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Computer Simulation of Accelerated Modes for Faster Testing of Friction Pairs Having Solid Lubricant Coatings

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Abstract—The approach to forecasting accelerated modes for faster testing of friction pairs having solid lubricant coatings using computer simulation is examined. Load and temperature test modes under which acceleration leads to faster testing were defined. Loads and temperatures have been revealed that determine the multiple transition from predominantly elastic and elastoplastic deformation of solid lubricant coatings to a predominantly elastoplastic and plastic one, which characterizes the maximum performance of high-resource friction pairs with solid lubricant coatings. Comparison of the results of the full-scale experiment and numerical experiments confirmed the correctness of the proposed method. It is shown that the ratio of elastoplastic contacting to all contacting protrusions determines the conditions under which the forcing of the modes leads to accelerated testing.

Keywords: faster testing, accelerated modes, solid lubricant coatings, computer simulation, numerical testing

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INTRODUCTION

Increasing demands on the reliability of mechanical systems and the introduction of new materials poses the problem of a reliable assessment of the durability of their friction pairs. Tribological properties of materials, lubricants, and coatings are evaluated at the stage of laboratory tests. Laboratory tests differ from full-scale and operational tests by idealization of their conditions and accurate registration of the investigated quantities. The results of these tests are data on the wear of rubbing bodies, the coefficient of friction, the life of the friction pair, and their dependence on the characteristics of samples, test conditions, and environmental parameters. The importance of laboratory tribotechnical tests is confirmed by the large number of standardized and non-standardized methodological recommendations regulating them and the variety of equipment used [1]. Testing under nominal conditions, as a rule, is associated with significant time expenditures; therefore, the development of methods for their acceleration is very relevant. The standard [2] regulates that in the case when accelerated tests are conducted with boosting modes, they must meet direct and indirect criteria for determining the permissible upper limit of boosting the acting factor. For friction pairs with solid lubricant coatings (SLCs), the most important are the criteria for maintaining the type of contact, the type of wear, and the moment of increase in the friction force [3]. However, the results of laboratory tribotechnical tests are not sufficiently reproducible due to the influence on experiments of uncontrolled processes occurring on contacting surfaces during their frictional interaction [4].

Aim of this study: Development of a method for predicting forced modes of accelerated tribological conjugate testing based on computer simulation of contact interaction, which can significantly increase the reliability of the obtained experimental results.

FORMULATION OF THE PROBLEM

Consider the criterion for maintaining the type of contact and its effect on the wear of an SLC. In [5], a computer program module was developed that allows simulating the contact interaction of rough surfaces under conditions of elastic and elastoplastic contact, including in the case of SLCs. The experimental data obtained in [6] on the study of the dependence of the wear rate on nominal pressure for VNIINP-212, VNIINP-230, and EONIT-3 SLCs (1st coating phenol-formaldehyde resin + MoS2; 2nd coating epoxy resin + MoS2; 3rd coating modified aminoimide resin + MoS2 + graphite) are presented in Fig. 1. A computer simulation of the quasistatic contact interaction of the equivalent tribo-conjugation model was carried out. In the modeling process for the given loads, the total number of protrusions that came into contact was determined, n_c, and the number of contacting irregu-

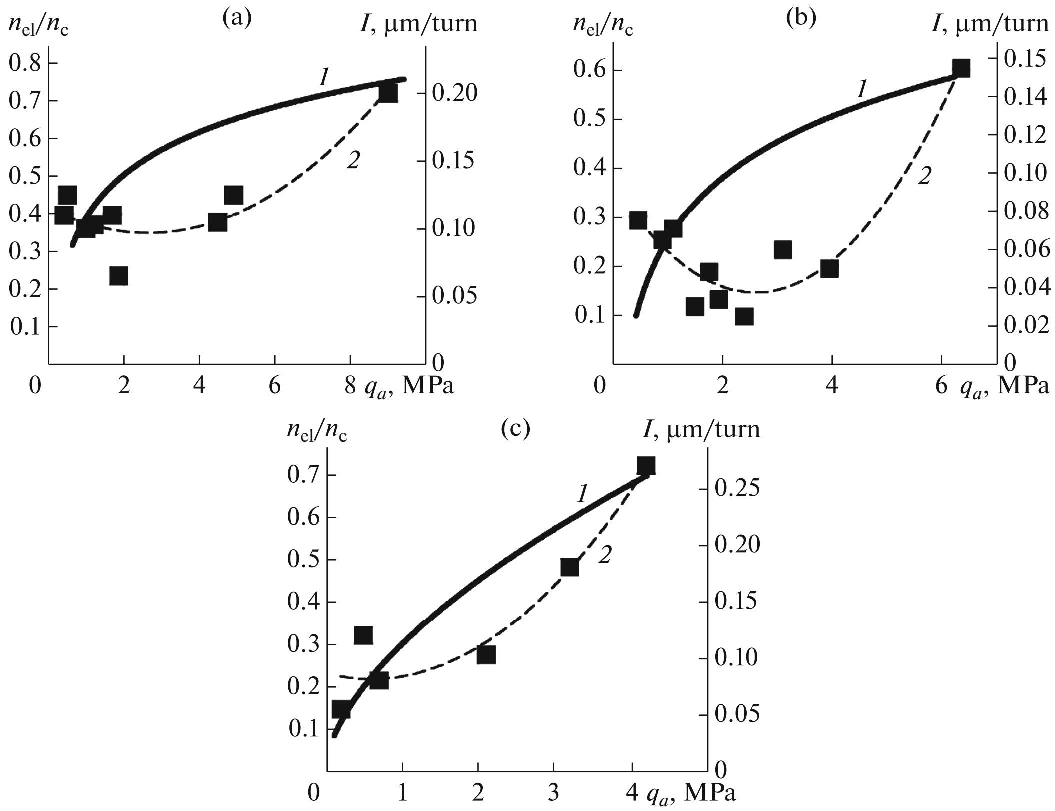

Fig. 1. Comparison of experimental research data on the effect of the load on the wear rate of the SLC with the results of computer simulation ((*1*) relations n_{ep}/n_c for subjects; (*2*) experimental dependences of the wear rate of the SLC on pressure, approximated by a polynomial dependence of the 2nd degree): (a) VNIINP-212; (b) VNIINP-230; (c) EONIT-3.

larities for which the deformation of the SLC has passed from elastic to elastoplastic, n_{el}. Modeling was carried out using microgeometry parameters of the worked-in samples [6], while for all coatings the thickness was taken equal to 0.007 mm, which is typical for friction pairs with SLCs after running-in. In the calculations the following mechanical properties of SLCs were used: VNIINP-212; J_1 = 0.00034 MPa^{-1}, HV_1 = 220 MPa; VNIINP-230 J_1 = 0.00031 MPa^{-1}, HV_1 = 280 MPa; and EONIT-3 J_1 = 0.00068 MPa^{-1}, HV_1 = 140 MPa, where $J_1 = (1-\mu_1^2)/E_1$.

RESULTS AND DISCUSSION

As can be seen from the presented results, all lines *2* (Fig. 1) have minima. For VNIINP-212, the minimum wear rate coincides with the load at which n_{el}/n_c ~ 0.6, and for VNIINP-230 and EONIT-3, n_{el}/n_c ~ 0.47 and n_{el}/n_c ~ 0.3, respectively.

A further increase in the share of microroughnesses of elastically-plastically deforming SLCs is accompanied by a significant increase in wear intensity. The extreme nature of the dependence of the wear rate on the load and n_{el}/n_c is explained by the following. At relatively low loads there is a large proportion of microroughness contacts in the case of elastic deformations of the coating. In this case [7, 8], the main mechanism is fatigue wear realized in the form of separation of wear particles due to the development of microcracks in the subsurface layers of rubbing bodies. An increase in the load leads to an increase in the fraction of microroughnesses in contact under the conditions of nucleation of elastoplastic deformations, the development of zones of which in the regions of the formed microcracks, leads to their healing and a decrease in the wear rate [9]. A further increase in the load, as follows from the results of computer simulation, leads to the formation of a saturated contact [8, 10], as a result of which the growth in the number of new microcontacts slows down, and the main compensation for the increasing load occurs due to an increase in the actual area and the further introduction of microirregularities that have already come into contact. When plastic deformations reach the surface of microcontacts, plastic displacement of the material begins [8] and, as a consequence, the observed increase in the wear rate.

The conducted studies allow us to draw the following conclusions. Acceleration of friction pair tests with SLCs due to load acceleration does not always give the

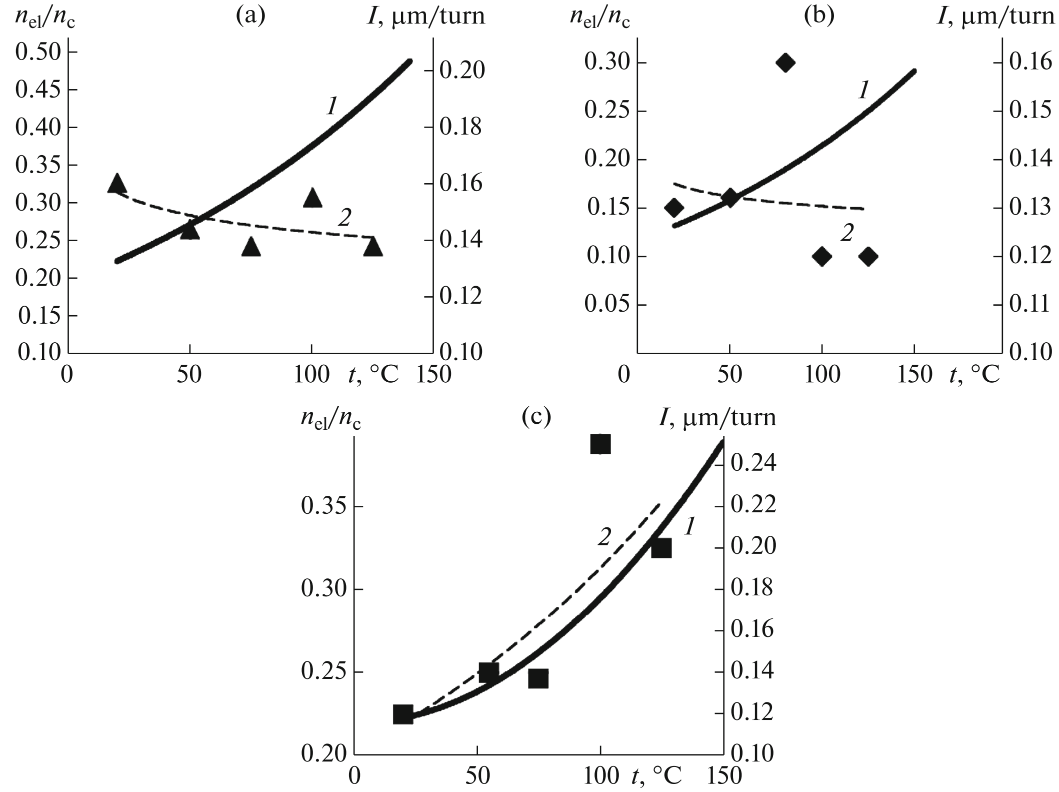

Fig. 2. Comparison of data from experimental studies of the effect of temperature on the wear rate of SLCs with the results of computer simulation ((*1*) results of computer modeling; (*2*) experimental dependencies approximated by 2nd degree polynomial dependence): (a) VNIINP-212; (b) VNIINP-230; (c) EONIT-3.

necessary effect and meets the requirements [2]. In the case when the operational load is in the zone of predominantly elastic deformations of microroughnesses, with its increase, the wear rate of SLCs decreases and the test is not accelerated. If the operating loads for the tribo-coupling with the SLC under consideration exceed values n_{el}/n_c typical for minimum wear rate, acceleration of tests due to load forcing is effective and meets the criteria of the standard. For all SLC examined, the minimum wear rate corresponds to the loads at which $n_{el}/n_c \sim 0.3–0.6$. This corresponds to the maximum durability of friction pairs with the studied SLC and should be considered when calculating the contact pressures of high-resource friction units with such coatings.

Another mode that accelerates the life tests of friction pairs is the ambient temperature. The effect of temperature on changes in the frictional contact characteristics can be considered by a change in the physicomechanical properties of interacting surfaces [8, 10]. In computer modeling, the characteristics of a quasistatic elastoplastic contact are determined by the elastic and plastic properties of interacting rough surfaces [11].

Based on experimental studies [11] temperature dependences of the elastic constant and microhardness were proposed for composite SLCs with polymer binders in the form of:

$$J_1(\theta) = J_0 e^{C_1\theta}, \quad (1)$$

$$HV_1(\theta) = HV_0 e^{-C_2\theta}. \quad (2)$$

Considering (1) and (2), the computer program [5] modeling the contact interaction of rough surfaces with SLCs was finalized. Its modernization made it possible to carry out numerical experiments to study the quasistatic contact interaction of tribo-coupled models with SLCs considering the influence of ambient temperature. The parameters of the temperature dependences of the mechanical properties of SLCa during computer simulation are presented in Table 1.

The experimental data [6] on the study of the dependence of the wear rate on the ambient temperature for VNIINP-212, VNIINP-230, and EONIT-3 are presented in Fig. 2.

Also, as in the case of studying the influence of the load as a result of computer simulation, the ratio is n_{el}/n_c. As can be seen from the presented results, the experimental temperature dependences of the wear rate of SLCs on the materials under consideration are of a different nature. So, in the studied temperature

Table 1. Parameters of temperature dependence of the mechanical properties of SLCs

SLC Brand	J_0, MPa^{-1}	HV_0, MPa	T_{lc}, K	T_{uc}, K	C_1	C_2
VNIINP-212	0.00018	550	153	473	1.7	2.1
VNIINP-230	0.00021	530	163	583	1.7	2.1
EONIT-3	0.00055	210	183	723	1.7	2.1

range, the wear rate of VNIINP-212 and VNIINP-230, considering the statistical spread of the experimental data, does not change significantly, and for EONIT-3, an increase with increasing temperature is observed.

The results of computer simulation (solid lines in Fig. 2) show that in this temperature range under a load of 0.43 MPa for VNIINP-212, n_{el}/n_c varies from 0.23 to 0.5, and for VNIINP-230, from 0.12 to 0.28.

This corresponds to relatively constant values of wear rate (Figs. 1a, 1b) with a predominance of elastic deformations of the SLC in the zones of actual contact. At the same time, for SLC EONIT-3, the proportion of such microirregularities increases from 0.22 to 0.38, which corresponds to the region of increase in the wear rate of this coating (Fig. 1c). An analysis of the obtained data shows that the influence of temperature on the wear mechanism of specific HSPs is determined by the parameters of the temperature dependence of their mechanical properties (Table 1), which are included in dependences (1) and (2).

CONCLUSIONS

Acceleration of friction pairs tests with SLCs due to a rise in temperature as well as in the case of load forcing, do not always meet the requirements [2]. When an increase in temperature does not lead to an excess of ratio n_{el}/n_c there are no test acceleration values that are optimal for these SLC materials. If an increase in temperature for the considered friction pair with an SLC leads to the fact that ratio n_{el}/n_c exceeds the optimal values, acceleration of tests due to temperature increase corresponds to [2].

Numerical experiments carried out using a computer model [5] made it possible to obtain data on the fraction of microcontacts of interacting rough surfaces, which determines the multiple transition from predominantly elastic and elastoplastic deformation of SLCs to predominantly elastoplastic and plastic ones. It is shown that the value of this fraction determines the necessary conditions under which the forcing of modes leads to the acceleration of tests. For a preliminary assessment of the modes of accelerated testing of friction pairs with SLCs having polymer binders of other types as the optimal value of ratio n_{el}/n_c you can use the average value for the studies carried out equal to 0.45.

NOTATIONS

J_1	elastic constant of SLCs under normal climatic conditions
μ_1	Poisson ratio of SLCs under normal climatic conditions
E_1	elastic modulus of SLCs under normal climatic conditions
$\theta = (T - T_{lc})/(T_{uc} - T_{lc})$	relative temperature
C_1, C_2	coefficients of the phenomenological model of SLCs
J_0	value of elastic constant of SLCs at $\theta = 0$
$J_1(\theta)$	elastic constant of SLCs at relative temperature θ
n_{ep}	the number of contacting microroughnesses for which the deformation of the SLC has passed from elastic to elastoplastic
n_c	total number of protrusions in contact
T	current temperature, K
T_{lc}	lower characteristic temperature of SLCs (glass transition temperature of polymer binder, lowest permissible operating temperature of SLCs), K
T_{uc}	upper characteristic temperature of SLCs (temperature of melting or thermochemical decomposition of polymer binder, upper permissible operating temperature of SLCs), K
HV_1	microhardness of SLCs under normal climatic conditions
HV_0	microhardness of SLCs at $\theta = 0$
$HV_1(\theta)$	microhardness of SLCs at relative temperature θ

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