Problems of Tribology, V. 28, No 1/107-2023, 81-91

Problems of Tribology
Website: http://tribology.khnu.km.ua/index.php/ProbTrib
E-mail: tribosenator@gmail.com

DOI: https://doi.org/10.31891/2079-1372-2023-107-1-81-91

The regularity of the change in the coefficient of friction of the coupling of "shaft-sleeve" parts using polymeric materials

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Received: 25 January 2022: Revised: 25 February 2023: Accept: 15 March 2023

Abstract

For the conjugation of samples and parts of the "shaft-sleeve" type, from the theoretical and experimental points of view, the laws of the change of the coefficient of friction for the combined polymer-metal material and coating were considered. Based on the law of energy conservation and transformation in the friction zone, expressions for estimating friction coefficients for polymer coatings and combined polymer-metal materials were obtained, taking into account the properties of thermal conductivity and elasticity and the geometric dimensions of the polymer and metal components. The consistency of the patterns of change in the friction coefficient has been clarified in tribocouplings of samples and parts from load and sliding speed in modes without lubrication and at extreme friction. To substantiate the effective operation of tribocoupling of parts made of combined polymer-metal materials, a criterion was introduced - the coefficient of wear, which is used to evaluate the tribological efficiency. It is shown that the obtained experimental results do not contradict the theoretical justification.

Key words: polymer-metal material, coefficient of friction, load, sliding speed, tribocoupling of samples and parts, non-equilibrium state, elasticity, deformation, wear coefficient

Introduction

The use of tribocouplers of samples and parts made of combined polymer-metal materials depends on the polymer material, the formation of the metal component, the coating technology, properties and geometric characteristics of the polymer and metal components.

During the operation of tribocoupled parts, the intensity of wear and the coefficient of friction are important. designing combined polymer-metal materials and coatings, they try to significantly reduce the intensity of wear and optimize the friction coefficient for a specific tribocoupling. There is no criterion by which it is possible to evaluate the effective operation of tribocoupling of parts made of combined polymer-metal material and coatings. It is important to control the value of the coefficient of friction by varying the geometric dimensions, properties of the components of the combined polymer-metal material, operating modes and load-speed characteristics.

Literature review

To effectively increase the durability of machine systems and units, tribo-coupling of parts made of polymer and polymer-metal materials is used [1-3]. But at the same time, it is necessary to solve the problem of optimal geometric dimensions, technologies for forming stress coatings in materials, intensity of their wear, development of methods for evaluating the efficiency and reliability of such tribocouplers [4,5].

It should be noted that when implementing such an operational property of materials as their wear resistance, the task is complicated due to the significant dependence of stresses on the ratio of constituent polymer-metallic materials, sizes, shapes of their constituents, as well as structural features of conjugated parts and properties of the working (technological) environment [6,7] .

The authors of works [8-10] the main cause of destructive processes in the surface layers of half-dimensional materials are contact stresses and deformations that arise under the influence of loads on the tribo-coupling of parts. This requires a detailed study of the features in the surface layers of the tribojoint materials of the parts. Studying the features of combined polymer-metal materials in the process of tribocoupling of parts allows us to approach unsolved problems from a single point of view. The use of physical and mathematical models [11,12] is appropriate. Attempts to compare the wear resistance and stressed and deformed state of the surface layers of such coatings on parts were made in [1].

The relationship between the wear process of combined polymer-metal materials and their tribological properties is given in works [13,14]. The results of studies of wear resistance with polymer and polymer-metal coatings show that in the first case it is lower than in the second due to faster equalization of contact pressure. The phenomenon of spontaneous establishment and maintenance of a stationary mode of wear was also revealed [1,15,16].

The existing results of studies of combined polymer-metal materials [17-20] do not allow to evaluate the effectiveness of the tribocoupling of parts according to the intensity of wear, and there is a need to relate them to the types of contacts and contact conditions.

Purpose

The purpose of this work is to identify the patterns of change in the friction coefficient of tribocouplers of parts made of combined polymer-metal materials and with applied polymer and polymer-metal coatings and to propose a criterion for their tribological efficiency in operation.

Results

Research results indicate that the heat resistance of the combined polymer-metal coating (PMeC) is higher than that of pure polymer (PC). This makes it possible to develop the formation of polymer-metal coatings as a technological process to increase the wear resistance and heat resistance of the range of parts that work as sliding bearings in machines.

For polymer materials, there is a fairly clear relationship between friction coefficients and temperature in the contact zone: lower temperatures correspond to lower values of the friction coefficient and vice versa. The temperature arising as a result of friction changes the elastic and strength properties of the polymer surface layers of tribocouples of samples and parts. This affects the change of the actual contact area of the surfaces and the force of friction, and therefore the coefficient of friction.

The temperature change observed in the friction zone is due to more intensive heat removal by combined polymer-metal coatings compared to pure polymer ones.

In the case of a combined polymer-metal coating (fig. 1), its two components should be considered: metal with a width a, height – h and polymer – with a width of b . Thermal conductivity of metal material – λ_3. The thickness of the polymer coating over the metal component is δ_1 .

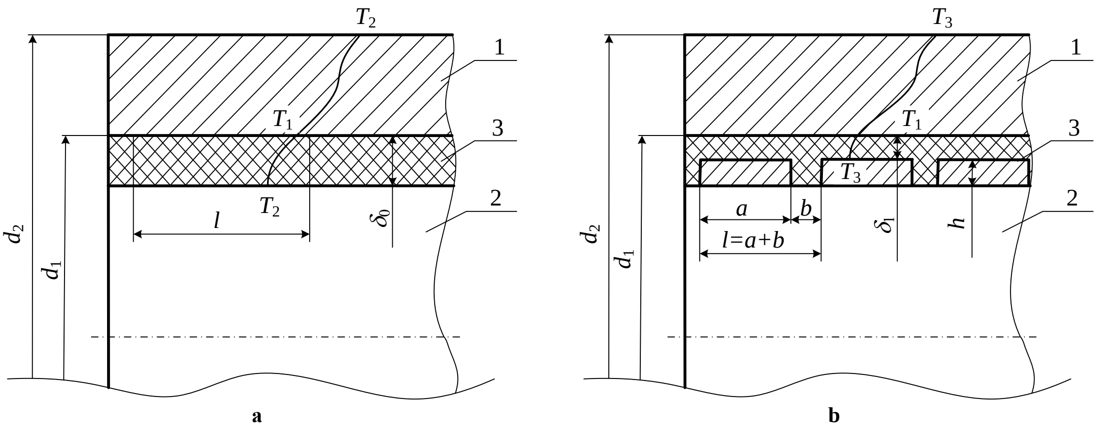

Fig. 1. Scheme of tribocoupling of parts "shaft-sleeve with polymer (a) and combined polymer-metal (b) coatings: 1 - sleeve; 2 - shaft; 3 - coating

Heat flows through the components of the combined polymer-metal coating of the cylindrical surface have the form:

– for the polymer component:

$$Q_P = (1-\gamma)(1-\beta)\frac{2\pi b\lambda_2(T_1 - T_2)}{\ln\dfrac{d_1}{d_1 - 2h_1 - 2\delta_1}}; \quad (1)$$

– for the metal component:

$$Q_{Me} = (1-\gamma)(1-\beta)\frac{2\pi a\lambda_3(T_1 - T_2)}{\ln\dfrac{d_1}{d_1 - 2h_1 - 2\delta_1}}, \tag{2}$$

where γ – the coefficient that takes into account part of the heat dissipated through the bushing friction surfaces;

β – the coefficient that takes into account part of the heat dissipated in the triboconjugation of samples and parts;

λ_2 – thermal conductivity of the polymer.

The flow of heat removed from the friction zone by the combined polymer-metal coating is equal to:

$$Q_{MeP} = \frac{(1-\gamma)(1-\beta)2\pi(T_1 - T_2)}{\ln\dfrac{d_1}{d_1 - 2h - 2\delta_1}}(b\lambda_2 + a\lambda_3). \tag{3}$$

We compare the heat flows Q_P and Q_{MeP} assuming that $h + \delta_1 = \delta_0$:

$$\frac{Q_{MeP}}{Q_P} = \frac{b\lambda_2 + a\lambda_3}{(a+b)\lambda_2}. \tag{4}$$

After some transformations (4) can be represented in the form:

$$\frac{Q_{MeP}}{Q_P} = 1 + \frac{a(\lambda_3 - \lambda_2)}{(a+b)\lambda_2}. \tag{5}$$

Since $\lambda_2 << \lambda_3$, then $\dfrac{Q_{MeP}}{Q_P} >> 1$, that is, the process of heat removal is significantly intensified by the combined polymer-metal material in comparison with the polymer one.

An increase in the relative sliding speed of the contacting tribocoupling of parts causes an increase in the temperature in the friction zone, which can affect both the mechanical properties of materials and the nature of the entire complex of physico-chemical processes. Based on the law of conservation of energy in the mode of steady friction, when the surfaces of the contacting parts are worn, the temperature in the contact zone can be calculated using the expression:

$$T_1 = \frac{k}{\lambda_1 + \lambda_2}\frac{f_P VN}{I \cdot r}, \tag{6}$$

where k – is a coefficient ranging from 0.25 to 0.32;

I – mechanical heat equivalent (I =43.57 kcal/J);

r – the radius of the contact spot;

V – sliding speed;

λ_1, λ_2 – thermal conductivity coefficients of contacting bodies;

f_P – the coefficient of friction of the polymer surface.

For a polymer-metal material, expression (6) has the form:

$$T_1 = \frac{k(a+b)}{(\lambda_1 + \lambda_3)a + (\lambda_1 + \lambda_2)b}\frac{f_{MeP} VN}{I \cdot r}, \tag{7}$$

where f_{MeP} – the coefficient of friction of the combined polymer-metal surface.

The expression for determining the step of the metal component in the combined polymer-metal coating is obtained using the law of conservation of thermal energy when it is removed through a cylindrical surface:

$$(1-\gamma)\frac{2\pi(a+b)\lambda_1(T_1 - T_2)}{\ln\dfrac{d_2}{d_1}} = \frac{(1-\beta)2\pi(T_1 - T_2)}{\ln\dfrac{d_1}{d_1 - 2h - 2\delta_1}}(b\lambda_2 + a\lambda_3)\cdot \tag{8}$$

After some transformations of equation (8), we obtain:

$$\frac{(a+b)\lambda_1(1-\gamma)}{\ln\dfrac{d_2}{d_1}} = \frac{(1-\beta)(\lambda_2 b + \lambda_3 a)}{\ln\dfrac{d_1}{d_1 - 2(\delta_1 + h)}}. \tag{9}$$

Assuming that in the first approximation we have:

$$\ln\frac{d_2}{d_1}=\ln\left(1+\frac{d_2-d_1}{d_1}\right)\approx\frac{d_2-d_1}{d_1}; \quad (10)$$

$$\ln\frac{d_1}{d_1-2(\delta_1+h)}=\ln\left(1+\frac{2(\delta_1+h)}{d_1-2(\delta_1+h)}\right)\approx\frac{2(\delta_1+h)}{d_1-2(\delta_1+h)}, \quad (11)$$

and also taking into account these expressions in equation (9), we have:

$$\frac{(a+b)\lambda_1(1-\gamma)d_1}{d_2-d_1}=\frac{(1-\beta)(\lambda_2 b+\lambda_3 a)}{2(\delta_1+h)}\left[d_1-2(\delta_1+h)\right]. \quad (12)$$

Having entered the variables ϕ_1 in ϕ_2 equation (12), we have:

$$b=\frac{\lambda_3\phi_1-\lambda_1\phi_2}{\lambda_1\phi_2-\lambda_2\phi_1}a, \quad (13)$$

where $\phi_1=(1-\beta)(d_1-2(\delta_1+h))(d_2-d_1)$. (14)

$\phi_2=2d_1(1-\gamma)(\delta_1+h)$. (15)

Taking into account the thermophysical characteristics of the material of the sleeve and the materials covering the cylindrical surface, as well as the geometric parameters of the parts and the coating, it is possible to calculate the technological parameter *b* of the combined polymer-metal material on the renewable cylindrical surface of the part for this tribocoupling of parts. The formation of combined polymer-metal materials on a cylindrical surface not only increases the speed of heat removal from the friction zone, but also improves the anti-friction properties of the mating surfaces.

From a theoretical point of view, let's consider the change of such an energy characteristic in the tribocoupling of "shaft-sleeve" parts as the coefficient of friction. We obtain an expression for the coefficient of friction for polymer and polymer-metal materials, based on the law of conservation of energy, taking into account the work of friction forces and the process of heat removal from the friction zone.

For a polymer coating, the work of friction forces can be calculated using the formula:

$$A_{mp_p}=\Omega f_P d_1\left(\frac{N\delta E_1E_2d_1(a+b)}{(d_1-\delta)\left[E_1(1-\mu_2)^2+E_2(1-\mu_1)^2\right]}\right)^{1/2}, \quad (16)$$

where Ω – the coefficient that takes into account the nature of the movement of the tribocoupling of parts ($\Omega=7{,}9$ - for rotational movement; $\Omega=3{,}2d^2_{\max}$ – for oscillating movement);

μ_1, μ_2, E_1, E_2 – are Poisson's ratios and modulus of elasticity, respectively, of the material of the shaft and sleeve.

Taking into account (16), in the law of energy conservation and transformation, we have:

$$\Omega f_P d_1\left(\frac{N\delta E_1E_2d_1(a+b)}{(d_1-\delta)\left[E_1(1-\mu_2)^2+E_2(1-\mu_1)^2\right]}\right)^{1/2}=(1-\beta)\frac{K2\pi(a+b)\lambda_2(T_1-T_2)}{\ln d_1/(d_1-2\delta_1)}+\gamma\frac{2\pi(a+b)\lambda_1(T_1-T_2)}{\ln d_2/d_1}, \quad (17)$$

where *K* – a coefficient that takes into account the material of the coupling parts and the presence of a lubricating medium.

From the obtained equation (17), it is possible to determine the coefficient of friction for the "shaft-sleeve" tribocoupling with a uniform polymer coating of the cylindrical surface of the shaft:

$$f_P=\frac{K2\pi(a+b)^{1/2}(T_1-T_2)\left[(1-\beta)\lambda_2/\ln\frac{d_1}{d_1-2\delta_1}+\gamma\lambda_1/\ln\frac{d_2}{d_1}\right]}{\Omega d_1\left(\frac{N\delta E_1E_2d_1}{(d_1-\delta)\left[E_1(1-\mu_2)^2+E_2(1-\mu_1)^2\right]}\right)^{1/2}}. \quad (18)$$

For a combined polymer-metal material on a section of a cylinder with a length of $l=a+b$, the work of friction forces can be calculated by the formula:

$$A_{MeP}=f_{MeP}d_1\Omega(a+b)\left(\frac{N\delta E_1}{d_1(d_1-\delta)}\right)^{1/2}\times\left[\left(\frac{bE_2}{E_1(1-\mu_2)^2+E_2(1-\mu_1)^2}\right)^{1/2}+\left(\frac{aE_3}{E_1(1-\mu_3)^2+E_3(1-\mu_1)^2}\right)^{1/2}\right], \quad (19)$$

where E_3, μ_3 – are the modulus of elasticity and Poisson's ratio of the metal component of the combined polymer-metal material, respectively.

Using (3) in the law of energy conservation and transformation, we have:

$$f_{MeP} d_1 \Omega (a+b) \left(\frac{N\delta E_1}{d_1 (d_1 - \delta)} \right)^{1/2} \cdot \left[\left(\frac{bE_2}{E_1 (1-\mu_2)^2 + E_2 (1-\mu_1)^2} \right)^{1/2} + \left(\frac{aE_3}{E_1 (1-\mu_3)^2 + E_3 (1-\mu_1)^2} \right)^{1/2} \right] = \\ = \frac{K 2\pi\gamma (a+b) \lambda_1 (T_1 - T_2)}{\ln \left(d_2 / d_1 \right)} + \frac{2\pi (1-\beta)(T_1 - T_2)}{\ln \left(d_1 / d_1 - 2h - 2\delta_1 \right)} (b\lambda_2 + a\lambda_3) \quad (20)$$

From equation (20), it is possible to determine the coefficient of friction for couplings of samples and parts made of a combined polymer-metal material:

$$f_{MeP} = \frac{K \cdot 2\pi (T_1 - T_2)}{d_1 \Omega \sqrt{\frac{N\delta_1 E_1}{d_1 (d_1 - \delta_1)}}} \cdot \frac{\left[\frac{\gamma (a+b) \lambda_1}{\ln \left(\frac{d_2}{d_1} \right)} + \frac{(1-\beta)(b\lambda_2 + a\lambda_3)}{\ln \left(\frac{d_1}{(d_1 - 2h) - 2\delta_1} \right)} \right]}{\left(\frac{bE_2}{E_1 (1-\mu_2)^2 + E_2 (1-\mu_1)^2} \right)^{1/2} + \left(\frac{aE_3}{E_1 (1-\mu_3)^2 + E_3 (1-\mu_1)^2} \right)^{1/2}} . \quad (21)$$

By substituting the mechanical and thermophysical characteristics of the materials of the conjugated parts, the coatings applied to them, the geometric dimensions, the components of the combined polymer-metal material, as well as the specified characteristics of the coatings into expressions (18) and (21), one can make sure that $f_{MeP} < f_P$. This indicates an improvement in the antifriction properties of polymer-metal materials and coatings.

Triboconjugation of samples and parts may be brought out of equilibrium under the influence of external friction conditions, random occurrences of natural inclusions on contacting surfaces, relaxation phenomena in combined polymer-metal materials and coatings, development of physico-chemical processes in the area of antifriction contact, etc. The process of deviation from the equilibrium state in them is described by the equation:

$$d\xi_{Me} = (I_{aMe} - I_{aP}) dL_{mp} , \quad (22)$$

where ξ_{Me} – the excess deformation of the polymer compared to the deformation of the metal;

I_{aMe}, I_{aP} – intensity of metal and polymer wear.

By integrating the differential equation (22), it can be shown that the tribosystem of the conjugations of parts returns to equilibrium, that is, it is stable:

$$I_{aMe} - I_{aP} = (I_{aMe} - I_P) \exp \left[L_{mp} \frac{(I_{aMe} - I_{aP})}{\xi_{Me} - \xi_{MeP}} \right], \quad (23)$$

where $I_{aMe} - I_P$ – the deviation from the initial value of the difference in intensity of metal and polymer wear;

$\xi_{Me} - \xi_{MeP}$ – the corresponding deviation of the excess deformation of the polymer.

Expression (23) shows that as the friction path increases, L_{mp} the wear intensities of metal and polymer asymptotically converge. The expression is obtained on the assumption that in a fairly small zone the equilibrium point $I_{aMe} - I_P$ depends linearly on the amount of deformation of the metal ξ_{Me}. Disturbing factors, without affecting the performance of tribocoupled parts, can lead to a temporary increase in the intensity of wear of the coupled surfaces. Due to the optimal choice of parameters a and b, this phenomenon can be minimized.

One of the indicators of the properties of materials to resist wear in the process of friction is the wear coefficient K_u, which is equal to:

$$K_u = \frac{u_h}{P_k L_{mp}} , \quad (24)$$

where u_h – linear wear;

P_k – nominal contact pressure;

L_{mp} – friction path.

The wear coefficient links the strength, speed and structural parameters of the couplings of parts taking into account their operation. For coupling parts of the "shaft-sleeve" type, the wear factor has the form:

$$K_u = \frac{4l^2 u_{h1}\left(u_{h1} + \frac{d_1}{2}\right)\sin\varphi}{(d_1+\delta)L_{mp}N}, \quad (25)$$

where l – is the length of the cylindrical surface;

u_{h1} – value of the maximum linear wear of the sleeve;

L_{mp} – friction path;

N_P – load reaction;

δ – nominal clearance of the bearing;

φ – half of the contact angle, determined by the expression:

$$\varphi = \arcsin\left[\frac{N_P l}{2\pi}\frac{\left(\frac{1+\mu_1}{E_1}+\frac{1+\mu_2}{E_2}\right)}{\delta}\left(\frac{d_1+\delta}{d_1}\right)\right]^{1/2} + \arccos\left[1-\frac{d_1+\delta-u_{h1}-u_{h2}}{d_1\left(\frac{\delta}{u_{h1}+u_{h2}}+1\right)}\right], \quad (26)$$

where the first term is the constant value of the contact angle, determined by the plastic deformation of the materials of the coupling parts, and the second term is the value of the contact angle, which depends on the wear of the sleeve and shaft;

u_{h2} – value of the maximum linear wear of the shaft.

Expression (26) for a uniform polymer coating of a shaft with length $l = a + b$, takes the form:

$$\varphi_P = \arcsin\left[\frac{N(a+b)}{2\pi\delta}\left(\frac{1+\mu_1}{E_1}+\frac{1+\mu_2}{E_2}\right)\left(\frac{d_1+\delta}{d_1}\right)\right]^{1/2} + \arccos\left[1-\frac{d_1+\delta-u_{h1}-u_{h2}}{(d_1-2\delta_0)\left(\frac{\delta}{u_{h1}+u_{h2}}+1\right)}\right], \quad (27)$$

and for a combined polymer-metal coating:

$$\varphi_{MeP} = \arcsin\left[\frac{N}{2\pi\delta}\left(\frac{1+\mu_1}{E_1}(a+b)+\frac{1+\mu_2}{E_2}b+\frac{1+\mu_3}{E_3}a\right)\left(\frac{d_1+\delta}{d_1}\right)\right]^{1/2} + \\ + \arccos\left[1-\frac{d_1+\delta-u_{h1}-u_{h2}}{(d_1-2\delta_1-2h)\left(\frac{\delta}{u_{h1}+u_{h2}}+1\right)}\right] \quad (28)$$

Having experimentally determined on the friction machine the wear values u_{h1} and u_{h2}, and also, knowing the dimensions of the conjugated samples and parts and the mechanical parameters of their materials, according to the expression (25), taking into account (27) and (28), it is possible to estimate the coefficient of wear and draw a conclusion about the expediency of using combined polymer-metal coatings in the restoration of parts and their tribological efficiency.

Experimental studies of the influence of the specific load and sliding speed on the friction coefficient in the triboconjugation of samples have shown that the use of polymeric materials in coatings allows to significantly increase the antifriction properties of working surfaces.

Theoretical estimates of the coefficient of friction, carried out according to formulas (18), (21), lead to a similar conclusion. The results of experimental and theoretical studies of the coefficient of friction without lubrication and in extreme friction modes for different surfaces under the same test conditions are given in table 1.

The analysis of the data presented in Table 1 shows that the coefficient of friction of PC is 1.2...1.3 times lower than that of a purely polymer coating and 1.6...2.1 times lower than the coefficient of friction of cast iron and steel without lubrication.

Table 1

The value of the friction coefficients in the contact zone of triboconjugation of materials (*P*=1.0 MPa, *V* = 0.5 m/s) according to experimental data and theoretical features

Surface	Coefficient of friction, f_{mp}			
	Experimental data		Theoretical evaluations	
	without lubrication	marginal friction	without lubrication	marginal friction
PC	0.302	0.244	0.280	0.220
PMeC	0.263	0.197	0.240	0.180
Cast iron CH18	0.543	0.320	-	-
Steel 45	0.447	0.286	-	-

In conditions of friction without lubrication, the value of the coefficient of friction decreases significantly due to the formation of polymer films and the increase in their density and thickness. The reduction of the friction coefficient in the presence of lubrication is associated with the facilitation of the process of deformation of the surface layers of the friction pairs.

On the basis of the obtained results, it can be noted that RS are distinguished by the specific feature of forming films and maintaining their density and thickness in the process of friction.

Tables 2 and 3 show the change in the coefficient of friction of various surfaces without lubrication and in the limit friction mode depending on the specific load.

Table 2

Dependence of the coefficient of friction of surfaces without lubrication on the specific load (V = 0.5 m/s)

Surface	Coefficient of friction, f_{mp}			
	Specific load, MPa			
	0.5	1.0	1.5	2.0
PC	0.350	0.302	0.287	0.254
PMeC	0.302	0.263	0.243	0.213
Cast iron CH18	0.497	0.543	0.675	0.720
Steel 45	0.421	0.447	0.574	0.628

Table 2

Dependence of the surface friction coefficient at the limit friction on the specific load (V=0.5m/s)

Поверхня	Coefficient of friction, f_{mp}			
	Specific load, MPa			
	0.5	1.0	1.5	2.0
PC	0.280	0.244	0.183	0.165
PMeC	0.210	0.197	0.120	0.113
Cast iron CH18	0.397	0.320	0.201	0.196
Steel 45	0.354	0.286	0.213	0.174

The analysis of the data in tables 2, 3 shows that with an increase in the specific load, the friction coefficient decreases both in the case of friction without lubrication and in the case of marginal friction, which corresponds to theoretical estimates within the confidence interval.

Experimental data were compared with theoretical calculations. According to the calculation data, theoretical curves of the dependence of the coefficient of friction on the specific load were constructed for the combined polymer-metal and pure polymer coatings, which are presented in fig. 2 and fig. 3.

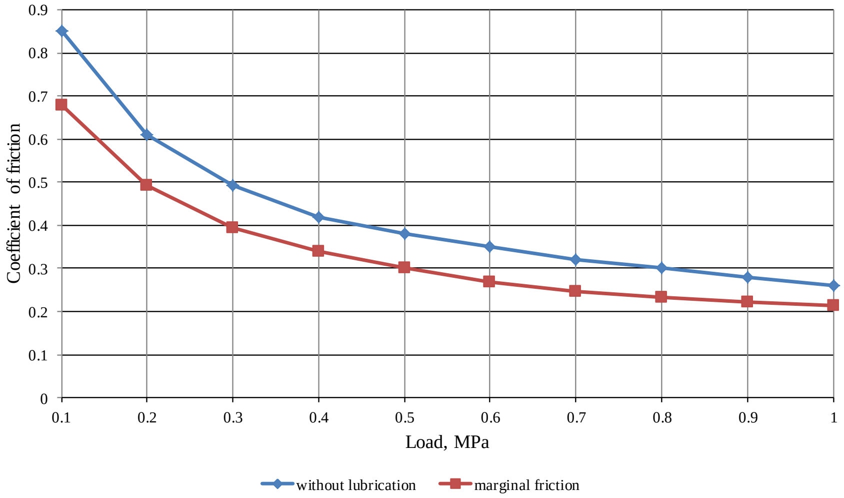

Fig. 2. Theoretical curves of the dependence of the coefficient of friction of the polymer coating (PC) on the specific load

The decrease in the coefficient of friction when the load increases indicates that the contact of the conjugated surfaces of the samples and parts in the considered range of loads is characterized by the condition of elastic contact.

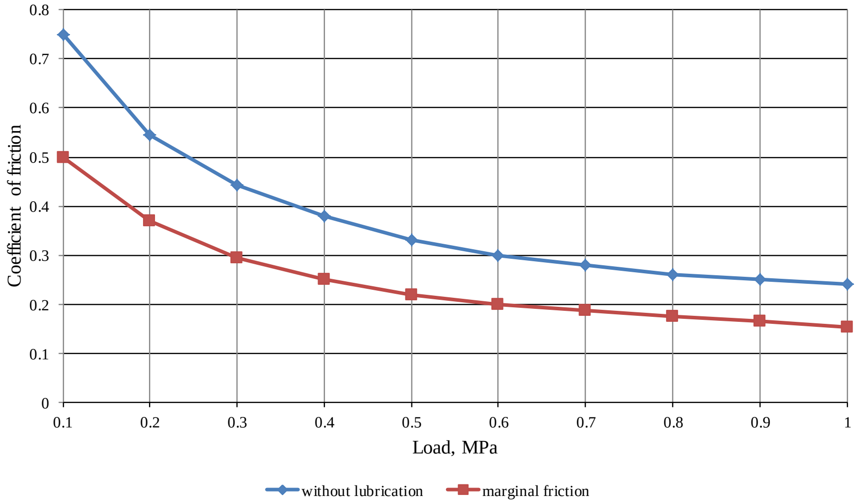

Fig. 3. Theoretical curves of the dependence of the coefficient of friction of the combined polymer-metal material (PMeC) on the specific load

At the limit friction of PMeC with an increase in load, an increase in surface cleanliness is also observed. The surface of the bushings working with combined polymer-metal coatings acquired a shiny polished appearance.

Experimental data on the dependence of the friction coefficients of various surfaces without lubrication and with extreme friction on the sliding speed are given in tables 4 and 5.

Table 4

Dependence of the friction coefficient on the sliding speed without lubrication at a specific pressure of P=1.0 MPa

Surface	Coefficient of friction, f_{mp}			
	Sliding speed, m/s			
	0.5	1.0	1.5	2.0
PC	0.28	0.42	0.45	0.37
PMeC	0.24	0.35	0.39	0.30
Cast iron CH18	0.54	0.71	0.68	0.62
Steel 45	0.45	0.67	0.61	0.55

Table 5

Dependence of the friction coefficient on the sliding speed at the limit of friction at a specific pressure of P=1.0 MPa

Surface	Coefficient of friction, f_{mp}			
	Sliding speed, m/s			
	0.5	1.0	1.5	2.0
PC	0.22	0.20	0.17	0.15
PMeC	0.18	0.16	0.13	0.09
Cast iron CH18	0.32	0.29	0.23	0.21
Steel 45	0.28	0.25	0.21	0.18

The regularity of the change in friction coefficients from the sliding speed for the combined polymer-metal coating under friction conditions without lubrication is illustrated in fig. 4, and at the limit of friction – fig. 5.

It can be seen that in conditions of friction without lubrication, the coefficient of friction changes in a complex way: when the sliding speed increases to 1.5 m/s, it increases, further increasing the sliding speed leads to a decrease in the value of the friction coefficient. The dependence of the friction coefficient on the sliding speed is, strictly speaking, the dependence of the friction coefficient on the temperature. As the sliding speed increases, the temperature on the friction surface increases, as a result of which the physical and mechanical properties of materials change, the area of actual contact increases, which is accompanied by an increase in frictional forces and, therefore, the friction coefficient. This corresponds to the increasing sections of the curve of the dependence of the coefficient of friction for PMeC in conditions of friction without lubrication on the speed of sliding (fig. 4).

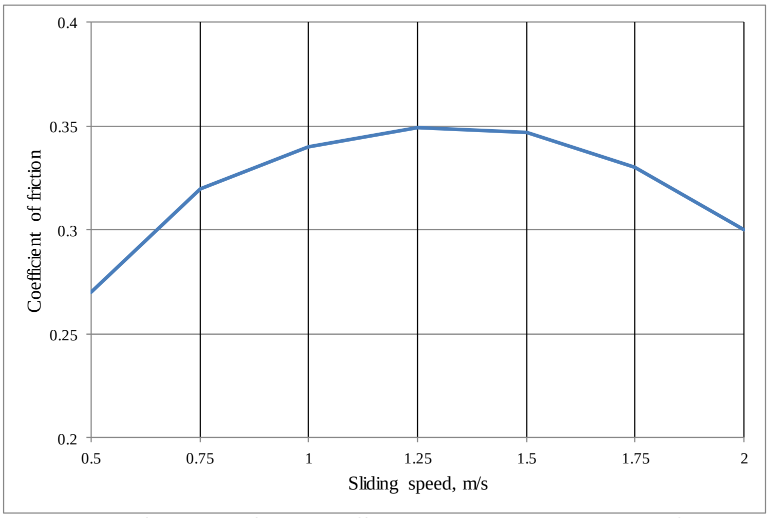

Fig. 4. Theoretical dependence of the PMeC friction coefficient on the sliding speed during friction without lubrication

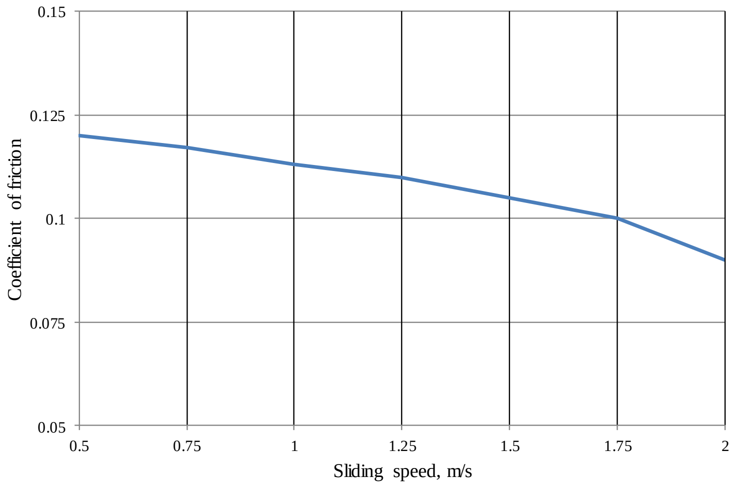

Fig. 5. Theoretical dependence of the PMeC friction coefficient on the sliding speed at the limit of friction

If in the zone of low sliding speeds (low temperature) a sufficient protective film does not have time to form, then with a further increase in speed (temperature), the intensity of film growth increases, its strength decreases, the nature of the film itself changes, and at the same time the shear resistance decreases, which reduces coefficient of friction. When the sliding speed increases, the plastic deformation does not have time to spread inward and is localized in a smaller volume. These features reduce the friction coefficient after the maximum.

Therefore, the transition from one type of violation of frictional bonds to another causes a change in the coefficient of friction and its transition through a maximum (fig. 4). At the limit of friction (fig. 5), the curve of the dependence of the coefficient of friction on the sliding speed has a decreasing character with increasing speed. The presence of an oil film on the friction surfaces changes the temperature regime, as well as the value of the friction forces due to the reduction of the area of direct contact of the friction surfaces.

As a result of experimental studies, it was found that combined polymer-metal coatings work better than pure polymer coatings. This is confirmed by theoretical justifications. As a result of temperature and deformation actions, the friction process of the combined polymer-metal material occurs in the presence of a polymer film with low shear resistance in the contact zone. This explains the decrease in the coefficient of friction. Triboconjugation of materials in operation, in the presence of a polymer, is accompanied by processes of interaction of mechanical destruction products with the metal surface. As a result of these interactions, polymer-metal compounds are formed, which also protect the contacting surfaces of tribo-bonding samples and parts from sticking. In addition, in the friction zone, the number of wear products between the friction surfaces decreases, as the polymer absorbs them from the friction surface, which also affects the reduction of wear intensity and the friction coefficient.

Conclusions

1. The coefficient of friction of PMeC is 1.2...1.3 times less than that of a pure polymer coating and 1.6...2.1 times less than the coefficients of friction of cast iron and steel without lubrication.

2. The decrease in the friction coefficient under the conditions of operation without lubrication is explained by the formation of polymer films on the surface with an increase in their density and thickness.

3. A criterion for evaluating the tribological efficiency of the combined polymer-metal material was

introduced, taking into account the strength, speed and structural parameters of the coupling of parts, taking into account their operating modes

4. The experimental data of the coefficient of friction obtained in the study agree positively with the theoretical calculations.

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Аулін В.В., Лисенко С.В., Гриньків А.В., Тихий А.А., Кузик О.В., Лівіцький О.М.
Закономірність зміни коефіцієнта тертя спряження деталей "вал-втулка" з використанням полімерних матеріалів

Для спряження зразків і деталей типу "вал-втулка" з теоретичної та експериментальної точок зору розглянуто закономірності зміни коефіцієнта тертя для комбінованого полімерометалевого матеріалу і покриття. Виходячи із закону збереження і перетворення енергії в зоні тертя, отримано вирази для оцінки коефіцієнтів тертя для полімерних покриттів і комбінованих полімерометалевих матеріалів з урахуванням властивостей теплопровідності і пружності та геометричних розмірів полімерної та металевої складових. З'ясована узгодженість закономірностей зміни коефіцієнта тертя в трибоспряженнях зразків і деталей від навантаження і швидкості ковзання в режимах без змащення і при граничному терті. Для обґрунтування ефективної експлуатації трибоспряжень деталей з комбінованих полімерометалевих матеріалів введено критерій – коефіцієнт зносу, за яким оцінюють трибологічну ефективність. Показано, що отримані експериментальні результати не суперечать теоретичним обґрунтуванням.

Ключові слова: полімерометалевий матеріал, коефіцієнт тертя, навантаження, швидкість ковзання, трибоспряження зразків і деталей, нерівноважний стан, пружність, деформація, коефіцієнт зносу