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MODELING AND SIMULATION OF MACHINED SURFACE LAYER MICROGEOMETRY PARAMETERS

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Abstract. The formation of the microtopography of the machined surface is one of the most critical factors in ensuring the effective operating properties of the product. These are indicators such as wear resistance, fatigue strength, provision of friction parameters of moving joints, etc. The most important reason for the formation of microroughness is vibration in the technological surface of the machine-tool-tool-tool-workpiece. This article is devoted to describing a new method of modelling the dynamic processes of machining. The peculiarity of this technique is using the results of rheological modelling (DEFORM). In addition, the consideration of regenerative vibrations of the tool is the difference of the described model. Regenerative oscillations arise due to surface roughness, which will be processed as a result of the previous technological stage of mechanical treatment. The mathematical model and the research results are described in the article. Recommendations for reducing oscillations are given.

Keywords: simulation, roughness, cutting, plastic deformation, surface microprofile, self-oscillation.

Introduction and Problem Statement

An integrated approach to the technological support of the optimal operating capacity of engineering products is based on assessing the quality indicators of machined products depending on design, mechanical and technological factors and predicting the functional properties of parts and their quality indicators. Quantitative and qualitative indicators of the operating efficiency of the operational surfaces of parts, such as wear resistance, fatigue strength, corrosion resistance, tribomechanical quality of joints, etc., are usually determined by indicators of the microtopology of the sliding surfaces of products, the quality of the surface layer (including residual stresses and strains), macrogeometric properties of parts, which is primarily a consequence of the implementation of the technological machining process. In engineering practice, the structure of technological processes for manufacturing parts with specified quality parameters is based, as a rule, on the technological principles of consistently increasing accuracy and reducing the roughness of the operational surfaces. However, this is not enough to effectively implement a functionally-oriented technological process and obtain a high functional quality of products. There is a need for a problem-oriented adjustment of the structure and parameters of technology under the conditions for the effective operation of engineering products.It is crucial in manufacturing precision parts and parts subjected to high mechanical, thermal, chemical, tribomechanical loads or a combination during operation. Indeed, such products often ensure the integrated operating capacity of the product. It is advisable for products that do not meet these operating conditions to use an algorithm that implements the traditional concept of object-oriented technological process planning.

The state of the surface layer loaded during the operation of surfaces is characterized by its hardness, microstructure, magnitude and sign of residual stresses and their occurrence depth. Factors that affect the roughness of the machined surface also affect its plastic deformation. Thus, the plastic strain, the depth of the hardened layer and the height of the roughness components of the treated surface have physical relations, which is too difficult to determine analytically or experimentally. The most effective research method is rheological simulation and confirmation of results experimentally. Such research results will allow the optimal planning of the technological process structure and parameters of considering the interconnected complex of the most significant factors of the part's shape forming process to ensure the specified functional properties of the product.

Thus, we propose a new methodology for planning the technological process of the mechanical processing of products. This methodology consists of offering such a structure and parameters of technological operations at the planning stage that will provide or improve the microgeometry and physical and mechanical state of the surface layer to ensure the quality of operation of heavily loaded parts.

Review of Modern Information Sources on the Subject of the Paper

The idea of functional-oriented technological process planning [1, 2] is to determine and analyze the altitude and step parameters of the roughness of the processed surface necessary to solve the problem of choosing such a structure and parameters of technological operations and steps, which will provide the optimal complex of functional properties of this product in the conditions of its potential operation. The microrelief of the treated surface is formed as a result of the vector addition of three components [3–5] (Fig. 1): the height of roughness component obtained in the process of copying the tool's cutting edge, taking into account the kinematic characteristics of its movement (Δ_1); the height of roughness component, which is determined by the oscillations of the cutting tool (Δ_2) and the component of the roughness profile caused by plastic strains in the workpiece-tool contact zone (Δ_3). It should be noted that the last component of roughness can be neglected because, because this value does not exceed 2–5 % of the machined surface roughness total value [6].

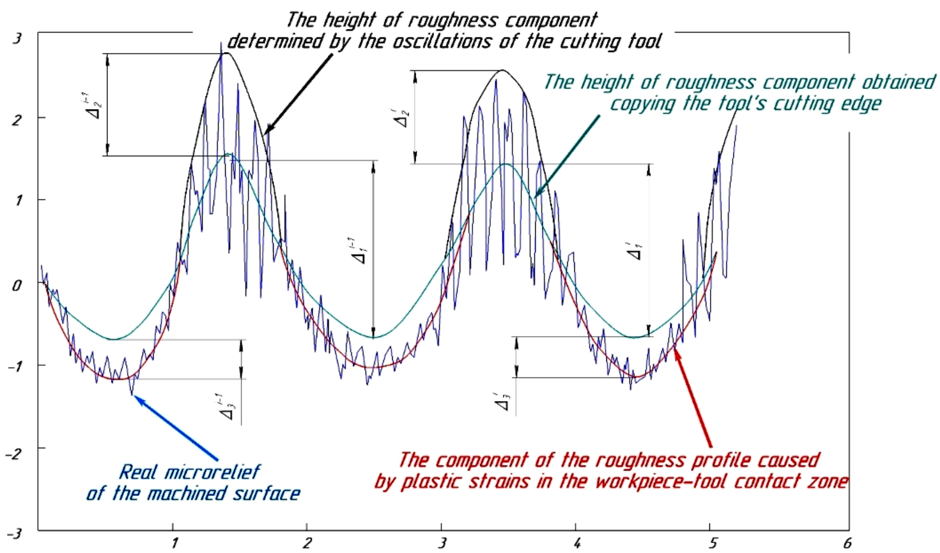

Fig. 1. Scheme for modelling the surface microprofile

Under different conditions of forming surfaces of the workpiece, the feed rate and geometry of the cutting tool (component Δ_1), plastic and elastic strains of the material been machined (component Δ_3), and vibration processes of the machine-device-tool-workpiece (MDTW) system (component Δ_2) distort the geometrically correct shape of roughness profile, breaking them regular distribution on the surface and greatly increasing their height. In some cases, plastic strains and vibrations cause the appearance of surface waviness, reaching significant sizes, and an increase in transverse roughness. As a rule, the dominant influence on the formation of surface roughness has one of the three reasons mentioned above, which determines the nature and magnitude of roughness [7, 8]. However, in some cases (for example, high-speed cutting or finishing), roughness occurs due to simultaneous and almost equivalent exposure to all the above reasons. Due to technical reasons, irregularities are interpreted as copying on the treated surface of the trajectory and shape of the cutting edges. From a geometric point of view, the size, shape and relative position of irregularities (direction of lines – a discrete trace of the tool's edge) are determined by the shape and condition of cutting blades and those elements of cutting parameters that affect the trajectory of the tool relative to the surface.

Geometric and kinematic reasons for the formation of roughness are obvious (Fig. 2): for one revolution of the workpiece (tool) tool (workpiece) moves to the feed rate S, leaving some part of the metal not destroyed by the cutting edge, which forms a residual comb height Δ_1. It is evident that the size and shape of the surface irregularities, consisting of residual combs, are determined by the feed and profile of this cutting tool. The height of the kinematic-geometric component of the roughness without considering the radius at the top of the cutting tool *r* is determined following the feed *S* and the main φ and auxiliary $\varphi_1$angle of the cutting edge.

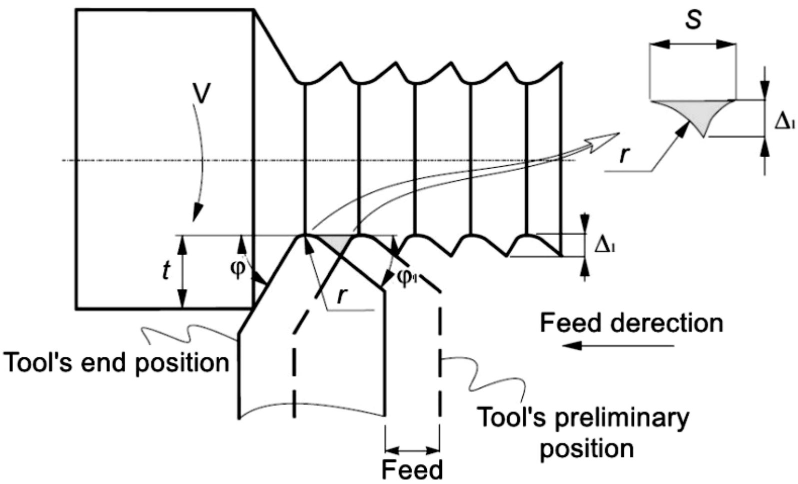

Fig. 2. Scheme of residual micro-relief formation on the machined surface
(a kinematic-geometric component of roughness Δ_1); *t* – cuttingdepth, mm; *r* – tool's corner radius, мм;
S – feedperworkpiecerevolution, mm; φ – side cutting edge angle; φ_1 – end cutting edge angle

Given the value of *r*, the calculation is complicated, as it is necessary to consider the ratio of the main and auxiliary angles in the plan. Using the recommendations [9, 10], the value of Δ_1 from the geometrical construction (Fig. 3) is determined by the following dependences:

– if $\varphi < \arcsin\left(\frac{S}{2r}\right)$ and c:

$$\Delta_1 = \frac{S \cdot \sin\varphi \cdot \sin\varphi_1}{\sin(\varphi + \varphi_1)}; \tag{1}$$

– if $\varphi > \arcsin\left(\frac{S}{2r}\right)$ and $\varphi_1 \geq \arcsin\left(\frac{S}{2r}\right)$ as a result of Chebyshev transform [9]:

$$\Delta_1 = \frac{S^2}{8r}; \tag{2}$$

– if $\varphi < \arcsin\left(\frac{S}{2r}\right)$ and $\varphi_1 < \arcsin\left(\frac{S}{2r}\right)$:

$$\Delta_1 = r\cdot(1-\cos\varphi_1) + \sin\varphi_1\left[S\cdot\cos\varphi_1 - \sqrt{S\cdot\sin\varphi_1(2r - S\sin\varphi_1)}\right]; \quad (3)$$

– if $\varphi < \arcsin\left(\frac{S}{2r}\right)$ and $\varphi_1 > \arcsin\left(\frac{S}{2r}\right)$:

$$\Delta_1 = r\cdot(1-\cos\varphi) + \sin\varphi\left[S\cdot\cos\varphi - \sqrt{S\cdot\sin\varphi(2r - S\sin\varphi)}\right]. \quad (4)$$

Main Material Presentation

During the cutting process, forced oscillations of the machine-workpiece system arise, caused by external forces and self-oscillations of the system, the appearance of which is associated with periodic hardening of the processed metal layer and changes in the conditions of force interaction. tools and workpieces. In addition, forced vibrations of the MDPV system are due to geometric errors in various machine mechanisms. Self-oscillations arise due to an imbalance of internal system factors, i.e., changes in the magnitude of the cutting and friction forces on the working surfaces of the tool, as well as the cross-sectional area of the cut metal layer; formation and violation of growths; elastic deformations of the workpiece and tool, etc. It was seen that the vibration of the cutting edge of the tool relative to the machined surface is an additional source of increasing the roughness of the machined surface. Moreover, the height of the surface roughness will be the more significant, the more twice the amplitude of vibrations of the tool edge to the surface being machined.

The physical mechanism of the occurrence of auto-oscillations (including regenerative ones) acts in the following sequence [11, 12]. Some random perturbation (dynamic processes when incoming or changing the movement of the tool, the unevenness of the allowance, the heterogeneity of the material being processed, the presence of errors that occurred at the stages of the previous processing, the radial whipping of the workpiece or tool, etc.), leads to the emergence of its fading vibrations of the technological system. These oscillations are always accompanied by a change in the shear angle and cutting force P (especially important is the influence of the radial cutting force P_Y on the formation of profile roughness), since the cutting zone is the closing link of the flexible technological system. And if the change in the cutting force is behind in time (phase shifts) relative to the difference in the thickness of the cut, or if with the increase in speed there is a decrease in the radial component of the cutting force (the falling characteristic of the cutting power from the speed), then its own fading oscillations can go into non-extinguishing auto-oscillations, where the energy needed to maintain the oscillation creates a variable cutting force. These two factors – the lag of the cutting force change from the cut thickness change (or the phase characterization of the cutting force) and the characteristic of the cutting force (or friction), which decreases as the cutting speed increases – and are the main primary sources of excitation of the tool's auto-oscillations

In the process of cutting, there are forced oscillations of the machine-tool-workpiece system caused by external forces and self-oscillations of the system, the appearance of which is associated with periodic hardening of the machined metal layer and changing conditions of force interaction of tool and workpiece. In addition, the forced oscillations of the MDTW system are due to geometric errors of different tool machine mechanisms. Self-oscillations occur due to the imbalance of internal system factors, that is, changes in the magnitude of the forces of cutting and friction on the working surfaces of the tool, as well as the cross-sectional area of the cut layer of metal; formation and disruption of outgrowths; elastic deformations of the workpiece and tool, etc. It was evident that the vibration of the cutting tool edge relative to the treated surface is an additional source of increasing the roughness of the machined surface. Moreover, the height of the surface roughness will be greater, the more double the amplitude of the oscillation of the tool edge to the treated surface.

Obviously, the change in cutting depth is equivalent to the shear cutting angle (Fig. 3). Thus, the mechanism of stochastic auto-oscillations can be illustrated by the example of the analysis of the rheological simulation pattern of the cutting process. The obvious is the shift in the phase of the maximum-minimum values of the shear angle and the radial component of the cutting force (Fig. 4).

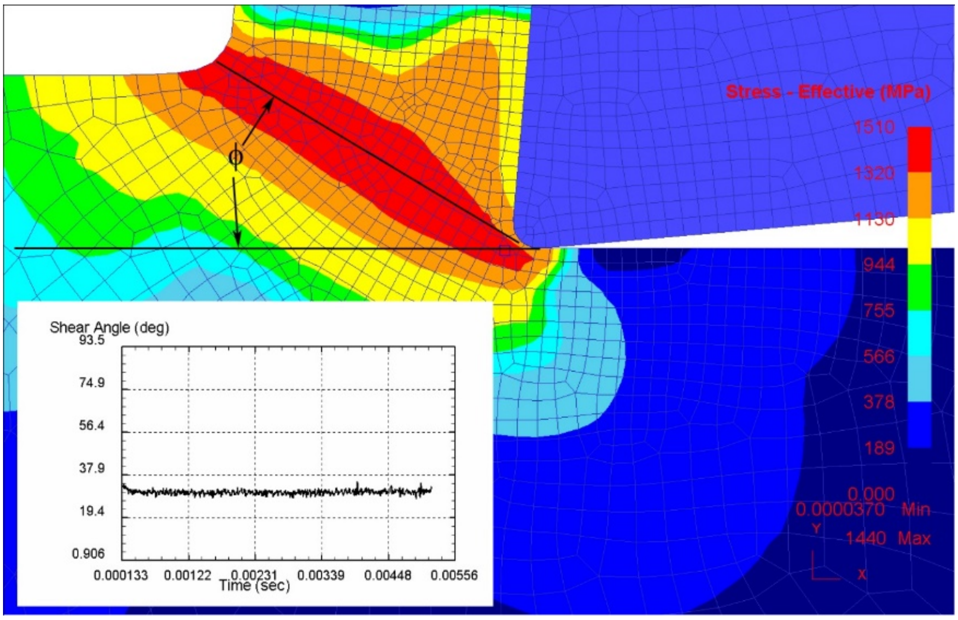

Fig. 3. Example of simulation of the shear angle dynamics during machining of steel part1524 (USA standard ASTM A29-93a)

In the study of self-oscillations, the model of the technological system shown in Fig.5 is used. In this model, the workpiece is considered as an absolutely rigid body with uniform rotational motion. The whole oscillating process involves only the movement of the cutter. The mass of the oscillating system is considered to be concentrated at the top of the edge. Elastic constraints are schematically represented in the form of springs on which the mass is suspended (Fig. 5). The flexible constraints are directed along the principal axes and the system's rigidity. In cutting the tool, taken out of equilibrium for some reason, it begins to oscillate in three directions.

The dynamic instability of the processing system when operating at intensive cutting parameters is mainly due to the secondary excitation (regeneration) of self-oscillations under the influence of a vibration trace on the cutting surface. To achieve maximum efficiency in the management of secondary self-oscillations, it is necessary to directly influence the mechanism of their regeneration, which requires a clear understanding of its nature and patterns. When regenerating self-oscillations, their phase relative to path fluctuations is set independently of the initial conditions, indicating the MDTW system's self-organisation [13, 14]. The disruption of this self-organization by forced change of the self-oscillation phase, for example, periodic smooth transition (modulation) of the cutting speed, opens up a new possibility to control the dynamic stability of the MDTV process system.

For elastic technological systems that carry out intensive auto-oscillations, when modelling them, you can use a design scheme, where the tool (or workpiece) is schematized as a point mass with two degrees of freedom, which oscillates in two mutually perpendicular directions. In each direction, the mass is fixed using elastic and damping elements. There is also a disturbing force on the mass, which is the result of the interaction of the tool's cutting edges with the workpiece material - the cutting force that can be represented through its components P_Z, P_Y. The design scheme for the nonlinear dynamic model of the turning process, taking into account the regenerative auto-oscillations of the cutting tool, is given in Fig. 6 [15].

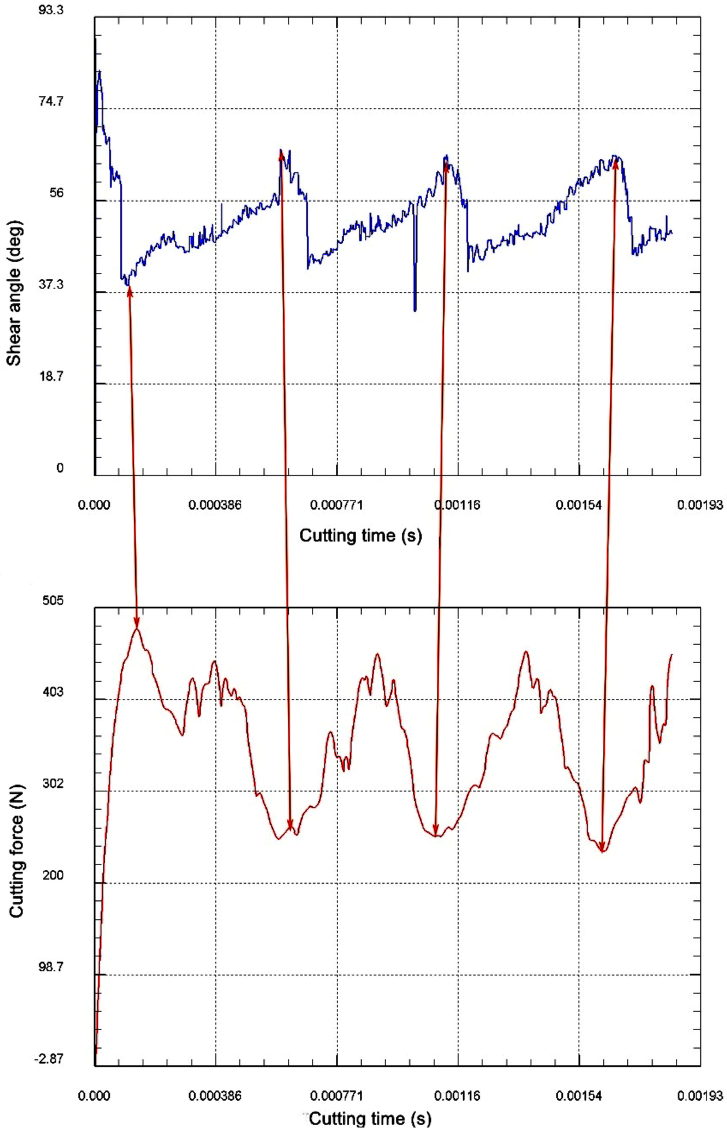

Fig. 4. Mechanism of self-oscillation perturbation (synchronism of phase shift of maximum-minimum values of shear angle (a) and radial component of cutting force (b)

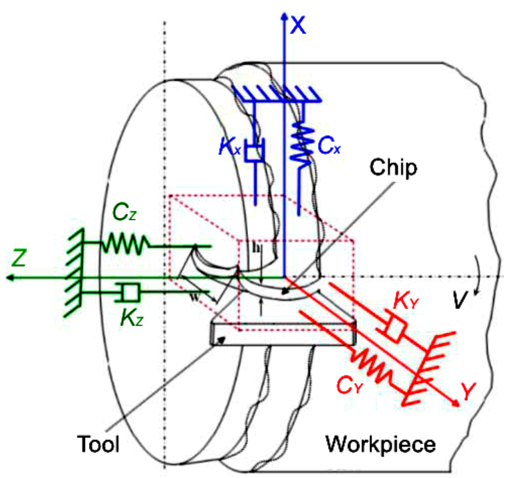

Fig. 5. 3-D diagram of the mechanical model of the technological cutting system with elastic constraints

In general, the classical equation of tool movement can be interpreted (Fig. 6) by a system of equations:

$$\begin{cases} M\ddot{z} + K_Z\dot{z} + C_Z z = P_Z \\ M\ddot{y} + K_Y\dot{y} + C_Y y = P_Y \end{cases}, \tag{5}$$

where M is the reduced mass of the system; K_Z, K_Y are the generalized damping coefficients on the Z and Y axes, respectively; C_Z, C_Y are the reduced system rigidity on the Z and Y axes, respectively; P_Z, $P_Y$are the value of the cutting forces on the axes Z and Y axes, respectively.

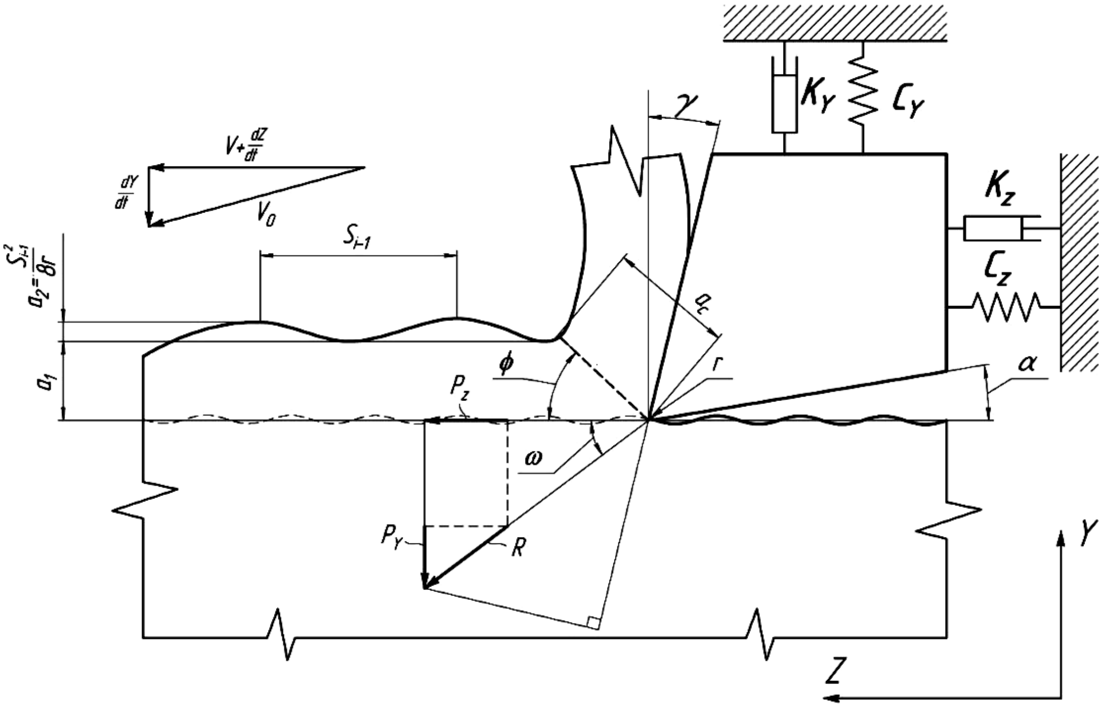

Fig. 6. The design scheme of the dynamic model of the cutting process, taking into account the tool's regenerative auto-oscillations

Solving this system of equations, you can get the values of the parameters that determine the movement of the cutter in the process of vibrations. This motion is the sum of two vibrational activities shifted by a phase angle ω in the direction of the Z and Y axes:

$$\begin{cases} z = A_Z \cdot \sin \varpi t \\ y = A_Y \cdot \sin(\varpi t - \psi) \end{cases}, \tag{6}$$

where A_Z, $A_Y$are the amplitude of cutter apex displacement by corresponding coordinate axes, ϖ is the frequency of oscillations, ψ is the phase shift of oscillations by different axes.

According to [16], the components of the P_Z and P_Y cutting forces can be written as functions that depend on the cutting conditions, tool angles and friction conditions between the tool and the workpiece, namely:

$$\begin{cases} P_Z = \dfrac{a \cdot b \cdot \tau \cdot \cos\omega}{\sin\phi \cos(\phi+\omega)} \\ P_Y = \dfrac{a \cdot b \cdot \tau \cdot \sin\omega}{\sin\phi \cos(\phi+\omega)} \end{cases}, \tag{7}$$

where τ is the tangent stress in the shear plane; ϕ is the shear angle; a and b are the thickness and width of the cutting, respectively; ω is the angle of action between the resulting force and the feed direction.

Taking into account the regenerative oscillations, the actual thickness of the cut a becomes a variable, depending on the constant given value of a_1, determined by the cutting depth, and the dynamic component a_2, formed by micro-and macro-roughness, which appears as a result of the surface layer deformations after the previous technological step or due to errors of the workpiece:

$$a = a_1 + a_2\left(x\right). \tag{8}$$

Since the most significant influence of tool vibrations on the formation of profile roughness is observed during finishing operations, for such conditions, the variable component of cutting depth can be determined by the formula:

$$a_2\left(x\right) = \frac{\Delta_1}{2}\left(1+\sin\left(\frac{2\pi x}{S_{i-1}} - \frac{\pi}{2}\right)\right). \tag{9}$$

Considering that $\Delta_1 = \frac{S_{i-1}^2}{8r}$ (for $\varphi > \arcsin\left(\frac{S}{2r}\right)$ and $\varphi_1 \geq \arcsin\left(\frac{S}{2r}\right)$):

$$a_2\left(x\right) = \frac{S_{i-1}^2}{16r}\left(1+\sin\left(\frac{2\pi x}{S_{i-1}} - \frac{\pi}{2}\right)\right), \tag{10}$$

where S_{i-1} is the feed rate at the previous technological transition; r is the tooltip radius.

The shear stress τ_{xy} slightly depends on the cutting speed [17], and can be represented as a constant value. Shear angle ϕ is a dynamic value that changes over time due to variables: cutting forces, the profile of the treated surface, geometric parameters and shape of the chips.

The average coefficient of friction between the tool and the workpiece is determined by the ratio of the components of cutting forces P_Z and P_Y acting in the formation zone and is derived as follows:

$$\mu = \frac{P_z + P_y \cdot \mathrm{tg}\gamma}{P_z - P_y \cdot \mathrm{tg}\gamma}. \tag{11}$$

In addition, it is known [16] that $a \cdot b = S_i \cdot t$.

The refined nonlinear dynamic model of self-oscillations of the technological system considers the regenerative mechanism of excitation of oscillations during the movement of the tool on the surface of the workpiece formed at the previous cutting movement. In the model, the cutting forces depend on the geometric parameters of the tool and the mechanical characteristics of orthogonal cutting:

$$\begin{cases} M\ddot{y} + K_Y\dot{y} + C_Y y = \tau_{yz}\cdot S_i \cdot \left(t + \frac{S_{i-1}^2}{16r}\left(1+\sin\left(\frac{2\pi z}{S_{i-1}} - \frac{\pi}{2}\right)\right)\right)\cdot\frac{\sin\omega}{\sin\phi\cdot\cos\left(\phi+\omega\right)} \\ M\ddot{z} + K_Z\dot{z} + C_Z z = \tau_{yz}\cdot S_i \cdot \left(t + \frac{S_{i-1}^2}{16r}\left(1+\sin\left(\frac{2\pi z}{S_{i-1}} - \frac{\pi}{2}\right)\right)\right)\cdot\frac{\cos\omega}{\sin\phi\cdot\cos\left(\phi+\omega\right)} \end{cases}, \tag{12}$$

where t is the cutting depth.

For high cutting speeds, taking into account the Merchant formula angle of action between the resulting force and the feed direction is $\omega = \pi/2 - 2\phi$. Then, taking into account the transformations:

$$\frac{\sin\omega}{\sin\phi\cdot\cos\left(\phi+\omega\right)} = \frac{\sin\left(\frac{\pi}{2}-2\phi\right)}{\cos\left(\frac{\pi}{2}-2\phi\right)\cdot\sin\phi} = \frac{\cos\left(2\phi\right)}{\sin\left(\phi\right)\cdot\sin\phi} = ,$$

$$= \frac{\cos^2\phi - \sin^2\phi}{\sin^2\phi} = \frac{\cos^2\phi}{\sin^2\phi} - 1 = \mathrm{ctg}^2\phi - 1$$

$$\frac{\cos\omega}{\sin\phi\cdot\cos(\phi+\omega)}=\frac{\cos\left(\dfrac{\pi}{2}-2\phi\right)}{\cos\left(\dfrac{\pi}{2}-2\phi\right)\cdot\sin\phi}=\frac{\sin(2\phi)}{\sin(\phi)\cdot\sin\phi}=$$

$$=\frac{2\sin\phi\cdot\cos\phi}{\sin\phi\cdot\sin\phi}=\frac{2\cos\phi}{\sin\phi}=2\mathrm{ctg}\phi\qquad,$$

formula (12) will take the form of:

$$\begin{cases} M\ddot{y}+K_Y\dot{y}+C_Y y=\tau_{yz}\cdot S_i\cdot\left(t+\dfrac{S_{i-1}^2}{16r}\left(1+\sin\left(\dfrac{2\pi z}{S_{i-1}}-\dfrac{\pi}{2}\right)\right)\right)\cdot\left(\mathrm{ctg}^2\phi-1\right) \\ M\ddot{z}+K_Z\dot{z}+C_Z z=\tau_{yz}\cdot S_i\cdot\left(t+\dfrac{S_{i-1}^2}{16r}\left(1+\sin\left(\dfrac{2\pi z}{S_{i-1}}-\dfrac{\pi}{2}\right)\right)\right)\cdot 2\mathrm{ctg}\phi \end{cases}. \tag{13}$$

For average cutting speeds, $(V<100\ \mathrm{m/xv})$ an expression is used to calculate the angle of action according to the Oxley formula: $\omega=(\phi-0.28\pi)/0.8$ [18]. Then the formula (13) will look like this:

$$\begin{cases} M\ddot{y}+K_Y\dot{y}+C_Y y=\tau_{yz}\cdot S_i\cdot\left(t+\dfrac{S_{i-1}^2}{16r}\left(1+\sin\left(\dfrac{2\pi z}{S_{i-1}}-\dfrac{\pi}{2}\right)\right)\right)\cdot\dfrac{\sin(1.25\phi-0.35\pi)}{\sin\phi\cdot\cos(2.25\phi-0.35\pi)} \\ M\ddot{z}+K_Z\dot{z}+C_z z=\tau_{yz}\cdot S_i\cdot\left(t+\dfrac{S_{i-1}^2}{16r}\left(1+\sin\left(\dfrac{2\pi z}{S_{i-1}}-\dfrac{\pi}{2}\right)\right)\right)\cdot\dfrac{\cos(1.25\phi-0.35\pi)}{\sin\phi\cdot\cos(2.25\phi-0.35\pi)} \end{cases}. \tag{14}$$

Integrating this system of equations by numerical methods using the MatLab software package, we find the amplitude-frequency characteristics of the oscillations of the technological system (Fig. 7).

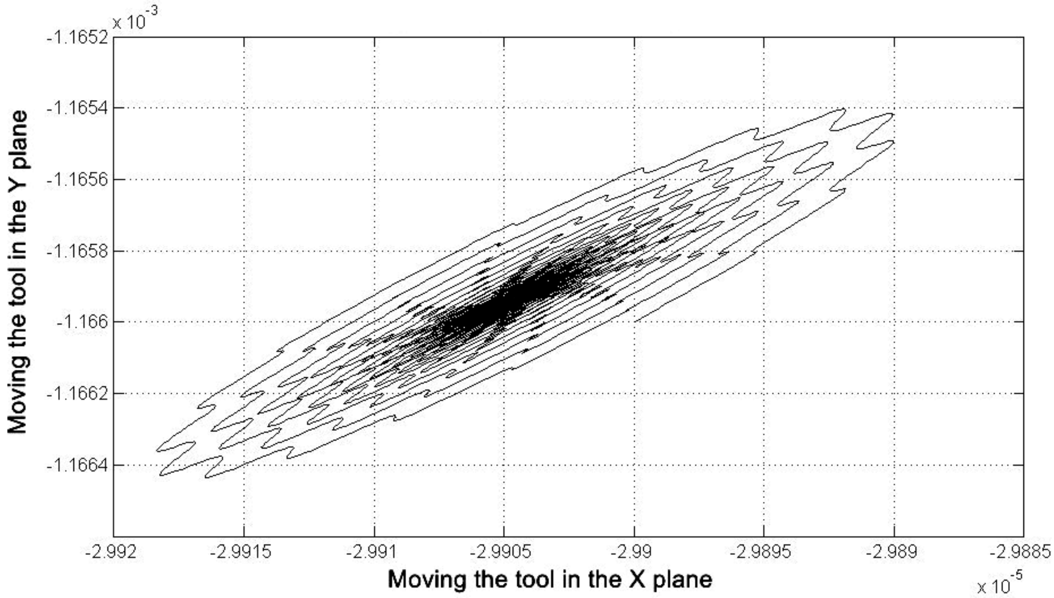

Fig. 7. Results of auto-oscillation simulation of the cutting tool (D = 50 mm; L = 250 mm) of steel AISI 1045 (feed S = 0.25 mm; cutting depth t = 1 mm; speed V = 120 mm/min)

Linear harmonic oscillations of the tool in the radial direction in combination with the main rotational motion of the workpiece and the translational feed course cause the formation of roughness in the longitudinal (coinciding with the direction of the tool's main movement) and radial (perpendicular to it) direction [19]. High-frequency tool oscillations have a significant effect on surface roughness.

The microrelief of the surface in the radial direction is modelled by superimposing on the array of movements of the tool profile of its vertex in the plan, which is described by an arc of radius *r*. In this case [19]:

$$R_{\max} = \frac{2A - H_в}{1000}, \tag{15}$$

where $H_в = R - (R - r)\cos\frac{\psi}{2} - \sqrt{r^2 - \left((R - r)\sin\frac{\psi}{2}\right)^2}$ is the tool marks after machining; $\psi = \arccos\left(1 - \frac{S^2}{2(R - r)^2}\right)$ is thenoseangle, rad.

Other roughness indicators, in particular the average of profile height deviations from the mean line Ra, can be determined by using the equation: $Ra = 0{,}17R_{\max}$

Conclusions

In machining, there are forced vibrations of the machine-tool-workpiece system caused by the dynamic action of external forces and self-oscillations of the system. The self-oscillation processes in terms of frequency are most significant in forming the vibration component of the microroughness. This process arises due to the imbalance of intra-system factors. The most important reasons for self-oscillations occurrence are lag of cutting force change from the change of cutting thickness and dynamic characteristic of cutting force value, which decreases with increased cutting speed. Moreover, the height of surface microroughness will be greater than the doubled amplitude of oscillation of the tool edge relative to the machined surface. The mechanism of self-oscillations appearance is illustrated in the example of the analysis of the rheological simulation picture of cutting, demonstrating a phase shift of the maximum-minimum values of the shear angle and the radial component of cutting force. Considering the regenerative oscillations, the actual cutting thickness becomes a variable value depending on the constant set value of the cutting depth and the dynamic component a. This last component is formed due to micro- and macro roughnesses, which are formed as a result of deformations of the surface layer of the part after a preliminary technological transition or due to errors in workpiece manufacturing.

To determine the vibration component of profile micro-irregularities, a nonlinear dynamic model of automatic oscillations of a technological system is constructed, which also considers the regenerative mechanism of oscillations excitation during tool motion on the workpiece surface during the previous machining steps. The cutting forces depend on the tool's geometric parameters and the orthogonal cutting's mechanical characteristics in the model. By integrating the system of equations by numerical methods using the software MatLab the amplitude-frequency characteristics of vibrations of the technological system are calculated, which allows establishing the value of the vibration component of the microroughness.

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