ISSN 2079-1372 Problems of Tribology, V. 30, No 3/117-2025, 41-48

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

DOI: https://doi.org/10.31891/2079-1372-2025-117-3-41-48

Dynamic processes in surface layers of parts as a source of their multicycle failure under friction and wear

Y. O. Malinovskyi[1] 0000-0001-5980-0908, **O.O. Mikosianchyk[2]** 0000-0002-2438-1333, **O. D. Uchytel[3]** 0000-0001-6241-1786, **O. O. Skvortsov[2]** 0009-0008-8778-6400, **D. P. Vlasenkov[1]** 0009-0008-4202-1885, **S. O. Sytnyk[1]**, **S. Y. Oliinyk[4]** 0000-0002-6169-8874

[1]Kryvyi Rih professional college of State University «Kyiv Aviation Institute», Ukraine
[2]State University «Kyiv Aviation Institute», Ukraine
[3]State University of Economics and Technology, Ukraine
[4]Krivyi Rih National University, Ukraine

E-mail: oksana.mikos@ukr.net

Received: 05 July 2025: Revised 30 July 2025: Accept: 15 August 2025

Abstract

During the operation of various machines and mechanisms, oscillatory movements may occur, excited by a non-stationary friction characteristic. These oscillations appear either at the contact area of two parts or in the zone located ahead of the moving part. In the contact area, a non-stationary friction force develops, leading to self-excited oscillations of the contact surface and to the occurrence of parametric oscillations in the area ahead of the active punch. At certain ratios of slip velocities and part movement speeds, self-excited and parametric motions may appear or disappear, as well as intensify or weaken. These oscillations are one of the causes of uncontrolled surface roughness (deformational), cracking, and spalling of interacting parts, as well as significant dynamic components during the loading of actuating, drive, and power mechanisms. Frictional and parametric oscillations in the surface layers of parts with deformation wave formation create residual plastic sinusoidal metal layers, which are sheared off during the interaction of parts. Due to the dynamic nature of interaction during friction, the forces acting in the contact plane (longitudinal) exceed the critical Euler force, which is a parametric load, and in some cases lead to dangerous parametric resonance. The work defines the frequency range near the parametric resonance, which is the area of dynamic instability ahead of the moving punch. The formulated and partially solved problem considers frictional and parametric oscillations during the interaction of parts, which lead to the formation of deformation waves, their partial or complete shearing, creating prerequisites for intensive wear and subsequent destruction of parts.

Key words: dynamic loads, friction, wear, frictional oscillations, self-oscillations, beam-strip, parametric oscillations, parametric resonance, primary instability zone, punch, elongated part, friction force, slip velocity, surface layers.

Introduction

Dynamic effects on frictional surfaces cause both elastic and non-elastic deformations in the contact zone. Elastic deformations are localized at discrete contact areas. In turn, impulse loads generate not only oscillations of the tribological pair but also surface waves in the contacting parts. Under certain friction conditions, a contact resonance mode arises, which abnormally increases the intensity of plastic deformation and damage accumulation. This accelerates diffusion processes, material transfer, and intensifies structural-energy phenomena in the surface layers of the material. Various processes occurring in the surface layers lead to the emergence of different types of material destruction during wear, since in the pre-destruction stage adsorption, physical, chemical, structural, and other transformations may occur. Under friction conditions, the influence of these processes is usually stronger than, for example, in contact or bulk fatigue. The shape, size, and surface texture of wear particles, as well as the degree of hardening/softening of the surface layers, are directly related to wear mechanisms and make it possible to draw certain conclusions about the nature and characteristics of deformation processes in the friction zone, about structural changes in the near-surface layer of the material, and about wear mechanisms [1].

Modeling of friction and wear processes is an important tool across a wide range of engineering disciplines, including contact mechanics, fracture and fatigue, structural dynamics, and others. In work [2] , systems of classification of friction and wear processes and criteria for their identification are presented, covering the physical processes of friction associated with the mechanics of deformable bodies.

In the present study, the influence of parametric and self-oscillatory processes arising from the interaction of components under dynamic loading conditions on the durability of the surface layers of the material is examined.

Literature review

During various technological processes occurring in the contact zone of the parts of kinematic pairs, oscillatory movements may take place, leading to local failures due to the manifestation of plastic and sometimes brittle properties by the surface layers of the parts [3]. In some cases, these properties are caused by the non-stationary friction characteristic between the surface layers of the interacting parts as a function of slip velocity [4]. Such oscillations may intensify during machine operation and lead to the accumulation of surface fatigue in the metal and to local brittle and plastic fracture of the surface layers [5, 6]. Such destruction can be mathematically described, taking into account the components of continuum mechanics and dislocation theory [5]. Therefore, to solve such a problem, in addition to the deformation wave components, it is necessary to introduce into the equations of the surface layer terms that also describe brittle properties and include multi-cycle loading. For the reliable inclusion of such components into the dynamic equations, additional experimental and theoretical studies are required.

Purpose

The aim of the work is to study the conditions for the occurrence and stabilization of self-excited and parametric processes under dynamic loading of surface layers that occur in the interaction areas of parts during friction and wear when brittle and elastic-plastic properties are manifested in the surface layers.

Statement of the main material

Let us consider the mechanism of occurrence of frictional self-oscillations in the interaction zone of a punch with another part, as well as parametric oscillations in the zone ahead of the punch (Fig. 1).

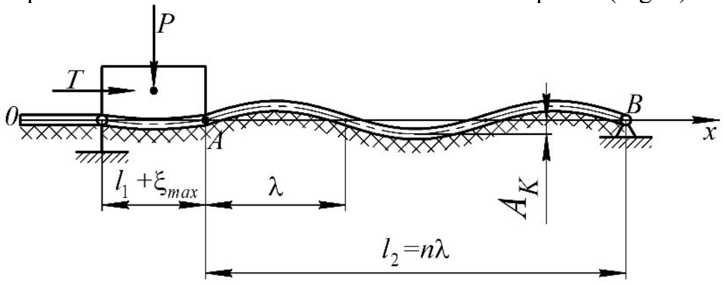

Fig. 1. Interaction of the punch with a half-space

The coefficient (force) of friction between two contacting parts can be approximated by a cubic function of slip velocity (Fig. 2). This friction characteristic has a decreasing section, which causes negative damping to appear in the oscillatory system, leading to self-excited oscillations that grow until the relative slip velocity of the parts reaches its critical value (Fig. 2).

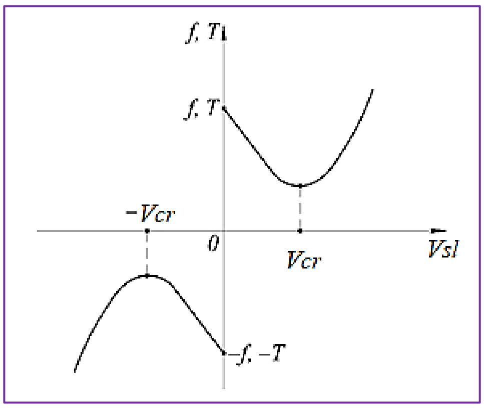

Fig. 2. Dependence of the coefficient (force) of friction on the slip velocity of parts

The presence of a nonlinear component in the friction characteristic indicates that after the slip velocity reaches its critical value, the influence of this component will increase, and the oscillation amplitudes will decrease. Thus, friction is accompanied by a self-oscillatory process that promotes additional frictional resistance and intensifies the fatigue wear of interacting surfaces.

Based on the conducted research, three problems of the theory of friction and wear concerning the rolls of rolling mills in the process of rolling sheets during metal processing or other similar processes were formulated:

1. Friction and wear of machined surfaces under the action of tangential forces suddenly applied to the outer layers of the machined part;
2. Friction and wear of machined surfaces under the action of periodic (impulse) forces applied to the outer layers of parts;
3. Friction and wear of machined surfaces as a result of the action of tangential loading caused by non-stationary friction between the forming tool and the part.

The formulated (and partially solved) problems are problems with phenomenological models for representing the processes of friction and wear.

Based on these three problems, it is highly likely that the sliding friction forces at the contact area, the resulting self-oscillations, and the parametric effects in the area in front of the punch are interrelated. Therefore, to describe the relationship between the processes at the contact area and ahead of the punch, let us consider these two adjacent sections on the beam-strip of the part's surface layer.

Let us distinguish two calculation schemes: the first within the framework of the contact area of the parts, where the tangential force T stretches the beam-strip of length l_1, and the second—where the tangential force T is applied to a beam-strip of length l_2 at the extreme point A, where the beam-strip (l_2) is in the compression zone (Fig. 1).

Considering the first calculation scheme, we can compose the equation of longitudinal displacements in the contact area of two parts of length l_1. If $q(x, t)$ can be defined as a function of oscillatory (or periodic) nature, then the variable $y(x, t)$ can be considered as the longitudinal displacement of the beam-strip during its oscillations.

Then the equation of longitudinal oscillations of a beam-strip loaded with distributed tangential loading along the Ox axis of the strip lying on an elastic foundation [4] takes the form:

$$\frac{\partial^2 y}{\partial t^2} = \frac{E_c F}{m} \cdot \frac{\partial^2 y}{\partial x^2} - \frac{\beta}{m} \cdot y + \frac{q}{m}, \tag{1}$$

where $y = y(x,t)$ – longitudinal displacement of the beam-strip during its deformation and oscillations; $E_c F$ – longitudinal stiffness of the beam-strip; m – distributed mass of the beam-strip; β – stiffness coefficient of the elastic foundation; $q = \frac{T}{b l_1}$ – intensity of the distributed load over the contact area of the surfaces; b – width of the contact area; l_1 – length of the contact area; P – external vertical load on the part; f_0 – static friction coefficient; $a = \frac{3(f_0 - f_{min})}{2V_{cr}}$ – linear coefficient of the friction characteristic; $\bar{b} = \frac{(f_0 - f_{min})}{2V_{cr}^2}$ – nonlinear coefficient of the friction characteristic; V_{cr} – critical relative velocity of the parts at which $f = f_{min}$; f – friction coefficient according to the cubic dependence on slip velocity [2]:

$$f = f_0 - \frac{3}{2} \cdot (f_0 - f_{min}) \cdot \frac{V_{\text{ск}}}{V_{\text{кр}}} + \frac{1}{2} \cdot (f_0 - f_{min}) \cdot \left(\frac{V_{sl}}{V_{cr}}\right)^3$$

V_{sl} – slip velocity of the parts.

Equation (1) is considered taking into account homogeneous boundary conditions:

$$\begin{cases} y|_{x=0} = 0 \\ \left.\frac{\partial y}{\partial x}\right|_{x=0} = 0 \end{cases}. \tag{2}$$

Expressions (2) represent the boundary conditions in the area of the beam-strip under the punch. Separately from conditions (2), we write the nonhomogeneous boundary condition (additional):

$$y|_{x=l_1} = \xi_{max}. \tag{3}$$

That is, at the right boundary of the contact area, we have the displacement value ξ_{max} (maximum).

Note that the value ξ_{max} is still undetermined

We take into account that the force $T = fP$. Then, considering the expression $f(V_{\text{ск}})$, and the coefficients a, $\bar{b}$ we solve equation (2) formally with respect to the function $y(x,t)$, and we consider this solution as approximate:

$$y(x,t) = -\frac{m}{\beta} \cdot \frac{\partial^2 y}{\partial t^2} + \frac{E_c F}{\beta} \cdot \frac{\partial^2 y}{\partial x^2} + \frac{mP}{b l_1 \beta} \cdot \left[f_0 - a \cdot \frac{\partial y}{\partial t} + \bar{b} \cdot \left(\frac{\partial y}{\partial t}\right)^3\right]. \tag{4}$$

Then, into the right-hand side of (4) we substitute the approximate value $y_1(x,t)$, which we seek in the form:

$$y_1(x,t) = \sum_{i=1}^{n} Y_1(x) z_1(t) = (C_1 cos P_n x + C_2 sin P_n x) \cdot \frac{v_0}{P_0} sin P_0 t. \tag{5}$$

where $C_1 = 0$; $C_2 = \frac{\xi_{max}\cdot}{sin\sqrt{\frac{mP^2-\beta}{E_cF}}\cdot l_1}$ – arbitrary constants determined using (5) for the first natural mode of oscillations;

$z_i(t)$ – time-dependent component of the function $y_1(t)$ [5] ($i = 1, 2, 3, ...$).

For the first approximation $z_1(t) = \frac{v_0}{P_0} sinP_0t$

v_0 – initial slip velocity of the parts; P_0 – natural frequency of oscillations of one of the parts.

Then:

$$y_1(x,t) = \frac{\xi_{max}}{sin\sqrt{\frac{mP^2-\beta}{E_cF}}\cdot l_1} sin\sqrt{\frac{mP^2-\beta}{E_cF}} \cdot x \cdot \frac{v_0}{P_0} sinP_0t. \quad (6)$$

After substituting expression (5) into equation (4) and neglecting the transient components, we write the expression for the displacement ξ_{max}

$$\xi_{max} = \frac{mP}{bl_1\beta} \cdot \left[f_0 - \xi_{max}v_0acosP_0t + \xi_{max}^3v_0^3\bar{b}cos^3P_0t\right]. \quad (7)$$

We take $t = 0$ then the displacement ξ_{max} is determined from the cubic equation, which has three solutions, according to Cardano's formula; one of them has the largest real root – this will be the displacement ξ_{max}

$$\xi_{max}^3 - \xi_{max}\left(\frac{a}{\bar{b}v_0^2} + \frac{bl_1\beta}{mP\bar{b}v_0^3}\right) + \frac{f_0}{\bar{b}v_0^3} = 0. \quad (8)$$

The solution (8) has three real roots if $D < 0$, and one real root if $D > 0$. The discriminant is written as

$$D = \frac{f_0^2}{4\bar{b}^2v_0^2} + \left(\frac{a}{3\bar{b}v_0^2} + \frac{bl_1\beta}{3mP\bar{b}v_0^2}\right)^3. \quad (9)$$

Thus, the maximum displacement of the beam-strip l_1 under the contact area during its deformation and oscillations is determined, we will consider that during longitudinal deformation of the beam-strip, the length of section l_1 increases to the value $l_1 + \xi_{max}$, and the length of section l_2 increases to the value $l_2 + \xi_{max}$, ξ_{max} is used for the increase of segment l_2, and for the development of a wave-shaped deformation of the strip l_2. The deformation of segmen l_2 will consist of n half-waves. Thus, in section l_2 the beam-strip becomes wavy, and the height of the corrugations will be considered as deformation micro-roughness. To determine the height of the corrugations of the deformed section l_2 it is necessary first to calculate the length and number of micro-waves of section l_2.

In order to determine the deflection arrow of section l_2 we assume that the beam-strip has lost its longitudinal stability. Therefore, as follows from [4], the length of the half-wave of the rod is equal to:

$$\lambda = \frac{\pi}{\alpha} = \pi \cdot \sqrt[3]{\frac{4E_cI}{E}}, \quad (10)$$

where α – number of half-waves of deformation of the section of the beam-strip of length π, that has lost longitudinal stability. as follows from [6], the length of the half-waves of deformation of the rod can be found through the modulus of elasticity of the surface and inner layers of the part, as well as the moment of inertia of the beam-strip; I – moment of inertia of the beam-strip cross section; E – modulus of elasticity of the inner layers of the part; E_c – modulus of elasticity of the surface layers of the part.

Then the flexibility coefficient of the rod on an elastic foundation according to [6] is equal to:

$$r = \frac{\beta}{EI} = \frac{E}{2}\alpha = \frac{1}{2l} \cdot \sqrt[3]{\frac{E}{4E_cI}}, \quad (11)$$

where: $l = l_2$ – unknown length of the beam-strip; β – stiffness of the elastic foundation of the beam-strip due to the elasticity of the inner layers of the part.

The flexibility coefficient of the rod on an elastic foundation can be related to the length of section l_2 and the number of half-waves n of the section when it loses its longitudinal stability, according to [6]:

$$r = \frac{\pi^4}{l^4}n^4(n+1)^2, \quad (12)$$

or, taking into account expression (11), we obtain:

$$\frac{1}{2l_2} \cdot \sqrt[3]{\frac{E}{4E_cI}} = \frac{\pi^4}{l_2^4}n^4(n+1)^2. \quad (13)$$

Expression (13) is transformed into a quadratic equation:

$$n^2\left(\frac{1}{2} - \frac{E}{4E_cI}\right) - 2n\frac{E}{4E_cI} - \frac{E}{4E_cI} = 0. \quad (14)$$

The solution of (14) has the form:

$$n = \frac{E}{4E_cI} \cdot \frac{1}{\left(\frac{1}{2} - \frac{E}{4E_cI}\right)} + \sqrt{\frac{E^2}{16E_c^2I^2} \cdot \frac{1}{\left(\frac{1}{2} - \frac{E}{4E_cI}\right)^2} + \frac{E}{4E_cI} \cdot \frac{1}{\left(\frac{1}{2} - \frac{E}{4E_cI}\right)}}. \quad (15)$$

The deformed part of the beam-strip, ahead of the active punch, takes a sinusoidal shape and shifts in the direction of the punch movement in the form of a moving (deformation) wave of lengthl_2 with a speed v_0.

The shape of the wave is established after the beam-strip loses longitudinal stability.

Turning to the beam-strip before the punch enters section l_2 we see that this section is loaded with a tangential force T. The tangential force T stretches section l_1 of the beam-strip and compresses section l_2. As a result of the tangential force, section l_2 receives a longitudinal bend, and in some cases loses longitudinal stability. The longitudinal bend of the beam-strip is described using the following equation for the surface layer in partial derivatives [5]:

According to [3] $v(x,t) = \sum_{k=1}^{n} z_k(t) \sin\frac{k\pi x}{l_2}$ – transverse deflection of the beam-strip during longitudinal bending (for the case of hinged support of the beam-strip);

β – coefficient of restitution (stiffness) of the elastic foundation of the beam-strip due to the elasticity of the inner layers of the part;

I – moment of inertia of the cross section of the beam-strip;

$T(x,t) = T_A(x,t) = \frac{P}{bl_1} \cdot \left[f_0 - \xi_{max} a cos P_0 t + \xi_{max}^3 v_0^3 \bar{b} cos^3 P_0 t\right]$ – limit value of the tangential force of the beam-strip.

Substituting expressions $v(x,t)$ and $T(x,t)$ into the differential equation [5], we obtain a set of differential equations in simple derivatives:

$$\ddot{z}_k + \omega_{0k}^2[1 - \alpha_k \cos P_0 t + \beta_k \cos^3 P_0 t]z_k = 0. \quad (16)$$

where $k = 1, 2, 3, \ldots$ – simple integers;

$\omega_{0k}^2 = E_cI \cdot \left(\frac{\pi^4 k^4}{m l_2^4} + \frac{\beta}{m} - \frac{\pi^2 k^2}{m l_2^2} \cdot \frac{P}{bl_1} \cdot f_0\right)$ – square of the natural frequency of oscillations loaded with a constant value of tangential force;

α_k, β_k – constant coefficients of the friction characteristic:

$$\alpha_k = \frac{\pi^2 k^2}{m l_2^2} \cdot \frac{P}{bl_1} \cdot \xi_{max} v_0 a \cdot \frac{\beta m l_2^2 b l_1}{E_c I k^4 \pi^4 b l_1 + \beta l_2^4 b l_1 + \pi^2 k^2 P l_2^2 f_0}$$

$$\beta_k = \frac{\pi^2 k^2}{m l_2^2} \cdot \frac{P}{bl_1} \cdot \xi_{max}^3 v_0^3 \bar{b} \cdot \frac{\beta m l_2^2 b l_1}{E_c I k^4 \pi^4 b l_1 + \beta l_2^4 b l_1 + \pi^2 k^2 P l_2^2 f_0}$$

We denote the function $\varphi_k(t)$, which represents the parametric load on the oscillatory system, from equation (16):

$$\varphi_k(t) = \beta_k cos^3 Pt - \alpha_k cos Pt, \quad (17)$$

if the condition [7] is satisfied:

$$\left|\frac{\varphi'_k}{\varphi_k}\right| + \frac{\omega_{0k}}{2\pi} \ll 1. \quad (18)$$

Then we write equation (16) in the form:

$$\ddot{z}_k(t) + \omega_{0k}^2[1 + \mu\varphi_k(t)]z_k(t) = 0. \quad (19)$$

If condition (18) is not satisfied, then the function $\varphi_k(t)$ is determined according to [7] without the transformation effect, through direct integration. According to [5], the generating solution of (19) is represented in the form:

$$z_k(t) = A_k \cos \Psi_k. \quad (20)$$

where $\Psi_k = \omega_{0k} t + \Theta_k$ – time variable; A_k – amplitude of deformation waves for the k-th harmonic; Θ_k – initial phase for the k-th harmonic.

Then, taking into account the generating solution, according to [5], we have:

$$A_k(t) = B_k exp\left[-\frac{\mu_k}{4}\varphi_k(t)\right] \approx B_k\left[1 - \frac{\mu_k}{4}\varphi_k(t)\right], \quad (21)$$

where B_k – constant determined from initial conditions; μ_k – constant parameter set within the range $0 < \mu_k \leq 1$, we take $\mu_k = 1{,}3$ taking into account the value of B_k.

Next, using simple reasoning, we determine the condition under which parametric oscillations in the system will not occur. We consider the expression in square brackets of (21); if it is set to zero, we obtain the transcendental equation:

$$\beta_k cos^3 Pt - \alpha_k cos Pt + 1 = 0. \quad (22)$$

We solve (22) with respect to $\eta = cosPt$, obtaining real values of the variable η, at which the functions $z_k(t)$ will equal zero.

We write instead of (22) the equation for the relative variable η:

$$\eta^3 - \frac{\alpha_k}{\beta_k}\eta + \frac{1}{\beta_k} = 0, \tag{23}$$

which has the solution:

$$\eta = \sqrt[3]{-\frac{1}{2\beta_k} + \sqrt{\frac{1}{4\beta_k^4} + \left(\frac{\alpha_k}{3\beta_k}\right)^3}} + \sqrt[3]{-\frac{1}{2\beta_k} - \sqrt{\frac{1}{4\beta_k^4} + \left(\frac{\alpha_k}{3\beta_k}\right)^3}}, \tag{24}$$

where $= 1, 2, 3, \dots$ – mode number for which zones of absence of oscillatory motions are established.

When considering parametric oscillations, it remains important to determine the frequency range in which the unstable state of the systems develops, leading to parametric oscillations and, in some cases, to parametric resonance.

As follows from [9], the critical state occurs when the parametric load equation takes the form of the Mathieu function and, in magnitude, is equal to or exceeds the critical Euler force [9]. Since the second part of the parametric load in the Hill form does not affect the development of parametric oscillations and resonance, when determining the critical frequencies we focus on the solutions and results obtained in solving the Mathieu equation [8].

Thus, after the transformations performed in [9], we note that the regions of dynamic instability are located around the frequencies that are parametrically excited:

$$\Theta_{*k} = \frac{2\omega_{0k}}{k} \; (k = 1, 2, 3, \dots), \tag{25}$$

where Θ_{*k} – natural frequency of the k-th mode of parametric oscillations during cutting; ω_{0k} – natural frequency of oscillations of the beam-strip for the mode with index k.

Thus, the main parametric resonance occurs when the frequency ratio is:

$$\Theta_* = 2\omega_0, \tag{26}$$

for $k = 1$ (if $k = 2, 3, 4, \dots$ – then condition (25) applies).

It should be noted that under self-excited and parametric oscillations on the surface layers of parts, deformation-wave micro-roughness appears, which can be immediately sheared off by the moving punch. Therefore, deformation micro-roughness, even in the absence of parametric resonance and when operating in the elastic region, are subject to continuous alternating displacements; that is, the surface layers of the parts are in a state of multi-cycle fatigue loading. Moreover, the amplitudes of deformation wave oscillations in the surface layers exceed the corresponding oscillation amplitudes of the subsurface layers. Such deformations promote the separation of the outer layers of the parts from the inner layers.

The internal layers of the materials of the parts tolerate volumetric compression deformation well due to their elastic-plastic properties. However, in the outer layers, due to their brittle properties, critical crack formation and local destruction are observed, which leads to intensive wear of the outer layers of parts during frictional interaction.

Conclusions

1. Under dynamic loading of interacting parts, the role of parametric and self-excited processes in the development of multi-cycle stresses and deformations in the areas of beam-strips under the punch and ahead of the punch increases significantly, which leads to the intensification of wear and failure of the contacting surfaces.
2. To study non-stationary processes in the outer layers of interacting parts, a calculation scheme is applied in which the surface layers of the parts are represented as anisotropic plates on an elastic foundation and loaded with a tangential force determined by a variable friction coefficient, which in magnitude can exceed the critical Euler force.
3. The causes of the occurrence of dynamically unstable states of the beam-strip are identified, in which violations of the integrity of the surface layers of the workpiece and the tool are possible due to the manifestation of supercritical stresses and deformations in the material of the outer layers of the interacting parts.
4. The results of determining dangerous states of the surface layers of parts or workpieces under the action of non-stationary loads in the initial moments of interaction, as well as at the moments of the end of the slip effect or at the moments of speed equalization during oscillations, are obtained.
5. The third dynamic problem for the surface layers of the workpiece is formulated and solved. The layers are represented in the form of a brittle beam-strip on an elastic foundation, loaded with a tangential force caused by non-stationary friction in the contact zone of the parts (under the punch) and in the zone of interaction of the punch edge and the beam-strip, which leads to crack formation and premature wear of kinematic pairs.
6. The practical significance of the studies lies in the fact that for operating mining, metallurgical, and transport machines, the zones of unstable operation are calculated, where conditions may be obtained that do not ensure the high operational quality of such machines.

References

1. T. M.A. Al-Quraan, Ilina O., Kulyk M., Mnatsakanov R., Mikosianchyk O., Melnyk V. Dynamic processes of self-organization in non-stationary conditions of friction. *Advances in Tribology*. 2023. Vol. 2023. Article ID 6676706. P. 13. https://doi.org/10.1155/2023/6676706

2. Alexeyev N.M., Kuzmin N.N., Trankovskaya G.R., Shuvalova E.A. On the similarity of friction and wear processes at different scale levels. Wear. 1992. Vol. 156, Is. 2. P. 251-261 https://doi.org/10.1016/0043-1648(92)90221-S

3. Uchitel' O. D., Malinovs'kij Ju. O., Panchenko G. M. ta in. Intensifikacija procesiv mehanichnoї vzaєmodiї instrumentu z zagotovkoju pri vikonanni visokotochnih ta energoєmnih tehnologichnih operacij metodom tisku i rizannja. *Metalurgijna ta girnichorudna promislovist'.* 2019. № 5-6. C. 96-116. (In Ukrainian)

4. Smirnov V. V., Jakovlev R. A. Mehanika privodov prokatnyh stanov. M., «Metallurgija»,1977. 216 c.

5. Malinovs'kij Ju. O., Vlasenkov D. P., Sitnik S. A., Ter'oshina S. S., Olijnik S. Ju. Traktuvannja energetichnih metodiv u teoriї tertja ta znoshuvannja z poziciї mehaniki sucil'nih seredovishh ta teoriї dislokacij. *Problemi tertja ta znoshuvannja*. 2023. № 4. C. 97-120. https://doi.org/10.18372/0370-2197.4(101).18083 (In Ukrainian)

6. Malinovs'kij Ju. O., Dubrovs'kij S. S., Malinovs'ka S. I. Deformacijno-hvil'ovi efekti pri terti ta znoshuvanni tverdih til. *Metalurgijna ta girnichorudna promislovist'*. 2017. № 2. C. 66-71. (In Ukrainian)

7. Cunningham W. J. Introduction to Nonlinear Analysis. New York : McGraw-Hill, 1958. 303 p.

8. Uchitel' O. D., Malinovs'kij Ju. O., Danilina G. V. ta in. Vpliv parametrichnogo rezonansu na mehanizm rujnuvannja kontaktujuchih poverhon' pri terti ta znoshuvanni. *Metalurgijna ta girnichorudna promislovist'.* 2018. № 4. C. 65-73. (In Ukrainian)

9. Uchitel' A. D., Malinovs'kij Ju. O., Panchenko A. N. ta in. Peredumovi viniknennja avtokolival'nih i hvil'ovih procesiv u formoutvorjuval'nih mashinah pid chas obrobki zagotovok i detalej metodom plastichnogo deformuvannja. *Metalurgijna ta girnichorudna promislovist'.* 2018. № 6. C. 21-29. (In Ukrainian).

Маліновський Ю. О. , Мікосянчик О. О., , Учитель О. Д. , Скворцов О.О., Власенков Д. П., Ситник С. О. , Олійник С.Ю. Динамічні процеси у поверхневих шарах деталей як джерело їх багатоциклічних руйнувань при терті і зношуванні

При роботі різноманітних машин і механізмів можуть мати місце прояви рухів коливального характеру, які збуджуються за нестаціонарної характеристики тертя. Ці коливання мають місце або на майданчику контакта двох деталей, або в зоні, розташованій попереду рухомої деталі. Так у зоні майданчику контакта розвиваються нестаціонарна сила тертя, яка приводить до автоколивань майданчику контакту, а також до виникнення параметричних коливань у зоні попереду діючого штампу. За певному співвідношенню швидкостей прослизання та швидкостей переміщення деталей, автоколивальні і параметричні рухи можуть проявитися, або зникнути, а також посилитись, чи послабитись. Ці коливання є однією з причин виникнення нерегламентованих шорсткостей (деформаційних), тріщинуватостей і лущення деталей, що взаємодіють, а також значних динамічних складових під час навантаження виконавчих, приводних та силових механізмів. Фрикційні та параметричні коливання в поверхневих шарах деталей з деформаційним хвилеутворенням формує залишкові пластичні синусоїдальні нашарування металу, які зрізаються під час взаємодії деталей. Через динамічний характер взаємодії деталей під час тертя, зусилля, що діють на площині контакту (поздовжні) перевищують критичне зусилля Ейлера, яке є параметричним навантаженням, у ряді випадків приводить до небезпечного параметричного резонансу. У роботі визначена область частот поблизу параметричного резонансу. Це є область динамічної нестійкості попереду рухомого штампу. У поставленій і частково вирішеній задачі розглянуті фрикційні та параметричні коливання при взаємодії деталей, які ведуть до утворення деформаційних хвиль, їх часткового, чи повного зрізання, що утворює передумови до інтенсивного зношування, та послідуючого руйнування деталей.

Ключові слова: динамічні навантаження, тертя, знос, фрикційні коливання, автоколивання, балка-смужка, параметричні коливання, параметричний резонанс, головна зона нестійкості, штамп, протяжна деталь, сила тертя, швидкість прослизання, поверхневі шари.