







Dissipative function of the tribosystem justification of significant parameters

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ABSTRACT

The paper presents a methodical approach to the study of the dissipative function of the tribosystem. The significant parameters of the friction process are determined and the dependences of the stress on the actual contact spots, the rate of deformation of the materials of the friction surfaces, the deformable volume of the material of the friction surfaces when changing the design, technological and operational factors are presented. It was established that the greatest contribution is made by the average arithmetic deviation of the points of the profile of the friction surfaces and the average step of unevenness along the center line, and then by the physical and mechanical properties of triboelement materials (modulus of elasticity and Poisson's ratio). The obtained dependences of the influence of significant parameters of the friction process in tribosystems will allow to determine the distribution of the dissipation rate between moving and stationary triboelements, which will be shown in the second part of the paper. The work will be devoted to the calculation of the dissipative function of the tribosystem and the establishment of a correlation relationship between the specified function and the wear rate and the friction coefficient.

Keywords: tribosystem, dissipative function, modeling, wear rate, friction force, actual contact area, dissipation rate, surface roughness.

INTRODUCTION

Recently, methods of calculation and modeling of friction and wear processes in tribosystems of machines and mechanisms have been actively developed, which allows to significantly reduce costs in the process of designing and finalizing new designs. The difficulties that arise in the development of such models are associated with the selection of parameters that affect the process under study.

Due to the roughness of the friction surfaces, contact of solid bodies is carried out discretely, in separate zones – actual contact spots (ACS). As a

rule, ACSs are formed when the peaks of irregularities come into contact, and the total contact area consists of many such microcontact zones.

The size of the ACS, as well as the size and shape of single contact spots, significantly affect the processes of friction and wear, because determine the stress-strain state in the surface layers of the contacted materials and form the thickness of the layer of the deformable material with a non-uniform distribution of stresses and strains. At a certain distance from the friction surface, the stresses decrease significantly, and at a certain depth their distribution becomes almost uniform.

The amount of stress in the material and the rate of deformation in the surface layers of materials on the ACS affect the “loading” of triboelements in the tribosystem, which can be estimated by the rate of dissipation. Dissipation work speed is an energy parameter and characterizes the speed of mechanical energy transformation processes, mainly into heat and other types of energy, which can be represented as a dissipative function of the tribosystem.

Therefore, when developing models for predicting the rate of wear and friction losses, it is necessary to take into account the energy parameters included in the dissipative function, which is related to the characteristics of the actual contact area, the physical and mechanical properties of the triboelement materials, and the tribological properties of the lubricating medium.

This work is the first part of the research on the dissipative function of the tribosystem and is aimed at determining the significant parameters of the friction process, which are the basis for calculating the rate of dissipation in tribosystems.

In the works of Ziegler [1–3] the derivation of the defining relations of the free energy and the dissipation function of the mechanical system is presented. Under the accepted assumptions that the simplest materials considered in the mechanics of continuous media are considered elastic, and the processes occurring in the materials are irreversible, the author introduced the dissipative function of the mechanical system. The dissipative function is related to the speed of dissipation in the mechanical system and depends on the stress and the rate of deformation. The author obtained expressions for calculating the rate of dissipation in a mechanical system. In our opinion, such a methodological approach can be applied to the development of the dissipative function of the tribosystem as an open mechanical system where irreversible processes take place.

To determine the speed of dissipation in a mechanical system [1–3], it is necessary to know the amount of stress on the elements of the system and the rate of deformation of the material in the system. For the tribosystem, these are the voltages on the spots of actual contact and the rate of deformation of the surface layer of the material of the triboelement on the spots of actual contact, taking into account the volume of the material involved in the deformation [21].

The importance of taking into account the size of the actual contact area is indicated by the

authors of the work [4]. In work [5] it is proposed to consider the contact of roughness’s both on the material and on the energy levels. The paper discusses the fundamentals of the energy process and models for experimental studies of bulk materials. In work [6], a contact model of a single unevenness was developed for the loading-unloading cycle taking into account friction. Expressions were obtained that show the relationship between the contact load and the actual contact area in the loading and unloading processes at different stages of deformation of three-dimensional spherical contact surfaces.

The works [9-11] are devoted to modeling the actual contact area. Modeling of the actual area and contact is performed taking into account the forces acting between the friction surfaces. First of all, contact models with one roughness are considered. These models include simple Hertz contacts. For example, in work [11] finite element models (FEM) are used to calculate the real contact area (RCA) of rough surfaces during friction, which, according to the authors, plays a key role in mechanical contacts.

Modeling of the actual contact area and the correlation of this parameter with voltages in the contact are presented in works [15–17]. The authors of the work [15] established that the mean and square deviation of the force friction can be used to determine the number of contact areas. Numerical experiments are presented in the work [16], where the values characterizing the contact, for example, the radius of a single contact, the contact area, and the contact voltage, are presented. These studies allowed the authors to develop a model of frictional elastoplastic contact of spherical roughness’s, which is used in modeling and the paper [17] presents the concept of estimating the stress that occurs on the spots of actual contact, taking into account the roughness of the friction surfaces obtained after mechanical processing. Stress assessment is performed for different applied loads and different types of materials. Examples of the correlation of the stress value with wear in practice are given.

From the analysis of the works devoted to the influence of the size of the actual contact area on the processes of friction and wear, it is possible to draw a conclusion about the correlation of this parameter with the amount of tension in the contact. The amount of stress on the spots of actual contact, which depends on the roughness of the surface and the physical and mechanical

properties of the material, will allow us to estimate the “load” of the tribosystem.

The works [18–21] are devoted to the study of the deformation of the surface layers of materials during friction. In work [18] load bearing contact between sliding solid bodies was studied and strain hardening curves were obtained. The hardened surface layers were studied using X-rays, optical and electron microscopy. The authors conclude that it is possible to determine the coefficient of friction and the hardness of the material on the actual contact spots using the slander curve. The fact of amorphization of metal on worn friction surfaces was established.

The authors of the work [19] it is concluded that the value of the actual contact area is 1% of the nominal area. It was established that the mechanical behavior of the material at the contact spots is determined by the usual dislocation structure. Deformations of materials remain elastic if the local pressure does not reach the hardness of a softer material. Small roughness values promote elastic deformation.

In works [20, 21], it is shown that the stationary process of friction is characterized by a balance between hardening and relaxation of dislocations in deformed surface layers and a balance between deformation and destruction due to the formation of wear particles. The authors, on the basis of the analysis of the dislocation structure of highly deformed surface layers, established that the contacts of irregularities provide plastic deformation of the surface layers first. However, after a change in the roughness of the friction surface, the plastic deformation turns into an elastic one. This leads to qualitative changes in the distribution of local pressures in the contact and the size of the holes contact areas [21]. In work [21], numerical experiments are presented to investigate the influence of roughness parameters on the magnitudes of stress and deformations on spots of actual contact. The paper presents a model of frictional elastoplastic contact of spherical bodies, which is used in modeling.

The presented review of works devoted to the deformation of surface layers during friction allows us to conclude that such parameters as the rate of deformation of the material and the depth of the spread of deformation on the spots of actual contact are significant and allow determining the rate of dissipation in the tribosystem.

By summarizing the analysis of publications devoted to such parameters of the friction process

as the actual contact area of rough surfaces, stresses on the contact areas, the rate of deformation of the material of the surface layer and the depth of deformation of the material on the actual contact spots, it is possible to conclude that these parameters characterize the rate of transformation of mechanical energy into heat and other types of energy, which depend on the wear resistance of tribosystems and friction losses. The nature of the changes in the specified significant parameters are the first part of the research presented in this paper, which is the basis for determining the rate of dissipation in tribosystems.

Purpose of study

Develop a methodical approach and perform mathematical modeling to study the influence of significant parameters of the friction process when changing the roughness of the friction surfaces, physical and mechanical properties of triboelement materials, structural features of the tribosystem, as well as tribological properties of the lubricating medium.

To study the influence of significant parameters, it is necessary to perform the following stages of modeling.

1. Modeling of stress changes on spots of actual contact taking into account the roughness of the friction surfaces and the physical and mechanical properties of the surface materials.
2. Modeling of changes in the rate of deformation of materials of friction surfaces on spots of actual contact, taking into account roughness, physical and mechanical properties of materials, and sliding speed.
3. Modeling of changes in the volume of materials of friction surfaces, which is involved in deformation at the spots of actual contact, taking into account roughness, physical and mechanical properties of materials and tribological properties of the lubricating medium.

Methodical approach in conducting research

The study of the rate of dissipation in tribosystems and the establishment of its correlation with the rate of wear and the coefficient of friction are based on the basic principles of system analysis, as strategies for studying complex systems, which include tribosystems. Mathematical modeling is used as a research method, and the main principle in modeling is the decomposition of a

complex system into simpler subsystems. With this approach, the mathematical model is built according to the block principle.

MODELING THE CHANGE IN STRESS AT ACTUAL CONTACT SPOTS

The structure of the tribosystem consists of movable and fixed triboelements, lubricants and the environment, which are in constant interaction with each other.

The input parameters that influence the friction and wear process are:

1. Technological parameters - roughness parameters of contacting friction surfaces:
 - $R_{a,mov}, R_{a,fix}$ – the average arithmetic deviation of the points of the profile of the movable and fixed triboelements, m;
 - $S_{m,mov}, S_{m,fix}$ – the average step of irregularities along the middle line of the profile of the movable and fixed triboelements, m.

The parameters R and S are determined according to the ISO468:1995 standard.

2. Physical and mechanical properties of contacting materials in the tribosystem:
 - E_{mov}, E_{fix} – modulus of elasticity of the material of movable and fixed triboelements, Pa
 - ν_{mov}, ν_{fix} – Poisson’s ratio of the material of the movable and fixed triboelements.
3. Design parameters of the tribosystem:
 - F_{min} – the smaller friction area of one of the triboelements, m².
4. Operating (working) parameters:
 - N – load on the tribosystem, i.e. triboelement pressing force, N;
 - $\sigma_n = N/F_{min}$ – nominal voltage when contacting triboelements, Pa.

The output parameters that are modeled include:

- the area of a single actual spot of contact A_{acs} , m²;
- the number of contact spots n , pcs.;
- voltage on a single actual spot of contact σ_{acs} , Pa.

The following assumptions were made when developing the mathematical model.

1. The contact of the friction surfaces of the movable and fixed triboelements is discrete, the contact spots are evenly distributed over the nominal area of friction, the interactions of roughness protrusions are random.
2. The type of contact on a single spot is elastic. Such an assumption is made on the basis of a

number of works, which are presented in the review above, where it is stated that during the first plastic contact of roughness’s and several times of pre-deformation of the surface layer of the material due to sliding, the contact becomes elastic.

3. The temperature that is generated on the actual contact spots does not change the modulus of elasticity and Poisson’s ratio of triboelement materials. This is true for the range where no damage to the friction surfaces occurs.
4. Based on the nature of the ongoing friction and wear processes, established regimes are considered after running-in.

Limitations adopted in the development of the mathematical model.

1. The tribosystem operates in boundary lubrication mode.
2. The tribosystem operates in a load-speed range where no damage to the friction surfaces occurs, while the activation energy is sufficient for the restructuring (texturing) of the surface layers.

The method of calculating the actual contact area (ACS), which is based on the theory of random fields [20], was applied in work [21] for the case of elastic contacting of an isotropic surface. When modeling the characteristics of the ACS, the following parameters are consistently determined.

1. Average arithmetic deviation of profile points (equivalent roughness parameters [21]):

$$R_a = \sqrt{R_{a,mov}^2 + R_{a,fix}^2}, \text{ m} \tag{1}$$

the average pitch of bumps along the middle line:

$$S_m = \frac{R_a}{\sqrt{\left(\frac{R_{a,mov}}{S_{m,mov}}\right)^2 + \left(\frac{R_{a,fix}}{S_{m,fix}}\right)^2}}, \text{ m} \tag{2}$$

When performing calculations in formulas (1) and (2), the dimension - m is used.

2. The surface gradient is determined according to [21]:

$$q = \pi^2 \frac{R_a}{S_m} \tag{3}$$

3. The reduced Young’s modulus of contacting materials is determined by the expression [21]:

$$\frac{1}{E} = \frac{1-\nu_{mov}^2}{E_{mov}} + \frac{1-\nu_{fix}^2}{E_{fix}} \tag{4}$$

4. The complex of surface contact conditions according to [21] is defined by the expression:

$$K = \frac{2,22\sigma_n}{E_q} \quad (5)$$

5. Relative actual contact area according to [21]:

$$\eta = 1 - \exp(-K) \quad (6)$$

6. Actual voltage in the contact zone [21]:

$$\sigma_{acs} = \frac{\sigma_n}{\eta}, \text{ Pa} \quad (7)$$

7. The level of deformation of the material is determined according to the work [21]:

$$h = \begin{cases} 3.95 \ln(5.25 - \ln K) - 6.982, K \leq 0.6827 \\ \frac{0.422}{\ln K + 1} - 0.845, K > 0.6827 \end{cases} \quad (8)$$

8. We will determine the density of contact spots according to work [21]:

$$d_c = \frac{1}{s_m^2} \left(\frac{\pi}{2}\right)^{\frac{1}{2}} \cdot \exp\left(-\frac{h^2}{2}\right) (\sqrt{h^2 + 0.4} + h), \frac{1}{m^2} \quad (9)$$

9. The average area of a single spot of contact is determined according to [21]:

$$A_{acs} = \frac{\eta}{d_c}, m^2 \quad (10)$$

10. The average diameter of a single ACS is determined by the formula:

$$d_{acs} = \sqrt{\frac{4A_{acs}}{\pi}}, m \quad (11)$$

11. Knowing the value of the smaller friction area of one of the triboelements F_{min} and the average area of a single contact spot, formula (10), taking into account the relative actual contact area, formula (6), we determine the number of

contact spots on the smaller friction surface:

$$n = \frac{F_{min}}{A_{acs}} \quad (12)$$

Using the developed method of modeling the characteristics of the ACS of friction surfaces, it is possible to obtain the dependence of the stress change on the spots of actual contact (σ_{acs}) taking into account the roughness of the friction surfaces (R_a and S_m) of the movable and fixed triboelements, the physical and mechanical properties of the combined materials in the tribosystem (E, ν), operational parameters (N, v_{sl}), as well as design parameters of the tribosystem (F_{min}).

The results of modeling the change in stress on a single ACS (σ_{acs}) depending on the load (N) and the combination of materials in the tribosystem are presented in Figure 1. Modeling was performed for three designs of tribosystems: steel + bronze; steel + cast iron series; steel + steel.

Initial data for modeling – roughness of friction surfaces ($R_a = 0.2 \mu m, S_t = 0.4 mm$); tribological properties of the lubricating medium, according to [20], $A = 145 \cdot 10^{11} J/m^3$; sliding speed $v_{sl} = 0.5 m/s$; The load on the tribosystem varies $N = 1000-4000 N$. The kinematic scheme of the ring-ring tribosystem, the shape factor of the tribosystem, which takes into account the geometric dimensions of the triboelements $K_f = 12 m^{-1}$ [21].

Dependence of the change in tension on the unit ACS (σ_{acs}) when the roughness of the friction surfaces changes (R_a and S_m) are presented in Figure 2. Dependencies are constructed for the construction of a tribosystem with a combination

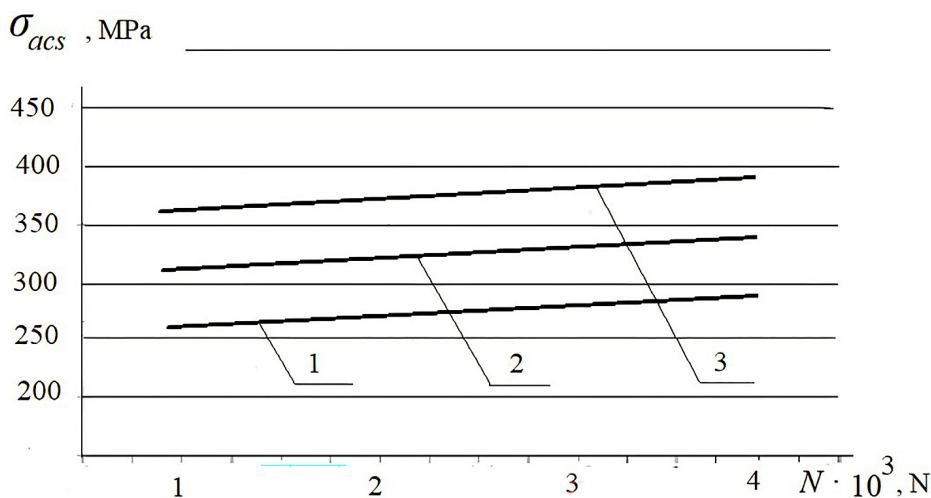


Figure 1. Dependence of the change in voltage on a single ACS (σ_{acs}) depending on the load (N) and the combination of materials in the tribosystem: 1 – steel + bronze; 2 – steel + cast iron; 3 – steel + steel

of materials: a movable triboelement with a larger friction area - steel ($E_{mov}=2.1 \cdot 10^{11}$ Pa; $\nu_{mov}=0.3$; $F_{max}=0.0003$ m²), a fixed triboelement with a smaller friction area is bronze ($E_{fix}=1.2 \cdot 10^{11}$ Pa; $\nu_{fix}=0.35$; $F_{min}=0.00015$ m²). Initial data for modeling: loading on the tribosystem $N = 2000$ N; sliding speed $v_{sl} = 0.5$ m/s; tribological properties of the lubricating medium, according to [21], $A = 145 \cdot 10^{11}$ J/m³. Kinematic diagram of the tribosystem “ring-ring”, shape factor of the tribosystem $K_f = 12$ m⁻¹ [21].

Analysis of the dependencies presented in Figure 1 and Figure 2 allows us to draw the following conclusions. The degree of influence of the load N on the value of the tension on the ACS, Figure 1, is linear in nature. At the same time, the change in the amount of stress is within the limits of $\sigma_{acs} = 260\text{--}380$ MPa, for the given design of the tribosystem and the amount of the load.

Changing the roughness parameters R_a and S_m has a greater influence on the stress value than the load parameter N , Figure 2. An increase in the R parameter from 0.2 to 0.8 μm leads to an increase in σ_{acs} by 4.3 times. Conversely, an increase in the S_m parameter from 0.2 to 0.8 mm leads to a 5-fold decrease in σ_{acs} .

Modern designs of tribosystems have a roughness of friction surfaces within the range R_a from 0.1 to 0.16 μm , with an average step of unevenness along the center line S_m equal to 0.8 mm. Based on the dependencies presented in Figure 2, it can be concluded that the stresses on a single ACS (σ_{acs}) do not exceed the yield strength of the materials from which the tribosystems are made.

From the conducted modeling of the influence of technological, physical-mechanical, structural and operational parameters on the amount of stress on the ACS, it follows that the greatest contribution is made by the average arithmetic deviation of the points of the profile of the friction surfaces R_a and the average step of unevenness along the middle line S_m , and then, physical-mechanical properties of triboelement materials (modulus of elasticity and Poisson’s ratio). An increase in R , with a simultaneous decrease in S_m , leads to a rapid increase in the voltage on the ACS.

A similar process is characteristic of an increase in the modulus of elasticity and Poisson’s ratio of the materials from which triboelements are made, Figure 1. The developed method of modeling the amount of stress on the ACS (σ_{acs}) will be included as a structural component in the general method of calculating the rate of dissipation in the tribosystem.

MODELING THE CHANGE IN THE DEFORMATION RATE OF MATERIALS AT ACTUAL CONTACT SPOTS

The rate of deformation of the material on the ACS ($\dot{\epsilon}$) of mobile and fixed triboelements, if they are made of different materials, is determined by the expressions given in the paper [21]:

For the material of the movable triboelement:

$$\dot{\epsilon}_{mov} = 75(1 + \nu_{mov})(0,86 - 1,05\nu_{mov}) \cdot \frac{\sigma_{acs} \cdot v_{sl}}{E_{mov} \cdot d_{acs}}, 1/s \quad (13)$$

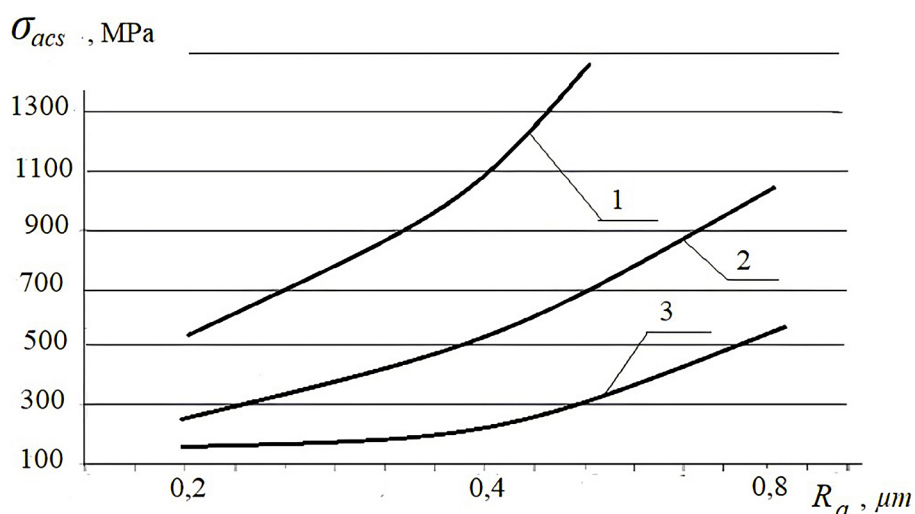


Figure 2. Dependences of the change in voltage on a unit ACS (σ_{acs}) depending on the surface roughness R_a : 1 – $S_m = 0.2$ mm; 2 – $S_m = 0.4$ mm; 3 – $S_m = 0.8$ mm

For the material of the fixed triboelement:

$$\dot{\epsilon}_{fix} = 75 \left(1 + v_{fix} \right) \left(0,86 - 1,05 v_{fix} \right) \cdot \frac{\sigma_{acs} \cdot v_{sl}}{E_{fix} \cdot d_{acs}}, \text{ 1/s} \quad (14)$$

where: v_{sl} – the sliding speed in the tribosystem, m/s, d_{acs} – the diameter of a single ACS is determined by formula (11).

The results of modeling the change in the rate of deformation on a single ACS ($\dot{\epsilon}$) depending on the speed of sliding (v_{sl}) and the combination of materials in the tribosystem are presented in Figure 3. Modeling was performed for three designs of tribosystems: steel + bronze; steel + cast iron series; steel + steel. Initial data for modeling: roughness of friction surfaces ($R_a = 0.2 \mu\text{m}$, $S_m = 0.4 \text{ mm}$); tribological properties of the lubricating medium, according to [21], $A = 145 \cdot 10^{11} \text{ J/m}^3$; the sliding speed varies $v_{sl} = 0.2\text{--}0.8 \text{ m/s}$; load on the tribosystem $N = 2000 \text{ N}$. Kinematic scheme of the tribosystem “ring-ring”, shape factor of the tribosystem $K_f = 12 \text{ m}^{-1}$ [21].

Dependencies of the change in the rate of deformation on the unit ACS ($\dot{\epsilon}$) depending on the speed of sliding (v_{sl}) when the roughness of the friction surfaces changes (R_a and S_m) are presented in Figure 4. Dependencies are constructed for the construction of a tribosystem with a combination of materials: a movable triboelement with a larger friction area – steel ($E_{mov} = 2.1 \cdot 10^{11} \text{ Pa}$; $v_{mov} = 0.3$; $F_{max} = 0.0003 \text{ m}^2$), a fixed triboelement with a smaller friction area is bronze ($E_{fix} = 1.2 \cdot 10^{11} \text{ Pa}$; $v_{fix} = 0.35$; $F_{min} = 0.00015 \text{ m}^2$). Initial data for

modeling: loading on the tribosystem $N = 2000 \text{ N}$; the sliding speed varies $v_{sl} = 0.2\text{--}0.5 \text{ m/s}$; tribological properties of the lubricating medium, according to [21], $A = 145 \cdot 10^{11} \text{ J/m}^3$. Kinematic scheme of the tribosystem “ring-ring”, shape factor of the tribosystem $K_f = 12 \text{ m}^{-1}$ [21].

Analysis of the dependencies presented in Figure 3 and Figure 4 allows us to draw the following conclusions. The degree of influence of constructive and operational factors on the magnitude of the rate of deformation of materials on ACS is linear. The change in roughness parameters (R_a and S_m), the technological factor, Figure 4, has a greater degree of influence on the deformation rate than the combination of materials in the tribosystem, the design factor, Figure 3. An increase in the R parameter from 0.2 to $0.8 \mu\text{m}$, with a simultaneous increase in the sliding speed $v_{sl} = 0.2\text{--}0.8 \text{ m/s}$, leads to a significant increase in the rate of deformation of the material on the ACS, more than 5 times.

The magnitude of the deformation rate of the material on the ACS that the roughness parameters of the friction surfaces (R_a and S_m) make the greatest contribution. An increase in R_a , with a simultaneous increase in the sliding speed v_{sl} , leads to a rapid increase in the rate of deformation of the material on the ACS.

The developed method of modeling the magnitude of the deformation rate of the material on the ACS ($\dot{\epsilon}$) in mobile and fixed triboelements will be included as a structural component in the general methodology for calculating the rate of dissipation in the tribosystem.

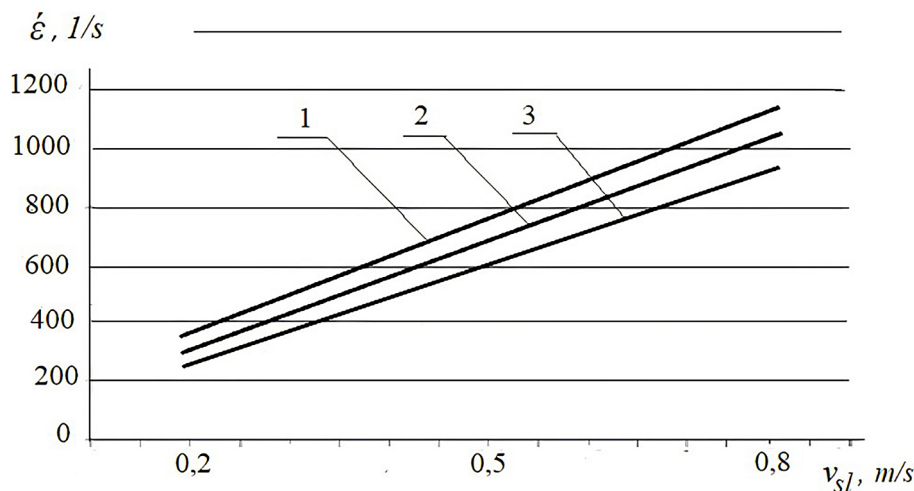


Figure 3. Dependences of the change in the rate of deformation of the material on the unit ACS ($\dot{\epsilon}$) depending on the sliding speed (v_{sl}) and the combination of materials in the tribosystem: 1 – steel + bronze; 2 – steel + cast iron; 3 – steel + steel

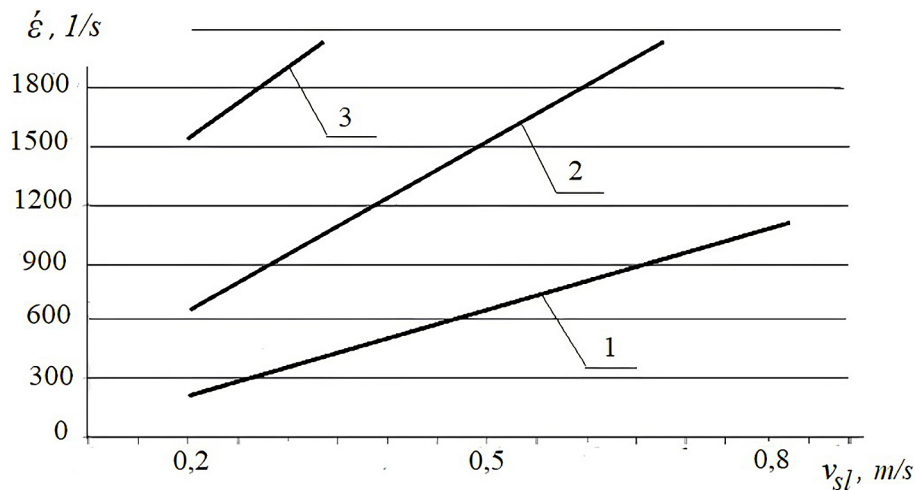


Figure 4. Dependencies of the change in the rate of deformation of materials on a unit ACS ($\dot{\epsilon}$) depending on the sliding speed (v_{sl}) and surface roughness (R_a): 1 – $R_a = 0.2 \mu\text{m}$; 2 – $R_a = 0.4 \mu\text{m}$; 3 – $R_a = 0.8 \mu\text{m}$

MODELING THE CHANGE IN THE VOLUME OF FRICTION SURFACE MATERIALS ON ACTUAL CONTACT SPOTS

The volume of the material in the previous models [21] was determined as the product of the area of a single ACS by the depth of deformation propagation h . At the same time, the depth h was assumed to be constant and equal to: $h = 0.5d_{acs}$. However, the analysis of works on the influence of the lubricant on the depth of the riveted layer in the material of the triboelement allows us to state that the depth of deformation h depends on the presence of surface-active substances in the lubricant, which can be taken into account by the integral indicator of the tribological properties of the lubricant – specific wear work $A, \text{J/m}^3$. Determination and calculation of parameter A is presented in work [21]. General experimental material on the influence of the lubricating medium on the depth of the riveted layer in work [21], the dependences for determining the depth of deformation in the material of the movable triboelement were obtained:

$$h_{mov} = 0.5d_{acs}(1 - e^{-D_{mov}}), \text{m} \quad (15)$$

in the material of the fixed tribocell:

$$h_{fix} = 0.5d_{acs}(1 - e^{-D_{fix}}), \text{m} \quad (16)$$

where: D_{mov} and D_{fix} are coefficients that take into account the ability of the material to deform under the action of surface-active substances, for materials of movable and fixed triboelements, respectively.

Based on the experimental data presented in [21], we obtained expressions for calculating the coefficients D_{mov} and D_{fix} :

$$D_{mov} = \frac{1.82 \cdot 10^7 \sigma_{acs}^2}{E_{mov} \cdot A} \quad (17)$$

$$D_{fix} = \frac{1.82 \cdot 10^7 \sigma_{acs}^2}{E_{fix} \cdot A} \quad (18)$$

The coefficients D_{mov} and D_{fix} are dimensionless. On the basis of the obtained expressions (17) and (18), modeling of the volume (V_d) of the material of the friction surface, which is involved in the deformation at the spots of the actual contact, taking into account the roughness, physical and mechanical properties of the materials, and tribological properties of the lubricating medium, was performed.

For a movable tribocell:

$$V_{d,mov} = h_{mov} \cdot A_{acs}, \text{m}^3 \quad (19)$$

For a fixed tribocell:

$$V_{d,fix} = h_{fix} \cdot A_{acs}, \text{m}^3 \quad (20)$$

The modeling results are presented in Figure 5 and Figure 6. The initial value of the depth of deformation based on the work [21] is taken to be $0.5d_{acs}$. Modeling was performed for a fixed triboelement of three designs of tribosystems: steel + bronze; steel + cast iron series; steel + steel. Initial data for modeling: roughness of the friction surfaces $R_a = 0.2 \mu\text{m}$, $S_m = 0.4 \text{mm}$; tribological properties of the lubricating medium vary: $A = 67 \cdot 10^{11} - 212 \cdot 10^{11} \text{J/m}^3$; sliding speed $v_{sl} = 0.5 \text{m/s}$;

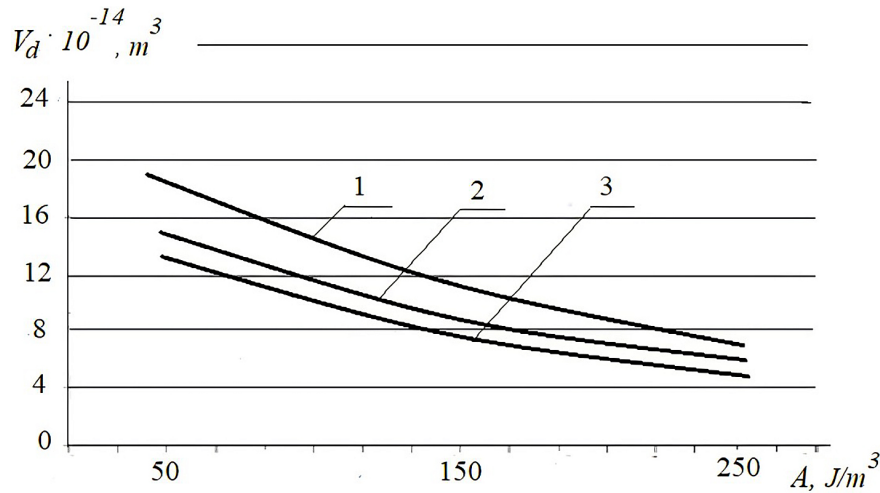


Figure 5. Dependencies of the change in the value of the deformed volume of the material of the fixed triboelement on the unit ACS (V_d) depending on the tribological properties of the lubricating medium (A): 1 – bronze; 2 – gray cast iron; 3 – steel

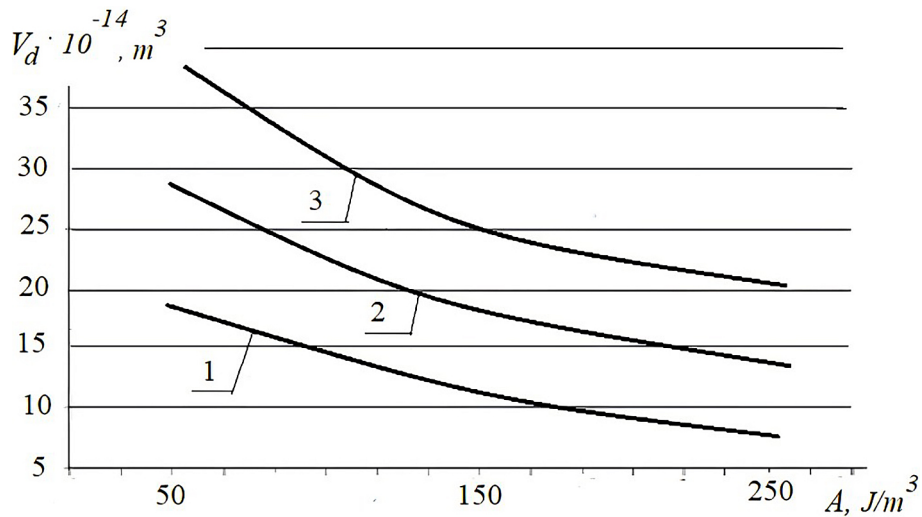


Figure 6. Dependencies of the change in the value of the deformed volume of the material of the fixed bronze triboelement on the unit ACS (V_d) depending on the tribological properties of the lubricating medium (A): 1 – $N = 2000$ N; 2 – $N = 3000$ N; 3 – $N = 4000$ N

load on the tribosystem $N = 2000$ N. Kinematic scheme of the tribosystem “ring-ring”, shape factor of the tribosystem $K_f = 12 \text{ m}^{-1}$ [21].

It follows from the analysis of the presented dependences that the tribological properties of the lubricating medium $A, \text{J/m}^3$, which are determined according to work [21], have an influence on the size of the volume of deformation in movable and fixed triboelements. This is due to the presence of surface-active and chemically-active substances in the lubricating medium, which contribute to the manifestation of the Rebinder effect.

It should be noted that the combination of materials in the tribosystem affects the volume

of material involved in deformation, this follows from expressions (17) and (18). The greater the difference in the modulus of elasticity of the materials of the movable and fixed triboelements, the greater the difference in the depth of deformation.

To confirm the functional relationship between the dissipative function and the wear rate, laboratory experimental studies of various tribosystem designs in various lubricating environments were conducted. During the experiments, the magnitude of the friction moment was recorded, which was used to calculate the friction coefficient f and the wear of the triboelements, which was determined using the artificial

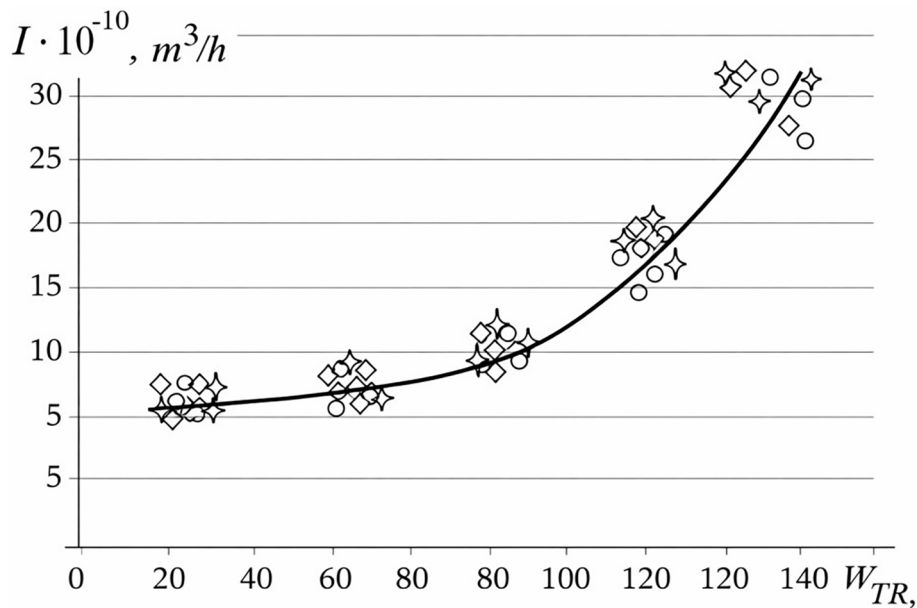


Figure 7. Dependencies of the change in wear rate (I) for various designs of tribosystems in various lubricating environments with a change in the value of the dissipative function (W_{TR}). \circ – steel ($E_{mov}=2.1 \cdot 10^{11}$ Pa; $\nu_{mov}=0.3$) + bronze ($E_{fix}=1.2 \cdot 10^{11}$ Pa; $\nu_{fix}=0.35$); \diamond – steel ($E_{mov}=2.1 \cdot 10^{11}$ Pa; $\nu_{mov}=0.3$) + gray cast iron ($E_{fix}=1.7 \cdot 10^{11}$ Pa; $\nu_{fix}=0.3$); \star – steel ($E_{mov}=2.1 \cdot 10^{11}$ Pa; $\nu_{mov}=0.3$) + steel ($E_{fix}=2.1 \cdot 10^{11}$ Pa; $\nu_{fix}=0.3$)

bases method. Based on the results of the measured wear, the wear rate I was determined, with the dimension m^3/h . The methodology for conducting laboratory tests, equipment (friction machine), means for recording friction parameters and statistical processing of test results are described in the works [19–21].

The dependences of the change in wear rate I on the value of the dissipative function W_{TR} are shown in Figure 7.

The correlation coefficient between the wear rate (I) for various designs of tribosystems in various lubricating environments and the value of the dissipative function (W_{TR}) was calculated and amounted to 0.88–0.93.

The obtained dependences of the influence of significant parameters of the friction process upon changing the roughness of the friction surfaces, the physical and mechanical properties of triboelement materials, the design features of the tribosystem, as well as the tribological properties of the lubricating medium will allow us to determine the distribution of the dissipation rate between the moving and fixed triboelements, which will be shown in the second part of the paper. The work will be devoted to the calculation of the dissipative function of the tribosystem and the establishment of a correlation between the specified function and the wear rate and the friction coefficient.

CONCLUSIONS

A methodological approach has been developed to investigate the influence of significant parameters of the friction process when changing the roughness of the friction surfaces, physical and mechanical properties of triboelement materials, structural features of the tribosystem, as well as tribological properties of the lubricating medium. The methodological approach has been developed and is valid under the following boundary conditions:

- contact between the friction surfaces of the movable and fixed triboelements is discrete, the contact patches are uniformly distributed over the nominal friction area, and the interactions between the roughness projections are random;
 - the contact type at a single contact patch is elastic;
 - the temperature generated at the actual contact patches does not change the elastic modulus or Poisson’s ratio of the triboelement materials.
1. Modeling of stress changes on spots of actual contact taking into account the roughness of the friction surfaces and the physical and mechanical properties of the surface materials was performed. It was established that changing the roughness parameters R_a and S_m has a

greater degree of influence on the voltage value than the load parameter. Increasing the parameter R_a from 0.2 to 0.8 μm , leads to an increase σ_{acs} in 4.3 times. Conversely, an increase in the parameter S_m from 0.2 to 0.8 mm, leads to a decrease σ_{acs} in 5 times.

2. Modeling of the change in the rate of deformation of the materials of the friction surfaces on the spots of actual contact has been carried out, taking into account the factors listed above. It follows from the conducted modeling that the roughness parameters of the friction surfaces (R_a and S_m) make the greatest contribution. Increasing the parameter R_a from 0.2 to 0.8 μm , with a simultaneous increase in the sliding speed $v_{sl} = 0.2 - 0.8$ m/s, leads to a significant increase in the rate of deformation of the material on ACS, more than 5 times.
3. Modeling of changes in the volume of materials of friction surfaces, which is involved in the deformation on the spots of actual contact, has been performed. It has been established that the tribological properties of the lubricating medium have an influence on the amount of deformation in movable and fixed triboelements. An increase in parameter A from 50 to 250 J/m^3 leads to a decrease in V_d by 4.15 times.

A further direction for the practical implementation of the developed methodological approach is to establish functional relationships between the dissipation rates of various tribosystem designs and the wear rate and friction coefficient, respectively. This will enable the development of methods for predicting the life of tribosystems.

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