Вісник Тернопільського національного технічного університету
https://doi.org/10.33108/visnyk_tntu
Scientific Journal of the Ternopil National Technical University
2020, № 4 (100) https://doi.org/10.33108/visnyk_tntu2020.04
ISSN 2522-4433. Web: ***visnyk.tntu.edu.ua***

UDC 621.7

MATHEMATICAL MODEL OF DYNAMIC PROCESSES DURING FRICTIONAL HARDENING OF THE CYLINDRICAL SURFACES OF PARTS

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Summary. *The mathematical model of the elastic machine system has been developed, and describes the dynamic processes that occur during the frictional hardening of cylindrical surfaces of parts using a tool with transverse grooves on its working part, which forms a surface hardened metal layer with nanocrystalline structure. Transverse grooves on the working part of the tool increase the intensity of deformation of the surface layer in the contact area of the tool-part and the oscillating processes of the system. Differential equations that describe this process are based on Lagrange equations of the second kind. Based on the solution of the model's the systems of equations, it is possible to determine the velocity and magnitude of displacement of a special device with autonomous drive of the tool, tool and treatment part during machining, reaction of device supports and spindle unit.*

Key words: *friction treatment, nanocrystalline layer, mathematical model, surface hardening.*

https://doi.org/10.33108/visnyk_tntu2020.04.029 *Received 02.08.2020*

Introduction. The main task of mechanical engineering is to ensure the appropriate reliability of machine parts during their operation. The operational properties of machine parts depend on the condition and quality parameters of the contact surfaces and the surface layer. It is necessary to use various methods of surface strengthening (hardening) to improve the operational properties of machine parts. The condition of contact surfaces and surface layers is determined by stereometric (profile deviation, waviness, roughness, load-bearing capacity, etc.) and physical, mechanical and chemical (thickness of the hardened layer, microhardness, residual stresses, structure, texture, phase and chemical compositions, etc.) [1].

One of the methods of improvement of the machine parts operational properties is to create amorphous and nanocrystalline structures in their surface layers [2, 3]. The formation of nanocrystalline structures in the surface layers of massive parts is possible due to the action of highly concentrated energy sources (ion implantation, laser, plasma treatment, etc.) [4, 5], as well as under the action of intense plastic deformation [6]. Under the action of highly concentrated energy sources, the surface layers of massive parts are heated to obtain a high-temperature equilibrium structure, which is then quickly cooled to a low temperature at which the metal structure is far from equilibrium [7]. The formed surface layers consist of nanosized blocks (crystallites), which differ in atomic structure, crystallographic orientation, chemical and phase composition. They are microstructurally heterogeneous.

Literature review. Friction treatment refers to surface hardening methods using highly concentrated energy sources. This energy flow is formed in the contact area of the tool and the part due to the high-speed friction of the tool on the treated surface. The metal of the surface layer is heated locally at high speeds to the austenitization temperature. After the energy source displacement, the surface layer is rapidly cooled due to removing of the heat to the part depth. Due to the tool friction in the contact area of the tool-part shear deformation of the metal in the surface layers of the part occurs during machining. A nanocrystalline reinforced (white) layer is formed in the surface layers of the metal [8].

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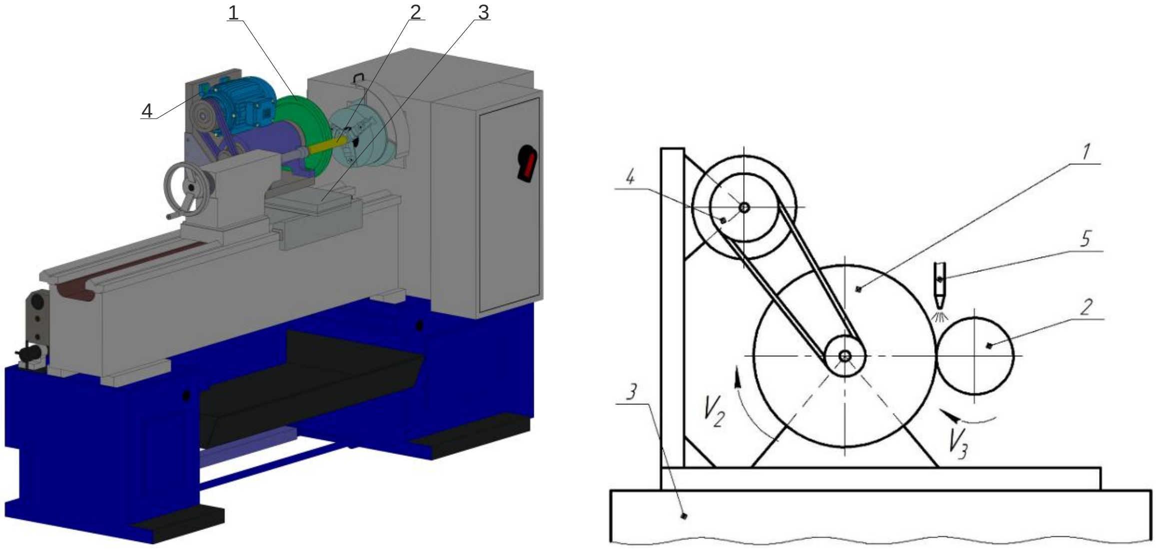
According to the kinematics of the process, friction treatment is similar to grinding. Flat or circular grinding machines are used to implement it, as well as special equipment based on a lather machine. A metal disk is used as a tool, which is installed instead of an abrasive wheel. The dimensions of the metal disc correspond to the dimensions of the abrasive wheel used on this machine. To form a concentrated energy source in the contact area of the tool-part, it is necessary that the linear velocity on the working peripheral surface of the tool should be 60–90 m/s. For this purpose, it is necessary to modernize the unit of the main drive of the machine [9–11].

Strengthening of cylindrical surfaces can also be carried out on the modernized lather machine on which instead of the tool-post the special device for the independent drive of the tool is established. (Fig. 1). The drive provides a tool rotation speed of 60–90 m/s. All machine movements are saved. The tool-disk was made of stainless steel. The outer diameter of the tool is 240 mm, the width of its working part is 6–8 mm (Fig. 2). To improve the displacement of the tool with a transverse feed, the rounding is made with a radius of 1–1.5 mm on both sides of the working part of the tool. The radial beating of the working surface of the tool wasn't more than 0.02 mm, and the roughness wasn't more than Ra 0.4 μm. The tool was mounted directly on the conical part of the spindle of a special device. Before the tool was installed on the spindle, it was statically balanced on the device for grinding wheels balancing.

In order to reduce the setting processes of the contact surfaces in the contact area of the tool-part and to improve the quality of the treated surface, the technological medium was fed into the processing area. Mainly mineral oil with active additives containing polymers is used as a technological medium. The technological medium is also a source of chemical elements for surface alloying of machined surfaces of parts. During processing under the action of high temperatures and pressures, the technological medium is decomposed into constituent chemical elements and the diffusion of the latter occurs into the metal surface layer of the machined parts.

During friction processing, the tool is pressed with a certain force to the treated surface. A source of concentrated energy appears in the contact area of the tool-part. The intensity of the heat flow that occurs in the contact area depends on the speed of rotation of the tool and the force of pressing the tool to the treated surface.



a

b

Figure 1. 3D model (a) and simplified line diagram of the treating process (special equipment for the hardening process) (b): 1 – tool (disk with transverse grooves); 2 – part (workpiece); 3 – carriage of the lathe; 4 – an electric drive of special equipment; 5 – nozzle for feeding the technological medium

To increase the shear deformation of the surface layer metal of the treated workpiece, transverse grooves were made on the working surface of the tool (see Fig. 2). The width of the groove was 3–4 mm and provided a complete escaping of the tool from contact with the treated surface. During the passing of the smooth part of the tool working surface through the contact area with the treated surface, it is heated due to friction. A source of thermal energy acts in the contact zone. At the moment of passing over the contact zone of the groove, the contact of the tool working surface with the treated surface is broken. In the contact area of the tool-part, the action of a heat stream stops, as well as it unloads. Under the action of elastic deformations, the treated surface returns to the previous position. While the next smooth part of the working surface of the tool coming into contact, shock load acts on the contact zone, as well as shear deformation of the surface layer occurs due to friction. The flow of thermal energy acts again in the contact zone.

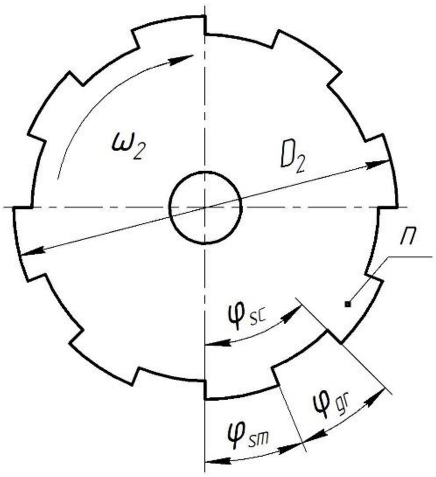


Figure 2. Tool geometry

During machining (turning, milling, etc.) of machine parts with the aim to improve the accuracy and quality of treated surfaces, the dynamic processes in the cutting area are attempted to be reduced. In the process of friction treatment for improving the quality parameters of the strengthened nanocrystalline layer, it is necessary to increase the intensity of dynamic processes in the treatment zone, which significantly affects the efficiency of technological equipment.

Purpose. Research of dynamic processes that take place during the formation of a strengthened nanocrystalline layer in the process of friction treatment was not conducted at all. Therefore, the purpose of this work is to develop a mathematical model of the machine elastic system dynamic processes during the friction treatment of the cylindrical parts working surfaces.

Dynamic model. To research the dynamic processes that take place during the friction treatment of round surfaces, we develop a calculation scheme of the machine elastic system, which is a multi-mass model (Fig. 3). For this, the machine is split into a number of units, each of which is a separate mass. In addition, a part or unit is defined, which is taken as a part with a conditionally infinite mass to which all other masses are «tied». The frame of the machine to which all other masses are «tied» is accepted as part with conditionally infinite weight. The calculation scheme of the machine elastic system is a three-mass model. The relationship between individual masses is described by elastic and damping connections. Impact loads that occur between the treated surface and the working surface of the tool (vertical) are simulated by contact stiffness (c7) and energy damping (μ7) of local elastic-plastic deformation of the part surface.

Symbols meanings used in these models: ω2 and ω3 – angular velocity of rotation of the tool and the part, respectively (rad/s); x1, y1 – horizontal and vertical displacements of special equipment (m); x2, y2 – horizontal and vertical displacements of the tool (m); x3, y3 – horizontal and vertical displacements of the machine table (m). m1 – mass of special equipment (kg); m2 – weight of the tool (disk) (kg); m3 – weight of the treated part (kg); c1 and c2 – stiffness of the machine carriage in the horizontal and vertical directions, respectively (N/m); c3 and c4 – stiffness of special equipment in the horizontal and vertical direction, respectively (N/m); c5 and c6 – stiffness of the machine spindle in the horizontal and vertical directions, respectively (N/m); c7 contact stiffness between the treated part and the tool (N/m); μ1 and μ2 – damping coefficient of the machine carriage in the horizontal and vertical directions, respectively (Ns/m); μ3 and μ4 – damping coefficient of special equipment in the horizontal and vertical directions, respectively (Ns/m); μ5 and μ6 – damping coefficient of the machine spindle in the horizontal and vertical directions, respectively (Ns/m); μ7 – damping factor between the tool and the part (internal damping) (Ns/m); FT – friction between the part and the tool (N).

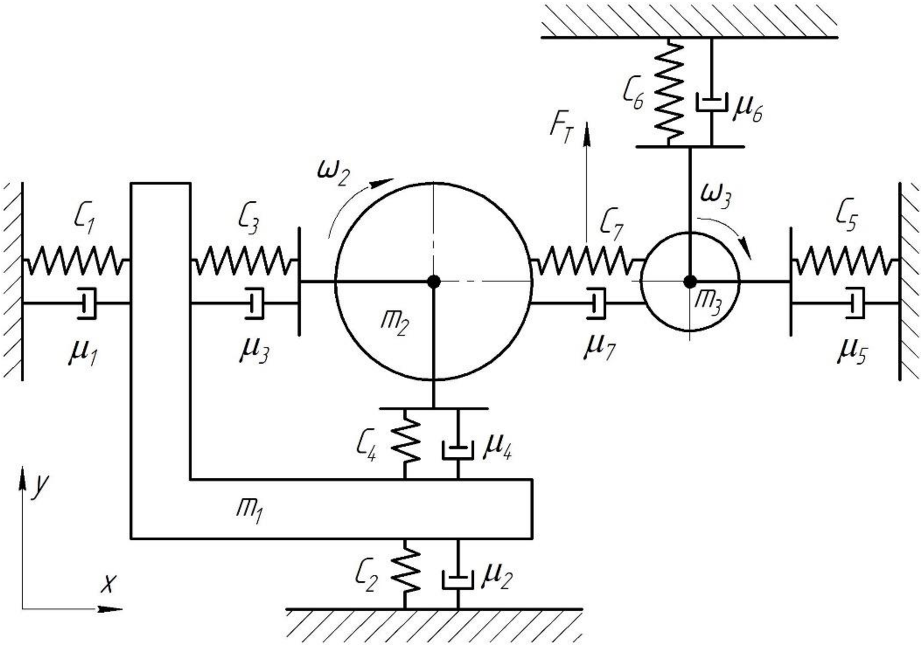


Figure 3. Calculation scheme of the machine

For the mechanical system of the machine, we can identify eight generalized coordinates that characterize the possible movements of the device, the tool, and the part in the horizontal and vertical planes, as well as the rotation of the tool and the part. The corresponding linear displacements of the device, the tool, and the part, and the rotation of the tool and the part are taken as generalized coordinates (Fig. 3).

The generalized coordinates $q_{i,j}$ in our case will be (where $i = 1,2,3$ – mass number, $j = 1,2,3$ – coordinate number):

- for a device of mass m_1: $q_{11} = x_1;\ q_{12} = y_1$.
- for a tool of mass m_2: $q_{21} = x_2;\ q_{22} = y_2;\ q_{23} = \varphi_2$.
- for a part (workpiece) of mass m_3: $q_{31} = x_3;\ q_{32} = y_3;\ q_{23} = \varphi_3$.

Differential equations that describe the system motion, represented on the basis of Lagrange equations of the second kind [12], and have the form:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{x}_i}\right)-\frac{\partial T}{\partial x_i}+\frac{\partial \Pi}{\partial x_i}+\frac{\partial \Phi}{\partial x_i}=Q_{x_i,y_i},$$

where T , Π – kinetic and potential energy of the system, respectively; Φ – energy dissipation function in the system (dissipative Rayleigh function); Q_{x_i,y_i} – generalized forces corresponding to the selected generalized coordinates x_i, y_i .

When forming a mathematical model, we accept the following assumptions: we assume that the law of stiffness change in the elastic elements of the system is in the measures of linearity and corresponds to Hooke's law. This is justified in the case of small deviations of the spring from the equilibrium position; we will consider the mechanical system of the machine as a system of absolutely solid bodies connected by ideal holonomic joints and elastic elements of strictly defined rigidity; in the dynamic model the coefficients of viscous friction in the form of dampers, which are proportional to the displacement velocity of moving sliders along the corresponding guide axes and reflect the energy dissipation in the corresponding elastic elements of the system [13, 14].

Then the generalized force, which is determined by the ratio of the virtual work of the forces $\sum \delta A(F_k)$ acting on each element to the increment of a certain generalized coordinate $\delta q_{i,j}$ for the corresponding masses will have the form:

$$Q=\frac{\delta A}{\delta q_{i,j}}.$$

Then, for special equipment, the generalized force will have the form:

$$Q_{x_1}=\frac{N\cdot\delta x_1}{\delta x_1}=N;\ \ Q_{y_1}=f\,\frac{N\cdot\delta y_1}{\delta y_1}=N.$$

For the tool:

$$Q_{x_2}=\frac{N\cdot\delta x_2}{\delta x_2}=N;\ \ Q_{y_2}=f\,\frac{N\cdot\delta y_2}{\delta y_2}=N;\ \ Q_{\varphi_2}=\frac{M_T\cdot\delta\varphi_2}{\delta\varphi_2}.$$

For the part:

$$Q_{x_3}=\frac{N\cdot\delta x_3}{\delta x_3}=N;\ \ Q_{y_3}=f\,\frac{N\cdot\delta y_3}{\delta y_3}=N;\ \ Q_{\varphi_3}=\frac{M_T\cdot\delta\varphi_3}{\delta\varphi_3}.$$

where f – is the coefficient of friction between the tool and the part; N – is the normal pressure of the tool to the part, which is formed by displacement x_0 of the carriage in the direction of the part (transverse feed on the lather machine), i.e.:

$$N=c_x^*\left(x_0-\Delta x\right),$$

where x_0 – is the displacement of the carriage in the direction of the part, when the smooth part of the disk is in contact with the treated surface, i.e. by means of this displacement the mutual forces of the pressure is formed; Δx – a value that reduces the mutual displacement of the tool to the part due to the non-coaxiality of the two bodies, which is formed by the mutual vertical displacement (Fig. 4); c_x^* – reduced stiffness of the system in the horizontal direction:

$$\frac{1}{c_x^*}=\frac{1}{c_1+c_3}+\frac{1}{c_5+c_7}.$$

If the part and the tool during treatment get mutual vertical displacement, then $a \le R_2+R_3$, and Δx is calculated according to the following relation:

$$\Delta x=\left(R_2+R_3\right)-\sqrt{\left(R_2+R_3\right)^2-\Delta y^2}.$$

$$\Delta y = y_3 - y_2$$

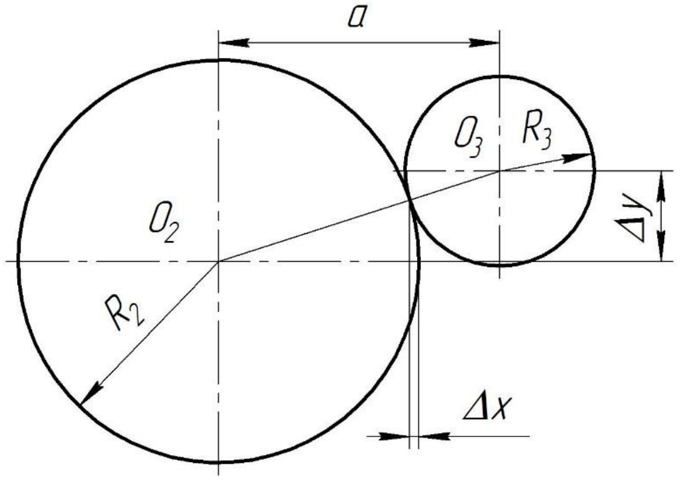


Figure 4. Change of centre distance due to mutual vertical displacement of bodies

Since the normal force varies depending on the contact of the smooth part or the groove on the working part of the tool with the treated surface, then the analytical dependences of the corresponding generalized forces Q_{x_i,y_i} have the form:

$$Q_{x_1}=\begin{cases} N, \quad when\ \omega t=\left(0\ldots\varphi_{sm}\right)+\dfrac{2\pi}{n}\cdot m \\ c_x^*\left(x_0-\Delta x-\left(R-R\cos\left(\omega t\right)\right)\right), \quad when\ \omega t=\left(\varphi_{sm}\ldots\dfrac{\varphi_{gr}}{2}\right)+\dfrac{2\pi}{n}m \\ c_x^*\left(x_0-\Delta x+\left(R-R\cos\left(\omega t\right)\right)-\left(R-R\cdot\cos\left(\dfrac{\varphi_{sc}-\varphi_{sm}}{2}\right)\right)\right), when\ \omega t=\left(\dfrac{\varphi_{gr}}{2}\ldots\varphi_{sm}\right)+\dfrac{2\pi}{n}m \end{cases}$$

The kinetic energy of the system will be defined as the sum of five members that take into account the rectilinear motion of special equipment, tools and parts in the vertical and horizontal planes, as well as the rotational motion of the tool and the part:

$$T=\frac{m_1\left(\dot{x}_1+\dot{y}_1\right)^2}{2}+\frac{m_2\left(\dot{x}_2+\dot{y}_2\right)^2}{2}+\frac{\mathrm{I}_2\left(\dot{\varphi}_2\right)^2}{2}+\frac{m_3\left(\dot{x}_3+\dot{y}_3\right)^2}{2}+\frac{\mathrm{I}_3\left(\dot{\varphi}_3\right)^2}{2}.$$

Let's find the corresponding derivatives of the kinetic energy expression, which are included in the left parts of the Lagrange equations of the 2nd kind:

- for special equipment:

$$\frac{\partial T}{\partial \dot{q}_{11}}=\frac{\partial T}{\partial \dot{x}_1}=m_1\dot{x}_1;\quad \frac{\partial T}{\partial \dot{q}_{12}}=\frac{\partial T}{\partial \dot{y}_1}=m_1\dot{y}_1;$$

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{x}_1}\right)=m_1\ddot{x}_1;\quad \frac{d}{dt}\left(\frac{\partial T}{\partial \dot{y}_1}\right)=m_1\ddot{y}_1;$$

- for the tool:

$$\frac{\partial T}{\partial \dot{q}_{21}}=\frac{\partial T}{\partial \dot{x}_2}=m_2\dot{x}_2;\quad \frac{\partial T}{\partial \dot{q}_{22}}=\frac{\partial T}{\partial \dot{y}_2}=m_2\dot{y}_2;\quad \frac{\partial T}{\partial \dot{q}_{23}}=\frac{\partial T}{\partial \dot{\varphi}_2}=\mathrm{I}_2\dot{\varphi}_2;$$

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{x}_2}\right)=m_2\ddot{x}_2;\quad \frac{d}{dt}\left(\frac{\partial T}{\partial \dot{y}_2}\right)=m_2\ddot{y}_2;\quad \frac{d}{dt}\left(\frac{\partial T}{\partial \dot{\varphi}_2}\right)=\mathrm{I}_2\ddot{\varphi}_2;$$

- for the part:

$$\frac{\partial T}{\partial \dot{q}_{31}}=\frac{\partial T}{\partial \dot{x}_3}=m_3\dot{x}_3;\quad \frac{\partial T}{\partial \dot{q}_{32}}=\frac{\partial T}{\partial \dot{y}_3}=m_3\dot{y}_3;\quad \frac{\partial T}{\partial \dot{q}_{33}}=\frac{\partial T}{\partial \dot{\varphi}_3}=\mathrm{I}_3\dot{\varphi}_3;$$

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{x}_3}\right)=m_3\ddot{x}_3;\quad \frac{d}{dt}\left(\frac{\partial T}{\partial \dot{y}_3}\right)=m_3\ddot{y}_3;\quad \frac{d}{dt}\left(\frac{\partial T}{\partial \dot{\varphi}_3}\right)=\mathrm{I}_3\ddot{\varphi}_3;$$

$$\frac{\partial T}{\partial x_i}=0;\quad \frac{\partial T}{\partial y_i}=0;\quad \frac{\partial T}{\partial \varphi_{2,3}}=0.$$

The potential energy in the system accumulates in the corresponding elastic elements. To find it, let's use the following dependence:

$$\Pi=\frac{c_1\cdot x_1^2}{2}+\frac{c_3\left(x_1-x_2\right)^2}{2}+\frac{c_7\left(x_2-x_3\right)^2}{2}+\frac{c_5\cdot x_3^2}{2}+\frac{c_2\cdot y_1^2}{2}+\frac{c_4\left(y_1-y_2\right)^2}{2}+F_t\left(y_2-y_3\right)+\frac{c_6\cdot y_3^2}{2}.$$

Let's find the corresponding derivatives of the potential energy expression, which are included in the left parts of the Lagrange equations of the 2nd kind:

$$\frac{\partial \Pi}{\partial x_1} = c_1 x_1 + c_3 x_1 - c_3 x_2; \quad \frac{\partial \Pi}{\partial y_1} = c_2 y_1 + c_4 y_1 - c_4 y_2;$$

$$\frac{\partial \Pi}{\partial x_2} = -c_3 x_1 + c_3 x_2 + c_7 x_2 - c_7 x_3; \quad \frac{\partial \Pi}{\partial y_2} = -c_4 y_1 + c_4 y_2 + F_t;$$

$$\frac{\partial \Pi}{\partial x_3} = -c_7 x_2 + c_7 x_3 + c_5 x_3; \quad \frac{\partial \Pi}{\partial y_3} = c_6 y_3 - F_t.$$

The dissipative function Φ for the system, assuming that the energy dissipation is directly proportional to the velocity, is calculated by the following expression:

$$\Phi = \frac{\mu_1 \cdot \dot{x}_1^2}{2} + \frac{\mu_3 \left(\dot{x}_1 - \dot{x}_2\right)^2}{2} + \frac{\mu_7 \left(\dot{x}_2 - \dot{x}_3\right)^2}{2} + \frac{\mu_5 \cdot \dot{x}_3^2}{2} + \frac{\mu_2 \cdot \dot{y}_1^2}{2} + \frac{\mu_4 \left(\dot{y}_1 - \dot{y}_2\right)^2}{2} + \frac{\mu_6 \cdot \dot{y}_3^2}{2}.$$

$$\frac{\partial \Phi}{\partial x_1} = \mu_1 \dot{x}_1 + \mu_3 \dot{x}_1 - \mu_3 \dot{x}_2; \quad \frac{\partial \Phi}{\partial y_1} = \mu_2 \dot{y}_1 + \mu_4 \dot{y}_1 - \mu_4 \dot{y}_2;$$

$$\frac{\partial \Phi}{\partial x_2} = -\mu_3 \dot{x}_1 + \mu_3 \dot{x}_2 + \mu_7 \dot{x}_2 - \mu_7 \dot{x}_3; \quad \frac{\partial \Phi}{\partial y_2} = -\mu_4 \dot{y}_1 + \mu_4 \dot{y}_2;$$

$$\frac{\partial \Phi}{\partial x_3} = -\mu_7 \dot{x}_2 + \mu_7 \dot{x}_3 + \mu_5 \dot{x}_3; \quad \frac{\partial \Phi}{\partial y_3} = \mu_6 \dot{y}_3.$$

The mathematical model that describes the mechanical system dynamics of the machine:

$$\begin{cases} m_1 \ddot{x}_1 + c_1 x_1 + c_3 x_1 - c_3 x_2 + \mu_1 \dot{x}_1 + \mu_3 \dot{x}_1 - \mu_3 \dot{x}_2 = Q_{x_1}; \\ m_2 \ddot{x}_2 - c_3 x_1 + c_3 x_2 + c_7 x_2 - c_7 x_3 - \mu_3 \dot{x}_1 + \mu_3 \dot{x}_2 + \mu_7 \dot{x}_2 - \mu_7 \dot{x}_3 = Q_{x_2}; \\ m_3 \ddot{x}_3 - c_7 x_2 + c_7 x_3 + c_5 x_3 - \mu_7 \dot{x}_2 + \mu_7 \dot{x}_3 + \mu_5 \dot{x}_3 = Q_{x_3}; \\ m_1 \ddot{y}_1 + c_2 y_1 + c_4 y_1 - c_4 y_2 + \mu_2 \dot{y}_1 + \mu_4 \dot{y}_1 - \mu_4 \dot{y}_2 = Q_{y_1}; \\ m_2 \ddot{y}_2 - c_4 y_1 + c_4 y_2 + F_T - \mu_4 \dot{y}_1 + \mu_4 \dot{y}_2 = Q_{y_2}; \\ m_3 \ddot{y}_3 + c_6 y_3 - F_T + \mu_6 \dot{y}_3 = Q_{y_3}; \\ I_2 \ddot{\varphi}_2 + c_7 \left(x_2 - x_3\right) f \, \dfrac{D_2}{2} = M_2; \\ I_3 \ddot{\varphi}_2 - c_7 \left(x_2 - x_3\right) f \, \dfrac{D_3}{2} = M_3. \end{cases}$$

where, M_2 – the driving moment of special equipment:

$$M_2 = \frac{N \cdot f \cdot D_2}{2 \cdot 1000}$$

M_3 – the driving moment of the machine spindle:

$$M_3 = \frac{N \cdot f \cdot D_3}{2 \cdot 1000}$$

The initial pressing force of the tool to the part when the contact occurs with a smooth part of the tool:

$$F_0 = x_0 \cdot c_x^*$$

Initial conditions:

$$\dot{x}_i\big|_{t=0} = 0, \quad \dot{y}_i\big|_{t=0} = 0, \quad \dot{\varphi}_2\big|_{t=0} = 0, \quad \dot{\varphi}_3\big|_{t=0} = 0,$$

$$x_1\big|_{t=0} = \frac{F_0}{c_1 + c_3},$$

$$x_2\big|_{t=0} = \frac{F_0}{c_1 + c_3 + c_7},$$

$$x_3\big|_{t=0} = \frac{F_0}{c_1 + c_3 + c_5 + c_7},$$

$$y_1\big|_{t=0} = 0, \quad y_2\big|_{t=0} = 0, \quad y_3\big|_{t=0} = 0,$$

$$\varphi_2\big|_{t=0} = 0, \quad \varphi_3\big|_{t=0} = 0.$$

The modelling of the tool interaction with the part is carried out by means of contact stiffness and energy damping of local elastic-plastic deformation. Therefore, the condition of checking the presence of mutual contact of the tool with the part is additionally introduced. That is, if the tool will have the displacement in the opposite direction from the part, so the contact stiffness and damping will be absent

$$If\ x_3 - x_2 < 0,\ then\ c_7 = 0,\ \mu_7 = 0.$$

Conclusions. The mathematical model of dynamic processes of the machine elastic system during the frictional strengthening of machine parts cylindrical surfaces is developed in the work.

To improve the quality parameters of the strengthened surface layer with a nanocrystalline structure, a tool-disk with a discrete working part is used, which leads to an increase in the of the system oscillating processes intensity.

Based on the models' system of equations solution, the displacement velocities and the values of the displacements of the tool-disk treated part and a special device for the autonomous drive of the tool, which is mounted on the carriage of the machine during friction treatment, are determined.

The obtained mathematical model allows to determine the supports reactions of the device and the spindle unit, as well as to check the existence of dangerous loads on the parts of the elastic system units of the machine during hardening.

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УДК 621.7

МАТЕМАТИЧНА МОДЕЛЬ ДИНАМІЧНИХ ПРОЦЕСІВ ПІД ЧАС ФРИКЦІЙНОГО ЗМІЦНЕННЯ ЦИЛІНДРИЧНИХ ПОВЕРХОНЬ ДЕТАЛЕЙ

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Резюме. *Підвищення експлуатаційних властивостей можна досягти за рахунок формування у поверхневих шарах масивних деталей нанокристалічних структур. Формування зміцнених шарів можливе при використанні методів обробки з використанням висококонцентрованих джерел енергії. Фрикційна обробка відноситься до методів поверхневого зміцнення з використанням висококонцентрованих джерел енергії, у процесі якої у поверхневих шарах формується зміцнений шар з нанокристалічною структурою. Утворений шар має специфічні фізичні, механічні, хімічні, а також підвищені експлуатаційні властивості, які значно відрізняються від основного металу. Фрикційна обробка плоских деталей за кінематикою процесу подібна до шліфування. Для інтенсифікації процесу формування зміцненого шару з нанокристалічною структурою на робочій поверхні інструменту утворені поперечні пази. Вони формують у зоні контакту інструмент–оброблювана поверхня деталі, додаткові ударні навантаження. Дані ударні навантаження підвищують зсувне деформування металу оброблюваної поверхні деталі під час обробки, що впливає на формування параметрів якості оброблюваної поверхні та поверхневого шару. Розроблено математичну модель пружної системи верстата, яка описує динамічні процеси, що відбуваються під час фрикційного зміцнення циліндричних поверхонь деталей, використовуючи інструмент з поперечними пазами на його робочій частині, у процесі якої формується поверхневий зміцнений шар металу з нанокристалічною структурою. Поперечні пази на робочій частині інструменту збільшують інтенсивність деформування поверхневого шару у зоні контакту інструмент–деталь та коливні процеси системи. Диференціальні рівняння, які описують даний процес, побудовані на основі рівнянь Лагранжа другого роду. На основі розв’язку систем рівнянь моделі можна визначити швидкості та величини переміщення спеціального пристрою для автономного привода інструменту, інструменту та оброблювальної деталі під час обробки, реакції опор пристрою та шпиндельного вузла.*

Ключові слова: *фрикційна обробка, нанокристалічний шар, математична модель, поверхневе зміцнення.*

https://doi.org/10.33108/visnyk_tntu2020.04.029 *Отримано 02.08.2020*