MODEL OF ACCUMULATION OF TRIBO DAMAGE IN HIGH-SPEED FRICTION

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Abstract: A model of the wear of bodies at high friction speeds in a probabilistic setting is proposed. The model is based on the thermokinetic theory of destruction of materials. The identification of the parameters of the wear models was carried out taking into account the random nature of the influencing factors. The model is presented in discrete form and adapted for numerical simulation using a step-by-step discrete calculation algorithm. As a result, it was found that the stress state of the surface layer of the parts of the tribosystem and, accordingly, wear significantly depend on the kinetics of the change in the coefficient of sliding friction during the transition from static to dynamic loading. It is proposed to use the kinetics of variation of the coefficient of friction to assess the effectiveness of using methods to increase the durability of tribosystems under conditions of high sliding speeds. As a result of the presented studies, a laboratory experiment was conducted to study the influence of the friction coefficient and relative sliding speed on the wear processes of samples from various materials. Experimental data confirm that the coefficient of change of the coefficient of friction is sensitive to the technology of formation of the surface layer.

Keywords: surface of friction, markov chain, tribological damage, computer simulation, laboratory test.

1. INTRODUCTION

Calculation methods for analyzing the durability of tribosystems are preferred in conditions of extreme force and speed impacts. At the same time, experimental studies are difficult to implement and expensive. At the same time, modeling the behavior of tribosystems at high friction speeds is also a difficult problem. It is due to insufficient knowledge of the processes on the surfaces of the tribosystem interaction, the probabilistic nature of external influences, and the influence of the operating conditions of the tribosystems. Thus, the stress state of the surface layer of parts of friction units requires taking into account dynamic processes caused by the tightening of speed characteristics. The dependence of the coefficient of friction on the relative sliding velocity in the mechanism should be used as a basic criterion. When developing analysis methods, it is necessary to take into account that wear is a probabilistic process depending on a set of random factors. Based on the features of the functioning of high-speed friction units, in most cases, computer simulation methods are used to analyze the influence of the most significant factors on wear processes. These methods involve the

2. LITERATURE REVIEW

When creating wear models for tribosystems at elevated sliding speeds, a number of features of the friction process are taken into account. They arise due to the relative displacement of parts of the friction system with sliding speeds of more than 80...100 m s⁻¹. First, there is a significant decrease in the friction characteristics for all pairs of contacting materials. is noted in [1, 2]. In [2], the results of experimental studies of high-speed steel-steel friction are presented, which show that the friction coefficient in this case can decrease to values of 0.0001. The determinants of the wear of elements of high-speed friction units [3–7] are the stress state, its dynamic nature and temperature effects. Wear of

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surfaces, as a result of the summation of tribological damage, belongs to the class of cumulative
damage. As a result of statistical processing of experimental data, the authors of [8, 9] analyzed
probabilistic models of the phenomenological processes of damage accumulation. It is shown that
models based on random processes (Markov’s chains with discrete time and states) adequately
characterize the processes of cumulative damage.

3. BUILDING A WEAR MODEL AND IDENTIFICATION PARAMETERS

The first stage of building the model was the task of discretization of the wear process. Using the
impact model [8, 9], the wear process is considered in discrete form. Assumptions were made to build
the wear model.

1. The elements of the friction unit come into tribological contact with a given frequency, called the
loading cycle. During the loading cycle, wear of the elements can occur, as a result of the
accumulation of damage in the layers of contact interaction. For such a system, it is possible to
determine the time of the frictional contact using the time periods of the actual contact, that is, the total
amount of time of the loading cycles. Thus, time in the tribological system under consideration is a
discrete quantity.

2. Experimental studies of physical processes during wear indicate that the accumulation of damage in
microvolumes during tribocontact interaction is discontinuous. The process of phased destruction of
the friction layer is considered as the transition of the tribosystem from one state to another. Then the
states of the system can be interpreted as periodic and transitional, that is, having a discrete character.

3. Due to the small time of the loading cycle, it is assumed that the characteristics that determine the
conditions of the wear process remain unchanged. Accordingly, the wear of the tribosystem is
determined by the values at the beginning and end of the loading period. Thus, the condition of the
Markov process is satisfied.

4. To determine the probabilistic characteristics of the wear process, it is assumed that damage can
occur only during the loading cycle. We denote \( w_{ii} \) is the probability that damage will not occur during
the loading cycle. Then the probability of occurrence of damage in this cycle is \( 1 - w_{ii} \), since the
events form a complete group. If the amount of wear exceeds a critical level, the system will go into
the internal state with a probability of exit from it equal to zero.

Thus, a model of the wear of the tribosystem is proposed, which is described by the Markov
probabilistic process with discrete states and time. The discrete model is embedded in the continuous
physical wear process. The parameters of the Markov chain are set if the vector of initial states is
determined and the values of the transition probabilities in the form of a matrix are given. The
components of the initial state vector \( \pi_i(t = 0) \), are determined based on the fact that at the beginning
the system had no damage and was in the first state:

\[
[\pi_i(t = 0)] = [1, 0, 0, \ldots, 0]
\]

In subsequent times \( t > 1 \) the probabilities of the states of the tribosystem were calculated as the
multiplication of the probability vector of unconditional transitions and the transition probability
matrix \( [W_{ij}] \) for the behavior of the tribosystem at time \( t \):

\[
[\pi_j(t)] = [\pi_j(t-1)] [W_{ij}], \quad i, j = 1, 2, \ldots, K_i
\]

where \([\pi_j(t-1)]\) is the vector of unconditional probabilities of finding the tribosystem in \( i \) - states
\((i, j = 1, 2, \ldots, K_{ij})\) at time \((t-1)\);

\( K_i \) is the quantity of system states.
The transition probability matrix is given if the form is given and the components of the matrix are determined.

The authors [8, 9] showed that the matrix of transition states with single jumps and the presence of an absorbing state most fully reflects the process of summing tribo damage. The components of the transition probability matrix were determined by the correspondence between the parameters of the numerical model and the physical parameters of the wear process at high friction speeds. Based on the physical model of the wear, it was assumed system transitions between successive states occur under the influence of the wear flow. When the wear flow event is implemented, the system transitions to the next state. In this case, the wear flow event is understood as wear by a certain value of \( h \). The wear flow, according to the central limit theorem of flows, will be Poisson. That is, it has the properties of ordinariness and absence after action, which does not violate the basic requirement of the Markov random process. Based on physical principles, the flux intensity \( \lambda(t) \) is the average number of transitions per unit time. For the elementary region \( \Delta t \) adjacent to \( t \) [11], the intensity of the wear flow \( \dot{\lambda}(t) \) at time \( t \) is defined as the wear rate at time divided by \( h \).

\[
\dot{\lambda}(t) = \frac{V(t)}{h}, \quad \text{[1/time]},
\]

where \( V(t) \) is the wear rate at time \( t \); \( h \) is the flow ordinary parameter and having the dimension of length, mass or volume, depending on what wear rate is used.

The wear parameter \( h \) is selected from the following conditions. In one loading cycle, the probability of a wear greater than value \( h \) is very small. To assess the wear rate \( V(t) \), the thermokinetic theory [10] is used, which makes it possible to study the combined effect of the stress state and temperature effects on tribological fracture. The durability of the loaded sample of material in accordance with to [9]:

\[
\tau = \tau_0 \exp \left( \frac{U_0 - \gamma \sigma}{kT} \right),
\]

In [12], this dependence was specified with respect to taking into account the influence of the external environment in overcoming the energy barrier. Further, replacing the Boltzmann constant \( R \) with the gas constant, we obtain:

\[
\tau = \tau_0 \exp \left( \frac{U_0 - \gamma \sigma \pm \Delta G}{RT} \right),
\]

where \( \tau_0 \) is the constant of time (the period of vibration of atoms in the body \( 10^{-13} \ldots 10^{-12} \) s); \( T \) is the medium temperature, K; \( U_0 \) is the activation energy of the leading mechanism of destruction, J/mol; \( \gamma \) is a structurally sensitive coefficient; \( \sigma \) is the load;

\( \Delta G \) is the coefficient taking into account the influence of the external environment (\( \Delta G < 0 \) – the environment softens the layer, \( \Delta G > 0 \) – strengthens, and \( \Delta G = 0 \) – has a neutral effect).

Considering the cyclicity of the loads, we represent the durability \( \tau \) through the number of loading cycle \( N \) and the actual loading time per cycle \( t_c \). We isolate the term \( \sigma \gamma \) from the expression, which reflects that the proportion of work that an external action does when the layer is destroyed:

\[
\sigma \gamma = U_0 - R \ln \left( \frac{N \cdot t_c}{\tau_0} \right) \pm \Delta G.
\]

If we assume that the specific work of the friction acts as the work of external forces, then we have:
where \( V_w \) is the volume of the wear layer, mol.

Given that \( A_f = F_f L_s = f \cdot F_N \cdot L_s \), \( V_w = (A_n \cdot h_w)/M \) and what attitude \( F_N / A_n \) represents contact pressure \( \sigma_N \) we have:

\[
\sigma_N = \left( \frac{f \cdot \sigma_N \cdot L_s \cdot M}{h_w} \right),
\]

(8)

where \( f \) is the friction coefficient; \( F_N \) is the normal force, N; \( L_s \) is the path of friction, m; \( M \) is the volume, m\(^3\)/mol; \( A_n \) is the area of nominal contact of surfaces, m\(^2\); \( h_w \) is the thickness of the wear, m.

We accept the Coulomb-Amonton friction model taking into account the Shribek effect,

\[
f = f_d + (f_s - f_d) \cdot \exp(-\beta v_s).
\]

Where \( f_d \) is the dynamic coefficient of friction; \( f_s \) is the static coefficient of friction; \( v_s \) is the relative slip velocity at the contact point; \( \beta \) is the coefficient.

This model takes into account variation of the coefficient of friction as a function of sliding speed. Based on the kinetic theory of destruction, durability is a fundamental characteristic of the strength of the material. It can be considered as a value that proportional to the average rate of the wear process:

\[
\tau = \frac{1}{hT} \exp \left( \frac{U_0 - \left[ \sigma_N(x, y, z, t) \cdot h_w \cdot (f_d + (f_s - f_d) \cdot e^{-\beta v_s}) \right]}{RT(x, y, z, t)} \right) \pm \Delta G,
\]

(9)

where \( V_i(x, y, z, t) \); \( \sigma_N(x, y, z, t) \); \( T(x, y, z, t) \) are the wear rate, contact pressures and contact temperature at the point with coordinates \((x, y, z)\) at time \( t \).

Thus, through the function of the wear rate, we can determine the main characteristic of the wear flow, represented in the form of a Markov chain – the wear flow intensity \( \lambda_i(t) \) as the transitions of the system between the states.

The probability of the transition \( w_{ij}(t) \) of the Markov chain from state \( i \) in which it was at time \( t \) to state \( j \) for an elementary time interval \( \Delta t \) is determined from the expression: \( w_{ij}(t) \approx \lambda_i(t)\Delta t \) for \( i \neq j \) as \( 0 \leq w_{ij} \leq 1 \); \( \lambda_i(t)\Delta t \leq 1 \); \( 0 \leq \Delta t \leq 1/\lambda_i \).

Obviously, the smaller \( \Delta t \), than the more accurately the transition probability of the system from state to state is determined. Thus, based on a probabilistic physical concept, the parameters of the surface wear model under high-speed friction are obtained, which is described by a random Markov process with discrete characteristics. The obtained model indicates that in estimating the wear of the layer, a significant role is played by the coefficient \( \Delta G \), which takes into account the influence of the external environment. If \( C < 0 \) – the external environment increases the wear rate of the layer, \( \Delta G > 0 \) – reduces the wear rate of the layer, and \( \Delta G = 0 \) – has a neutral effect. In the case of wear, the coefficient \( \Delta G \) can be seen as a coefficient that takes into account the technology of formation of the surface layer and
its effect on the energy of activation of layer destruction processes. The proposed phenomenological model makes it possible to isolate and combine the main factors, distinguish their relationships and analyze the degree of influence on the wear of friction surfaces under conditions of high sliding velocity. An analysis of the obtained dependences shows that an increase in the sliding velocity, according to (9), leads to a decrease in the coefficient of friction in the contact area. However, the degree of influence will substantially depend on the value of the coefficient β. An increase in the sliding velocity will lead to an increase the dynamic loads and temperature in the contact zone, and, accordingly, to a decrease in the activation energy and an increase in destructive processes in the layer. At the same time the weight coefficients at the indicated factors, contact pressures and temperature will have the prevailing effect from the wear of surfaces. Using the presented model, it was possible to carry out a number of studies aimed at assessing the degree of influence of key factors on processes under high-speed friction. To confirm the conclusions drawn from the analysis of the model, an experimental analysis of the effect of changes in the coefficient of friction on the sliding velocity on the wear processes under conditions of high friction speed was carried out.

4. RESULTS OF EXPERIMENTAL STUDIES OF WEAR UNDER CONDITIONS OF HIGH-SPEED FRICTION

The tests were carried out on a UMT–1 friction machine according to the disk – pin scheme (Fig. 1) with a maximum sliding speed of 60 m s⁻¹. A disk made of Steel 5140 with a diameter of 400 mm was used as a counter sample. The friction coefficient was determined by the moment of friction, which was fixed by the potentiometer of the friction machine for sliding speeds respectively 5; 10; 20; 40; 60 m s⁻¹. Samples modified by various methods of chemical-thermal treatment were tested.

![Figure 1. The laboratory test scheme.](image-url)

The experimental values of the friction coefficients for various slip velocities are presented in the Table 1.

<table>
<thead>
<tr>
<th>Material</th>
<th>Sliding speed, m s⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>A414 Grade A – Nitriding (N)</td>
<td>0.2 0.1 0.065 0.04 0.03</td>
</tr>
<tr>
<td>Steel 5140 – Nitriding (N)</td>
<td>0.2 0.088 0.058 0.035 0.026</td>
</tr>
<tr>
<td>A414 Grade A – Chemical-thermal treatment (CTT)</td>
<td>0.22 0.083 0.053 0.03 0.022</td>
</tr>
<tr>
<td>Steel 5120 – Nitro carbonization (NC)</td>
<td>0.22 0.07 0.04 0.028 0.024</td>
</tr>
<tr>
<td>Steel 5140 – Chemical-thermal treatment (CTT)</td>
<td>0.2 0.1 0.065 0.04 0.03</td>
</tr>
</tbody>
</table>

A graphical interpretation of the test results is presented in Figure 2.
An analysis of the results indicates that in the entire range of the studied sliding velocities with increasing speed, a decrease in the coefficient of friction is observed from 0.2 (boundary, semidry friction) to 0.02 (friction through a liquid film). For some materials (Steel 5140 (CTT), Steel 5120 (NC)) stabilization of low values of the coefficient of friction takes place, starting from speeds of 40...50 m s⁻¹. Experimental data confirm the conclusion that the coefficient taking into account the rate of change of the coefficient of friction is sensitive to the technology of formation of the surface layer. This, in turn, recommends that the coefficient β be used as a numerical criterion for evaluating the effectiveness of methods for increasing wear resistance at high sliding speeds.

4. CONCLUSIONS

1. A model of the wear process under conditions of high-speed friction is constructed. The model is based on the thermokinetic theory of fracture. It made it possible to unite the main factors and analyze their degree of influence on the wear of units operating in conditions of high sliding speed.

2. A generalized analysis of the results showed that the prevailing factor that affects the stress-strain state of the studied tribosystem and, accordingly, the wear processes, is the rate of decrease of the coefficient of friction.

3. As a criterion for evaluating the effectiveness of the use of materials, technological processes of coating, heat treatment, and other ways to increase the resistance of tribosystems in conditions of high-speed sliding, the rate of change of the friction coefficient can be used. In this case, the coefficient β is taken as a quantitative assessment of the criterion.

REFERENCES