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# MODELING THE PLASTIC DEFORMATION STATE OF THE CONTACT SURFACE DURING FRICTION

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***Abstract.*** *The mechanics of contact destruction of compounds during friction under conditions of complex thermodynamic loading was researched. The possibility of a mathematical description of complex damage to friction units and wear intensity is shown, taking into account the peculiarities of the surface layer formation during contact. A method for calculating the surface strength and durability of tribo-compounds is presented. This allows us to relate the parameters of the stressed state of a point (friction coefficient, shape factor) with the thermomechanical parameters of the process. By assessing changes in the friction coefficient and shape parameters, it becomes possible to determine the yield stress and establish structural transformations corresponding to a given stress state.*

**Keywords:** friction, load, plasticity theory, deformation, stress, tribocompounds.

## 1. Introduction

The main vector of modern mechanical engineering development is not only the creation of new materials, but also the study of their behavior during operation [1-2]. Currently, the results of research in the field of wear of materials under particularly severe conditions of mechanical and thermal loads, which are dynamic in nature, do not allow with a high degree of reliability to select (or develop) certain design and technological measures that are aimed at increasing the durability of products. This is caused, first of all, by the research conditions, which often do not correspond to the actual operating conditions of tribounits, since most of the parts of tribounits operate under conditions of complex dynamic loading associated with vibrations acting in different directions, which affects unstable synergetic processes [3].

The processes of friction and wear, as well as the destruction of surface layers of tribocompounds, are determined by the dynamic nature of the application of loads in contact, the amplitudes of mutual movements, creating specific conditions for contact interaction [4]. At the same time, most tribocompounds operate under conditions of complex three-dimensional dynamic loading: impact and slipping in two mutually perpendicular directions with exposure to both high and low temperatures. Such loading conditions cause a complex stress state of the surface layers of contacting pairs [5]. This explains the limited capabilities of the general provisions of the theory of friction, as well as most of the results of experimental studies.

## 2. Research methods

The solution of the contact problem of fracture mechanics of tribocompounds, which are operated under conditions of complex thermomechanical loading, is possible within the framework of assessing the heterogeneity of the plastic deformation state, which is the main feature of metal products shaped by pressure processes. As a result, the metal of the product has different mechanical properties and fatigue resistance.

It is obvious that under contact loading conditions, the near-surface layers of the material are more damaged than the deep ones. Under repeated loading, fatigue microcracks appear on the surface even in the absence of contact loads and are located in active sliding planes, in which maximum shear stresses act [6]. Four successive stages of processes in the material can be distinguished in accordance with the characteristics of deformation and destruction of materials during fatigue: strengthening of the material due to an increase in the dislocation density in local volumes to a critical value; initiation and development of submicroscopic cracks; development of microcracks to the size of macrocracks; development and merging of macrocracks prior to spalling of surface elements.

The accumulation of defects, leading to the formation of microcracks, is determined by the characteristic features of the main structural elements of the material. Under the action of repeated impulse loads, the initial structure of the deformed material changes significantly. The subsurface zone (depth from several units to hundreds of micrometers) is a plastically deformed layer of material with a certain size and orientation of crystallites. The relationship between mechanical properties and structural parameters given in [7] shows that the resistance to brittle fracture depends not only on the grain size, but also on the size of the mosaic block. Moreover, the grain size does not uniquely determine the mechanical properties of the metal. The flow stress linearly depends on the size of the subgrains - the element of the substructure. A conclusion is made about the determining influence of the degree of misorientation on the resistance to destruction of the metal.

The need for an analytical solution to the spatial problem of plasticity theory is obvious. In general, the stressed and deformed state of the metal at each point of the deformation zone is different. This leads to heterogeneity of the physical and mechanical properties of the metal, ambiguity in determining the power parameters of the process, and energy consumption. Works have appeared showing the influence of plastic deformation on structural-phase transformations in metal. In this regard, determining the stress state at each point of the deformation zone is an urgent problem [8, 9].

## 3. Results and discussion

As shown by preliminary studies [9-12], complex three-dimensional loading (impact and sliding in two mutually perpendicular directions) creates conditions for the formation of fragments of the surface layer with relatively easy passage of dislocations through these crystallites to their boundaries. This helps to reduce the level of external stresses necessary for the mechanism of rotational plasticity to operate in the analyzed structures. The result is a surface layer with a more even texture, which is accompanied by increased wear. A change in the nature of the loading leads to a change in the state of the surface layer and, as a consequence, a change in the wear resistance of the tribocompounding.

Studies using an electron microscope made it possible to establish that as a result of plastic deformation, a developed cellular structure is formed in the surface layers, oriented along the direction of friction [13]. Fracture is initiated by cell edges perpendicular to the sliding direction, and the initial crack runs along these edges. Therefore, with relative sliding of surfaces, the initiation of differently oriented cracks is possible. Especially in the case of friction with sliding in two mutually perpendicular directions.

In the general case, the formation and growth of microcracks under cyclic loading significantly depends on both the structural state of the material and the number of loading cycles N. To describe the development of microstructurally short cracks, the equation presented in [14] is applicable:

$$\frac{db}{dN} = C(\Delta\gamma)^m (d - b), \tag{1}$$

where $b$ – crack depth; $\Delta\gamma$ – shear strain range; $d$ – characteristic size of a structure element; C and m – experimentally determined material constants.

From this equation it follows that as a crack grows to grain size, its speed decreases down to zero. At stresses above the endurance limit, the crack does not stop, but only slows down its growth or may stop for some time.

Moreover, the nature of the accumulation of deformations under the action of repeated impulsive and pulse loads is approximately the same [15]. Thus, under impact loading, the dependence of contact deformation on the number of cycles is nonlinear with three sections: in the first section, the hardening stage (approximately up to N = 20), contact deformation occurs; in the second section there is a slow accumulation of contact strain at an approximately constant rate (up to N = 103 ... 104); in the third section, a significant increase in deformation and intensive destruction of the surface are observed.

It has been established [6] that wear under impact loading is a nonlinear function of the number of cycles and normal stress:

$$W = BN^n\sigma^m, \quad (2)$$

where *B, n, m* – coefficients.

In this case, the normal stress σ and the maximum contact pressure are determined by the impact force, which in turn depends on the speed, contact geometry and material properties.

Cyclic stresses lead to fatigue damage, both at the surface and at some depth. The phenomenon of surface fatigue is a consequence of normal collisions of micro-roughnesses, which lead to the occurrence of tangential stresses under the roughnesses, acting at a depth of the order of the heights of the protrusions (micrometers). The maximum shear stress under the protrusion is:

$$\tau'_m = \left(E'/\pi^2\right)\varphi, \quad (3)$$

where $E'$ – modulus of elasticity; $\varphi$ – protrusion angle coefficient.

It is obvious that microscopic (second kind) maximum shear stresses can indeed be the cause of the formation of initial cracks under the surface.

The general case of a diagram of vertical surface and horizontal subsurface cracks under friction with three-dimensional dynamic loading is shown in Fig.1.

The surface is loaded with normal alternating stress q(z) under impact loading and tangential stresses $\tau x$ and $\tau y$ during reciprocating sliding in two mutually perpendicular directions of the counter-specimen.

The analysis shows that if it is possible to mathematically describe the areas of transition from one zone of plastic flow of a metal to another, then it becomes possible to analytically solve problems in the theory of plasticity. In [16-20], an analytical solution to the plane problem of plasticity theory using harmonic functions was proposed. The spatial problem is solved in stresses [21]. The use of harmonic functions, as further analysis shows, allows us to analytically obtain a closed solution to the spatial problem, both taking into account the statistical and kinematic components.

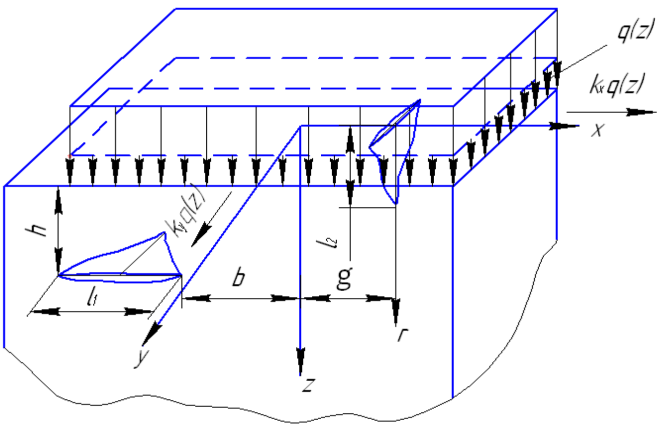


**Fig.1**. Scheme of horizontal and vertical cracks during friction with three-dimensional dynamic loading.

Takes the $\tau_{xy}$=0. In many problems of metal forming, the influence of this component of the stress tensor is neglected [22, 23]. Hence, in the formulation part of the closed problem of plasticity theory, the system should contain 14 equations.

*Problem formulation*

1. Equilibrium equations:

$$\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xz}}{\partial z} = 0,$$

$$\frac{\partial \tau_{yz}}{\partial z}+\frac{\partial \sigma_{y}}{\partial y}=0, \tag{4}$$

$$\frac{\partial \tau_{xz}}{\partial x}+\frac{\partial \tau_{yz}}{\partial y}+\frac{\partial \sigma_{z}}{\partial z}=0$$

4. Generalized equilibrium equations:

$$\frac{\partial^2 \tau_{xz}}{\partial x^2}-\frac{\partial^2 \tau_{xz}}{\partial z^2}=\frac{\partial^2}{\partial x \partial z}2k_1\sqrt{1-\left(\frac{\tau_{xz}}{k_1}\right)^2}, \tag{5}$$

$$\frac{\partial^2 \tau_{yz}}{\partial y^2}-\frac{\partial^2 \tau_{yz}}{\partial z^2}=\frac{\partial^2}{\partial y \partial z}2k_2\sqrt{1-\left(\frac{\tau_{yz}}{k_2}\right)^2}$$

3. Connection equations:

$$\frac{\sigma_x-\sigma_z}{2\tau_{xz}}=\frac{\xi_x-\xi_z}{\dot{\gamma}_{xz}}=\frac{2\xi_x+\xi_y}{\dot{\gamma}_{xz}}, \quad \frac{\sigma_y-\sigma_z}{2\tau_{yz}}=\frac{\xi_y-\xi_z}{\dot{\gamma}_{yz}}=\frac{2\xi_y+\xi_x}{\dot{\gamma}_{yz}} \tag{6}$$

4. Incompressible equation:

$$\xi_x+\xi_y+\xi_z=0 \tag{7}$$

5. Continuity equations for strain rates:

$$\frac{\partial^2 \xi_x}{\partial z^2}+\frac{\partial^2 \xi_z}{\partial x^2}=\frac{\partial^2 \dot{\gamma}_{zx}}{\partial z \partial x}, \quad \frac{\partial^2 \xi_y}{\partial z^2}+\frac{\partial^2 \xi_z}{\partial y^2}=\frac{\partial^2 \dot{\gamma}_{zy}}{\partial z \partial y} \tag{8}$$

6. Boundary conditions:

$$\tau_{n1}=k_1\cdot Sin(\mathrm{A}_1\Phi_1-2\alpha_1),\ \tau_{n2}=k_2\cdot Sin(\mathrm{A}_2\Phi_2-2\alpha_2), \tag{9}$$

$$\gamma_{n1}=2\cdot\beta_1\cdot Sin(\mathrm{B}_1\Phi_1-2\alpha_1),\ \gamma_{n2}=2\cdot\beta_2\cdot Sin(\mathrm{B}_2\Phi_2-2\alpha_2)$$

The use of generalized equilibrium equations (5) allows us to bring the obtained result into conformity with equations (8). Boundary conditions (9) mathematically describe the transition zones from one section of the plastic flow of a metal to another, both in stress and strain. The solution of plane problems in analytical form is presented in [16-20]. To satisfy boundary conditions of the form (9) it is necessary:

$$\tau_{xz}=k_1\cdot Sin\mathrm{A}_1\Phi_1, \quad \tau_{yz}=k_2\cdot Sin\mathrm{A}_2\Phi_2, \tag{10}$$

where $A_1$ and $A_2$ – constants that determine the parameters of the plastic medium; $\Phi_1$ and $\Phi_2$ – unknown coordinate functions determined by the solution of the problem; $k_1$, $k_2$ – resistance to plastic shear deformation along the X and Y axes, depending on the coordinates of the deformation zone.

A special feature of solving equations (5), in addition to trigonometric substitution, is the use of fundamental functions. They are used if the partial differential equation is linear [24–28]. Therefore:

$$k_1=C_{\sigma 1}\cdot\exp\theta_1', \quad k_2=C_{\sigma 2}\cdot\exp\theta_2', \tag{11}$$

where $C_{\sigma 1}$ and $C_{\sigma 2}$ – constants that determine the dimension of shear resistance in the directions of the X and Y axes; $\theta_1$ and $\theta_2$ – coordinate unknown functions determined by solving the problem along the same axes.

It must be borne in mind that $\tau_{xz}=f(x,z)$, $\tau_{yz}=f(y,z)$. Putting the introduced functions (10) and (11) into (5) we obtain:

$$\begin{aligned} &C_{\sigma 1}\left[\theta_{1xx}'+(\theta_{1x}'+\mathrm{A}_1\Phi_{1z})^2-\theta_{1zz}'-(\theta_{1z}'-\mathrm{A}_1\Phi_{1x})^2\right]\cdot Sin\mathrm{A}_1\Phi_1+\\ &+C_{\sigma 1}\left[2\cdot(\mathrm{A}_1\Phi_{1x}-\theta_{1z}')\cdot(\theta_{1x}'+\mathrm{A}_1\Phi_{1z})+(\mathrm{A}_1\Phi_{1xx}-\mathrm{A}_1\Phi_{1zz})\right]\cdot Cos\mathrm{A}_1\Phi_1=\\ &=-2\cdot C_{\sigma 1}\cdot\mathrm{A}_1\Phi_{1xz}\cdot Sin\mathrm{A}_1\Phi_1+2\cdot C_{\sigma 1}\cdot\theta_{1xz}'\cdot Cos\mathrm{A}_1\Phi_1 \end{aligned} \tag{12}$$

Identical brackets $(\theta_{1x}'+\mathrm{A}_1\Phi_{1z})$ and $(\theta_{1z}'-\mathrm{A}_1\Phi_{1x})$ appear in operators of trigonometric functions (12). Taking them equal to zero, we get rid of nonlinearity and obtain the Cauchy–Riemann equations, which turn the equations into an identity. Let's show it. We have

$$\theta'_{1x} = -A_1\Phi_{1z}, \quad \theta'_{1z} = A_1\Phi_{1x} \tag{13}$$

$$\theta'_{1xx} = -A_1\Phi_{1zx}, \quad \theta'_{1zz} = A_1\Phi_{1xz}, \quad \theta'_{1xz} = A_1\Phi_{1zz} = -A_1\Phi_{1xx} \tag{14}$$

From relations (13) and (14) the functions $\theta'_1$ and $A_1\Phi_1$ are determined. They are harmonic and satisfy the Laplace equation, i.e.:

$$\theta'_{1xx} + \theta'_{1zz} = 0, \quad A_1\Phi_{1xx} + A_1\Phi_{1zz} = 0 \tag{15}$$

Similar transformations take place for the second generalized equilibrium equation when substituting (10) and (11) into (5). We can write:

$$\begin{aligned} &C_{\sigma 2}\left[\theta'_{2yy} + (\theta'_{2y} + A_2\Phi_{2z})^2 - \theta'_{2zz} - (\theta'_{2z} - A_2\Phi_{2y})^2\right]\cdot Sin A_2\Phi_2 + \\ &+ C_{\sigma 2}\left[2\cdot(A_2\Phi_{2y} - \theta'_{2z})\cdot(\theta'_{2y} + A_2\Phi_{2z}) + (A_2\Phi_{2yy} - A_2\Phi_{2zz})\right]\cdot Cos A_2\Phi_2 = \\ &= -2\cdot C_{\sigma 2}\cdot A_2\Phi_{2yz}\cdot Sin A_2\Phi_2 + 2\cdot C_{\sigma 2}\cdot\theta'_{2yz}\cdot Cos A_2\Phi_2 \end{aligned} \tag{16}$$

next:

$$\begin{aligned} &\theta'_{2y} = -A_2\Phi_{2z}, \quad \theta'_{2z} = A_2\Phi_{2y}, \\ &\theta'_{1yy} = -A_2\Phi_{2zy}, \quad \theta'_{2zz} = A_2\Phi_{2yz}, \quad \theta'_{2yz} = A_2\Phi_{2zz} = -A_2\Phi_{2yy}, \\ &\theta'_{2yy} + \theta'_{2zz} = 0, \quad A_2\Phi_{2yy} + A_2\Phi_{2zz} = 0 \end{aligned} \tag{17}$$

Taking into account (16), (17), certainty appears for the functions $\theta'_2$ and $A_2\Phi_2$.

Substituting expressions for tangential stresses into equilibrium equations (4), integrating, we obtain analytical dependences for normal stresses. The components of the stress tensor have the form:

$$\begin{aligned} &\sigma_x = C_{\sigma 1}\cdot\exp\theta'_1\cdot Cos A_1\Phi_1 + \sigma + f(y,z) + C_1, \\ &\sigma_y = C_{\sigma 2}\cdot\exp\theta'_2\cdot Cos A_2\Phi_2 + \sigma + f(x,z) + C_2, \\ &\sigma_z = -\left(C_{\sigma 1}\cdot\exp\theta'_1\cdot Cos A_1\Phi_1 + C_{\sigma 2}\cdot\exp\theta'_2\cdot Cos A_2\Phi_2\right) + \sigma + f(x,y) + C_3, \\ &\tau_{xz} = C_{\sigma 1}\cdot\exp\theta'_1\cdot Sin A_1\Phi_1, \quad \tau_{yz} = C_{\sigma 2}\cdot\exp\theta'_2\cdot Sin A_2\Phi_2 \end{aligned} \tag{18}$$

at $\theta'_{1x} = -A_1\Phi_{1y}$, $\theta'_{1y} = A_1\Phi_{1x}$, $\theta'_{1xx} + \theta'_{1zz} = 0$, $A_1\Phi_{1xx} + A_1\Phi_{1zz} = 0$, $\theta'_{2y} = -A_2\Phi_{2z}$, $\theta'_{2y} = A_2\Phi_{2x}$, $\theta'_{2yy} + \theta'_{2zz} = 0$, $A_2\Phi_{2yy} + A_2\Phi_{2zz} = 0$.

The conditions for the existence of the introduced functions and the differential equations that determine their values are determined. Thus, solutions (18) satisfy the system of equations for the spatial problem in stresses. It becomes possible to connect the parameters of the stressed state of a point (friction coefficient, shape factor) with the thermomechanical parameters of the process (degree, rate, and temperature of deformation). In this case, production factors and loads are directly linked. By setting the parameters of the stress state, it is possible to determine, using different calculation methods, the thermomechanical parameters of the process. As an example, for the contact surface of samples of 10HFTBch two–phase steel type, is calculated the intensity of normal stresses σi from various friction coefficients and shape parameters (stress state) in the MathCAD program. The ratio of the length of the deformation zone to the height l/h = 1 and l/h = 6 is considered. By setting different friction coefficients (0.1; 0.2...0.5), the maximum values of the σi curves for a point on the contact are obtained (Table 1).

**Table 1.** Maximum values of normal stress intensity for various shape parameters and friction coefficients

| l/h | Friction coefficient | | | | |
|---|---|---|---|---|---|
| | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 |
| 1 | 1.155 | 1.31 | 1.442 | 1.532 | 1.564 |
| 6 | 1.286 | 1.574 | 1.828 | 1.997 | 2.058 |

Fig.2 shows the change in normal stress intensity values along the length of the deformation zone (along the X axis). Along the X and Y axes, the stresses $\sigma_i$ are distributed along a convex curve, which is determined by the tangential contact stresses $\tau_{xz}$ and $\tau_{yz}$. It has been established that the greater the $\sigma_i$, he higher the yield strength.

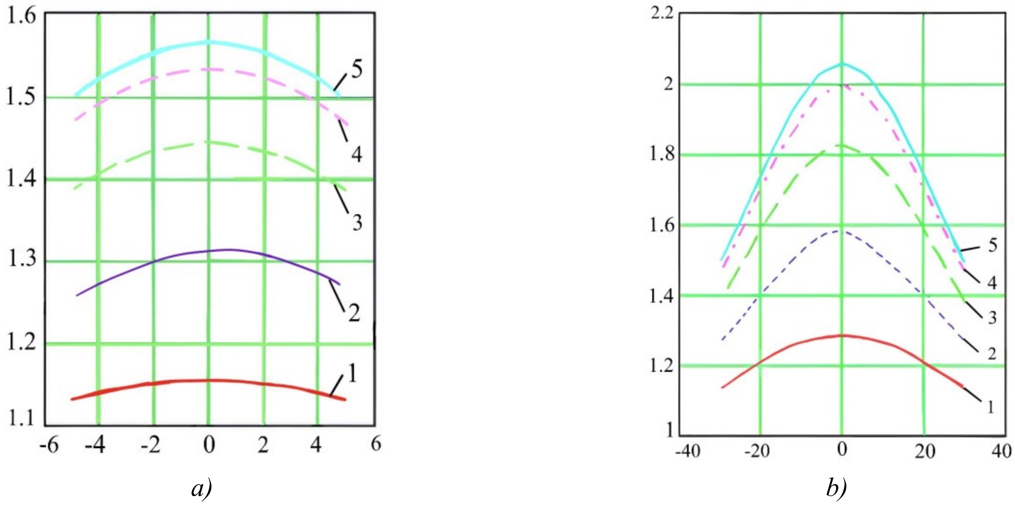


**Fig.2.** Change in the intensity of normal stresses along the length of the deformation zone:
a) – l/h= 1; b) – l/h=6.
1 – f=0,1; 2 – f=0,2; 3 – f=0,3; 4 – f=0,4; 5 – f=0,5

Thus, $\sigma_i$ depends on the friction coefficient and the shape parameter (stress state), that is, the ratio l/h and b/h. Analysis of the results of calculating the intensity of normal stresses from the parameters of shape and friction coefficient shows that it is possible to increase this parameter compared to unhardened metal. There is an increase in this indicator by 1.13...2.0 times. This means that, based on the Huber–Mises's hypothesis, the physical quantity, that is, the yield strength, also increases by 1.13...2.0 times. With an increase in the friction coefficient and shape parameters, we determine the yield stress, which in this case, through the temperature factor and recrystallization diagrams, makes it possible to establish structural transformations corresponding to a given stress state.

## 4. Conclusion

The presented models confirm the relevance of the mathematical description of complex damage to friction units. An assessment of the mechanics of contact fracture should be made on the basis of studying the behavior of surface layers of materials in connection with the peculiarities of thermomechanical loading of tribocompounds under real operating conditions. The use of harmonic functions allows one to analytically obtain a closed solution to a spatial problem, both taking into account the statistical and kinematic components. In turn, the development of methods for calculating surface strength assessment is a necessary prerequisite for the development of more wear–resistant tribounits.

**Conflict of interest statement**
The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

**CRediT author statement**
Tsyganov V.: Conceptualization, Resources; Sheyko S.: Methodology, Supervision, Hrechanyi O.: Project administration, Writing – review & editing, Vasilchenko T.: Data Curation, Writing - Original Draft.
The final manuscript was read and approved by all authors.

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