tribocouples of parts on their friction surfaces an elastic contact is realized. Note that in the simplified calculation of the triad of parts with PCM in the first approximation, the following is taken into account:

– materials of tribocouples of the corresponding details consist of matrices M_1 and M_2 and fillers H_{1i} and H_{2j};

– the number of fillers in the material of the first part is i, and in the second – j;

– all parts of the total friction surface are real in triad conjugation;

– the structure of the PKM and the mutual orientation of the details of the triad coupling ensure the independence of the fraction of the area occupied by one type of contact from their displacement along the direction of friction;

– the relative volume content of the filler in the surface layer of the parts is constant, the effect of their self-lubrication is absent, and secondary structures are not formed.

In the case of flat surfaces, with a nominal contour area of contact, the proportion of the area occupied by a particular type of contact is found by the expressions:

$$\left.\begin{aligned}
&\alpha_{M_1-M_2}=\left(1-\sum_{i=1}^{n}\alpha_{1i}\right)\left(1-\sum_{j=1}^{m}\alpha_{2j}\right);\\
&\alpha_{M_1-M_{2j}}=\left(1-\sum_{i=1}^{n}\alpha_{1i}\right)\alpha_{2j};\\
&\alpha_{M_2-M_{ij}}=\left(1-\sum_{j=1}^{m}\alpha_{2j}\right)\alpha_{2j};\\
&\alpha_{H_{1i}-H_{2j}}=\alpha_{1i}\alpha_{2j};\ i=\overline{1,n};\ \ j=\overline{1,m}.
\end{aligned}\right\}\tag{7}$$

We assume that the nominal area of the entire friction surface is equal to A_a. The area occupied by contacts of the corresponding type (their nominal area) can be determined by multiplying the components of the system of equations (7) by A_a.

Since the friction surfaces of the parts conjugations are pressed by the force N, the different types of contacts account for the forces: $N_{M_1-M_2}$, $N_{M_1-H_{2j}}$, $N_{M_2-H_2j}$, $N_{H_{1i}-H_{2j}}$. The equilibrium condition of the friction surfaces in the General case has the form:

$$N_{M_1-M_2}+\sum_{j=1}^{m}N_{M_2-H_{2j}}+\sum_{i=1}^{n}M_{M_2-H_{1i}}+\sum_{j=1}^{m}\sum_{i=1}^{n}N_{H_{1i}-H_{2j}}=N\ .\tag{8}$$

Equation (8) makes it possible to obtain the equilibrium condition for any particular case of tribocontact with PCM material. For example, if both triad coupling parts are made of matrix single-phase materials M_1 and M_2, respectively, then $N_{M_1-M_2}=N$. In the case of contact of single-phase material M_1 with multiphase M_2+H_{2j}, the equilibrium condition will look like:

$$N_{M_1-M_2}+\sum_{j=1}^{m}N_{M_1-H_{2j}}=N\ .\tag{9}$$

When estimating the forces $N_{M_1-M_2}$, $N_{M_1-H_{2j}}$, $N_{M_2-H_{2j}}$ and $N_{H_{1i}-H_{2j}}$, assume that the micro-irregularities on the friction surfaces are deformed elastically and are located on a rigid base. There is no mutual influence of conjugate surfaces of parts, as the contact of nominally flat surfaces is considered. Convergence of friction surfaces under the action of force N in this case can be determined from the equation:

$$a=\left\{\frac{3N_c k_{fp}\left(R_{\max_{1c}}+R_{\max_{2c}}\right)^{\nu_c-\gamma_c}\left[\left(E_{1c}\left(1-\mu_{2c}^2\right)\right)+E_{2c}\left(1-\mu_{1c}^2\right)\right]\left(\rho_{1c}+\rho_{2c}\right)}{4q_c\rho_{1c}\rho_{2c}E_{1c}E_{2c}\alpha_c b_c\left(\nu_c-\gamma_c\right)\beta\left(\frac{5}{2};\nu_c-\gamma_c\right)A_a}\right\}^{\frac{2}{3+2(\nu_c-\gamma_c)}},\tag{10}$$

where N_c – the force acting on the contacts; $R_{\max_{1c}}$, $R_{\max_{2c}}$ – the maximum height of the irregularities in the contact areas of the surfaces of the first and second parts of the tribocoupling; b_c, ν_c – parameters of the reference curve of the equivalent surface; ρ_{1c}, ρ_{2c}, E_{1c}, E_{2c}, μ_{1c}, μ_{2c} – respectively, the radii of curvature of the vertices of micro-inequalities, the modulus of elasticity of Jung and the Poisson's ratios of the materials of the first and second parts of the tribocouple; γ_c, k_{fp} – coefficients that depend on the shape of the protrusions; $\beta\left(\frac{5}{2};\nu_c-\gamma_c\right)$ – beta function; q_c – the number of protrusions per unit area of the equivalent surface; α_c – the proportion of the friction surface area in the corresponding types of contacts of expression (7) c; A_a – nominal area of friction. Note that the number of equations of the form (10) is equal to the number of types of contacts in this triad of parts.

Using the equilibrium condition (8) and expression (10), we can trace the influence of the phase composition of the PCM on the amount of pressure that develops in the contacts of each type under the total force N. For clarity, it is convenient

– single-phase material M_1 is in contact with the second, (or the same M_1) single-phase M_2;
– single-phase material M_1 is in contact with multiphase $M_2 + H_{2j}$;
– multiphase material $M_1 + H_{1i}$ is in contact with multiphase $M_2 + H_{2j}$.

During the operation of tribocouples of parts of the first kind, the external force N is balanced by the forces on the contacts M_1 - M_2, ie $N_{M_1-M_2} = N$. Dividing this equality by the nominal area of friction A_a, we obtain that in this case the pressure $P_{M_1-M_2}$ is equal to the nominal pressure P_a. To eliminate the adhesion of materials in the tribocouple of this kind, it is necessary to reduce the force N until P_a is below the critical pressure $P_{cr_{M_1-M_2}}$ determined for the contact of the matrix M_1 with the matrix M_2 or experimentally by equation $P_{cr} = C_u \sigma_{cr}$.

During the operation of the tribocoupling of the second kind, the pressure in the contacts of different types in the general case should be different. To estimate it, it is necessary to use the equilibrium condition (9) and the equation of the form (10).

Solving the system of equations of the form (10), giving values $N_{M_1-H_{2j}}$ through $N_{M_1-M_2}$ and substituting them in equation (9), we can calculate the forces at the contacts of types M_1 - M_2 and M_1 - H_{2j}. Analytically, a system consisting of expressions (9) and (j + 1) expressions of type (10) cannot be solved. However, using the appropriate experimental data, it is easy to do with application packages on a PC.

If the tribocoupling of parts of the second kind and the composite consists of a matrix of M_2 and j fillers, then solving the system of equations (9) and (j + 1) equations of type (4), find the forces at the contacts M_1 - M_2 and M_1 - H_{2j} by the formulas:

$$N_{M_1-M_2} = \frac{N}{1 + \dfrac{1+x}{x\left(1-\sum\limits_{j=1}^{m}\alpha_{2j}\right)} \sum\limits_{j=1}^{m} \dfrac{\alpha_{2j} z_j}{(1+z_j)}}; \quad (11)$$

$$N_{M_1-H_{2j}} = \frac{N\alpha_{2j}(1+x)z_j}{\left(1-\sum\limits^{m}\alpha_{2j}\right)x(1+z_j) + (1+x)(1+z_j)\sum\limits_{j=1}^{m}\dfrac{\alpha_{2j} z_j}{(1+z_j)}}, \quad (12)$$

where $x = \dfrac{E_{M_2}}{E_{M_1}}$; $z_j = \dfrac{E_{H_{2j}}}{E_{M_1}}$. (13)

If PCM $M_2 + H_{2j}$ consists of two phases, j = 1; $\alpha_{2j} = \alpha_{1i}$, the equation of the form (10) has the form:

$$a = \left\{ \frac{3N_{M_1-M_2} k_\phi (2R_{\max})^{\nu-\gamma}\left[E_{M_2}\left(1-\mu_{M_1}^2\right) + E_{M_2}\left(1-\mu_{M_2}^2\right)\right]}{2q\rho E_{M_1} E_{M_2}(1-\alpha_{21}) b(\nu-\gamma)\beta\left(\dfrac{5}{2}; \nu-\gamma\right) A_a} \right\}^{\frac{2}{3+2(\nu-\gamma)}}, \quad (14)$$

or

$$a = \left\{ \frac{3N_{M_1-H_{21}} k_\phi (2R_{\max})^{\nu-\gamma}\left[E_{H_{21}}\left(1-\mu_{M_1}^2\right) + E_{M_2}\left(1-\mu_{H_{21}}^2\right)\right]}{2q\rho E_{M_1} E_{H_{21}} \alpha_{21} b(\nu-\gamma)\beta\left(\dfrac{5}{2}; \nu-\gamma\right) A_a} \right\}^{\frac{2}{3+2(\nu-\gamma)}}. \quad (15)$$

For two-phase PCM, based on formulas (12) and (13), we have:

$$N_{M_1-H_{21}} = \frac{N_{M_1-M_2}\left[E_{M_2}\left(1-\mu_{M_1}^2\right) + E_{M_1}\left(1-\mu_{M_2}^2\right)\right] E_{H_{21}} \alpha_{21}}{\left[E_{H_{21}}\left(1-\mu_{M_1}^2\right) + E_{M_1}\left(1-\mu_{H_{21}}^2\right)\right] E_{M_2}(1-\alpha_{21})}. \quad (16)$$

Solving equations (16) and (9), we find:

$$N_{M_1-M_2} = \frac{N(1-\alpha_{21}) E_{M_2}\left[E_{H_{21}}\left(1-\mu_{M_1}^2\right) + E_{M_1}\left(1-\mu_{H_{21}}^2\right)\right]}{\left[E_{M_2}\left(1-\mu_{M_1}^2\right) + + E_{M}\left(1-\mu_{M_2}^2\right)\right] E_{H_{21}} \alpha_{21} + \left[E_{H_{21}}\left(1-\mu_{M_1}^2\right) + E_{M_1}\left(1-\mu_{H_{21}}^2\right)\right] E_{M_2}(1-\alpha_{21})}; \quad (17)$$

$$N_{M_1-H_{21}}=\frac{N\alpha_{21}E_{M_2}\left[E_{M_2}\left(1-\mu_{M_1}^2\right)+E_{M_1}\left(1-\mu_{M_2}^2\right)\right]}{\left[E_{M_2}\left(1-\mu_{M_1}^2\right)++E_{M}\left(1-\mu_{M_2}^2\right)\right]E_{H_{21}}\alpha_{21}+\left[E_{H_{21}}\left(1-\mu_{M_1}^2\right)+E_{M_1}\left(1-\mu_{H_{21}}^2\right)\right]E_{M_2}\left(1-\alpha_{21}\right)}. \quad (18)$$

To calculate the nominal pressures in the considered types of contact, we accept: $\frac{N}{A_a}=P_a$; $E_{M_2}=xE_{M_1}$; $E_{H_{11}}=Z_1E_{M_1}$; $\mu_{H_{11}}=\mu_{M_1}=\mu_{M_2}$. Taking into account equation (7), we have the following formulas:

$$P_{M_1-M_2}=P_a\frac{x(1+Z_1)}{x(1+Z_1)(1-\alpha_{21})+(1+x)Z_1\alpha_{21}}=\xi_1P_a; \quad (19)$$

$$P_{M_1-H_{21}}=P_a\frac{Z_1(1+x)}{x(1+Z_1)(1-\alpha_{21})+(1+x)Z_1\alpha_{21}}=\xi_2P_a. \quad (20)$$

Analysis of expressions (19) and (20) shows that the triad coupling of parts with PCM will work effectively under the condition: $P_{M_1-M_2}<P_{cr_{M_1-M_2}}$ and $P_{M_1-H_{21}}<P_{cr_{M_1-H_{21}}}$, for the matrix M_1 and filler H_{21}.

Given the conditions for the existence of contacts of type M_1 - M_2 and M_1 - H_{21}, equation (19) should be used at $0\le\alpha_{21}<1$, and equation (20) – at $0<\alpha_{21}\le 1$.

The use of PCM in the details of tribocouples of the second kind is appropriate in the following cases: $x=Z_1$; $Z_l>x$. In the first case, the nominal pressures in the contacts of different types do not depend on the content of the filler and are equal to the nominal pressure P_a, the limit value of which should be below $P_{cr_{M_1-M_2}}$ and $P_{cr_{M_1-H_{2I}}}$. For this filler, the force N on the tribocouple cannot be increased, because the pressure $P_{M_1-M_2}$ will exceed the allowable pressure. It is determined that the use of high-modulus filler is appropriate if you can change the coefficient of friction in the contact of the filler from one of the matrices, which will be lower than the coefficient of friction in the contact M_1 - M_2.

In the second case, when $Z_1>x$, the filler can be introduced only in the matrix that has in contact with the filler less critical pressure P_{cr}. If such a matrix is M_2. Then, when introducing a filler with $Z_1>x$ into this matrix, the value $\xi_1<1$ and the voltage at the most dangerous contacts M_1 - M_2 can be reduced several times, which will increase the nominal force N acting on the tribocouples of parts.

If in one of the details of the tribocoupling of the second kind to enter j – fillers, the feasibility of this procedure is determined by the same conditions as when introducing one filler ($x=Z_i$ i $Z_j>x$). However, so that the pressure on them does not exceed the critical value when increasing N, you need to control a larger number of types of contacts.

In order to simplify the previous expressions, we accept: $E_{M_2}=xE_{M_1}$; $E_{H_{2j}}=z_iE_{M_1}$; $E_{H_{1i}}=y_iE_{M_1}$; $\mu_{M_1}=\mu_{M_2}=\mu_{H_{2j}}=\mu_{H_{1i}}$ and solving together equations (8) and (10), we express the forces on the contacts of different types through a set of data: N; x; Z_j; Y_j; $\alpha_{1з}$; α_{2j}. Then we have:

$$\left.\begin{aligned}
N_{M_1-M_2}&=N\frac{x\left(1-\sum_{i=1}^{n}\alpha_{1i}\right)\left(1-\sum_{j=1}^{m}\alpha_{2j}\right)}{\xi};\\
N_{M_2-H_{1i}}&=N\frac{(1+x)y_i\alpha_{1i}\left(1-\sum_{j=1}^{m}\alpha_{2j}\right)}{(1+y_i)\xi};\\
N_{M_1+H_{2j}}&=N\frac{(1+x)z_j\left(1-\sum_{i=1}^{n}\alpha_{1i}\right)\alpha_{2j}}{(1-Z_j)\xi};\\
N_{H_{1i}-H_{2j}}&=\frac{y_iz_j(1+x)\alpha_{1i}\alpha_{2j}}{(y+z_j)\xi},
\end{aligned}\right\} \quad (21)$$

$$\xi=x\left(1-\sum_{i=1}^{n}\alpha_{1i}\right)\left(1-\sum_{j=1}^{m}\alpha_{2j}\right)+(1+x)\left\{\left(1-\sum_{i=1}^{n}\alpha_{1i}\right)\sum_{j=1}^{m}\frac{\alpha_{2j}z_j}{(1+z_j)}+\left(1-\sum_{j=1}^{m}\alpha_{2j}\right)\sum_{i=1}^{n}\frac{\alpha_{1i}y_j}{(1+y_i)}+\sum_{j=1}^{m}\alpha_{2j}z_j\left[\sum_{i=1}^{n}\frac{\alpha_{1i}y_i}{(y_i+z_j)}\right]\right\}. \quad (22)$$

Dividing equation (19) by the area of the surface occupied by contacts of different types, and accepting $\frac{N}{A_a} = P_a$, we obtain expressions for calculating the pressure at the corresponding contacts:

$$P_{M_1-M_2} = P_a \frac{x}{Q}; \quad P_{M_1-H_{2j}} = P_a \frac{(1+x)z_j}{(1+z_j)Q};$$
$$P_{M_2-H_{1i}} = P_a \frac{(1+x)y_i}{(1+y_i)Q}; \quad P_{H_{1i}-H_{2j}} = P_a \frac{(1+x)y_i z_j}{(y_i+z_j)Q}. \tag{23}$$

Experimental studies have shown that the tribocoupling of parts will be able to work if the pressure on the contacts of different types of this type does not exceed the critical value for its constituent materials tribocoupling of parts.

Using equations (19), (20) and (23), we can quantify the dependence of the critical load on the tribocoupling of parts on the composition and tribological properties of structural components. As a criterion for the effectiveness of the filler in PCM, we take the ratio of the nominal critical pressure $P_{a\,cr}$ in the triad of parts made of PCM to the nominal critical pressure $P_{cr_{M-M}}$ of the triad of parts made of the same matrix material.

Assuming that in equations (19) and (20) $P_{M_1-M_2} = \delta P_{cr_{M-M}}$, a $P_{cr_{M_1-H_{21}}} = \chi P_{cr_{M-M}}$, the value of the nominal critical pressure for tribocoupling of parts of the second kind can be found by equations:

$$P_{a\,cr} = \frac{\delta P_{cr_{M-M}}}{\xi_1}; \quad P_{a\,cr} = \frac{\chi P_{cr_{M-M}}}{\xi_2}. \tag{24}$$

The calculation of $P_{a\,cr}$ tribocouples of parts must be performed on both equations. The smaller of the two obtained values of $P_{a\,cr}$ and will represent the limit value of $P_{a\,cr}$ on the triad, one of the parts of which is made of PCM.

We present equation (24) in the form:

$$\frac{P_{a\,cr}}{P_{cr_{M-M}}} = \frac{\delta}{\xi_1}; \tag{25}$$

$$\frac{P_{a\,cr}}{P_{cr_{M-M}}} = \frac{\chi}{\xi_2}. \tag{26}$$

A smaller value $\frac{P_{cr}}{P_{cr_{M-M}}}$ of the ratio can be taken as the value of the criterion of the effectiveness of the filler for a given critical load.

It was found that the introduction of a high-modulus filler in a polymer matrix with a smaller modulus of elasticity $P_{M_1-H_{2j}} = 5P_{cr_{M_1-M_2}}$ can significantly increase the value of $P_{a\,cr}$ tribocoupling of parts, but not higher $P_{cr_{M_1-H_{21}}}$. In tribocouples of parts of the third kind, when two PCM are in contact with the macroheterophase structure, the criterion of filler efficiency $\frac{P_{a\,cr}}{P_{cr_{M-M}}}$ is selected by the minimum value of the ratio $\frac{P_{a\,cr}}{P_{cr_{M-M}}}$ calculated for the contacts *M-M*, *M-H* and *H-H*. If a matrix and a filler with different modulus of elasticity are used in triad couplings of parts with such a combination of contact types, the contacts made of materials with a smaller modulus of elasticity will be underloaded and the criterion value $\frac{P_{a\,cr}}{P_{cr_{M-M}}}$ will be lower. When $E_н = 10E_м$ and $P_{M_1-H_{2j}} = 5P_{cr_{M_1-M_2}}$, the criterion $\left[\frac{P_{a\,cr}}{P_{cr_{M-M}}}\right]_{\alpha_H=0,8} \approx 4$. This value, although lower $\frac{P_{a\,cr}}{P_{cr_{M-M}}}$, with the same modulus of elasticity of the matrix and filler, but higher than in layered PCM with other combinations of contact types.

Conclusions

1. The field of stresses in tribocouples of parts made of polymer-composite materials is considered, taking into account the properties of friction surfaces. It is revealed that the critical pressure in the tribocouples of parts is determined primarily by the energy of motion of dislocations in the surface layers of their materials.

2. It was found that to ensure the process of minimal wear in the triad of parts of polymer-composite

materials should create conditions when in the process of their operation are realized elastic contacts. For the case of flat conjugate surfaces of details the basic requirements are formulated, expressions for a share of the areas occupied by this or that contact of the details made of polymeric composite materials are received.

3. Efforts on different types of contacts of tribocouples of details taking into account the modulus of elasticity and Poisson's constant of matrix materials and fillers, share of the areas occupied by this or that type of contact are considered, and also nominal pressures in them are defined.

4. It is shown that the efficiency of tribocouples made of polymer-composite materials should be evaluated by the critical pressures at the contact surfaces of parts.

5. It is determined that for the manufacture of both antifriction and friction polymer composite materials it is more effective to use fillers whose modulus of elasticity is greater than the matrix. In order to increase the strength of the parts, it is advisable to use tribocoupling of parts of the third kind, and in terms of saving filler – the second kind.

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Аулін В.В., Гриньків А.В., Лисенко С.В., Лівіцький О.М. Обґрунтування умов ефективної працездатності трибоспряжень деталей, виготовлених з полімерних композитних матеріалів з високомодульними наповнювачами

Дана робота присвячена дослідженню умов ефективної працездатності трибоспряжень деталей, виготовлених з полімерних композитних матеріалів. Напружений стан матеріалу пов'язано з характеристиками скупчення дислокацій, енергією активації їх руху. Визначено усереднене напруження, напруження тертя. На основі цього отримано вирази для оцінки критичних напружень та навантаження на трибоспряження деталей. Визначено розподіл зусилля на трибоспряження деталей з врахуванням характеристик якості поверхонь тертя, модулів пружності та сталої Пуассона компонентів полімерного композитного матеріалу. Цю задачу розглянуто для трибоспряжень деталей різного роду.

Отримано вирази для розрахунку номінальних тисків у різних типів контакту матеріалу деталей трибоспряження, а також наведені рівняння, за якими можливо оцінити в них значення номінального критичного тиску.

З'ясовано умови ефективного функціонування трибоспряження деталей з полімерокомпозитних матеріалів. Визначено, що значне підвищення номінального критичного тиску на трибоспряження можливе використанням високомодульних наповнювачів, модуль пружності матеріалу яких більший за модуль пружності полімерної матриці.

Ключові слова: полімерний композитний матеріал, макрогетерофазний матеріал, високомодульний наповнювач, трибоспряження деталей, матриця, наповнювач, поле напружень, пружний контакт, критичний тиск, номінальний тиск