STUDY OF DYNAMIC CHARACTERISTICS OF THE ROTARY HONING PROCESS IN THE PROCESSING OF NON-RIGID THIN-WALLED PARTS

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Abstract

The article studies the dynamic characteristics of the rotary honing process when machining high-precision non-rigid thin-walled parts. The process is modeled and optimized to determine its rational parameters, providing the lowest cutting forces.

Keywords: rotary honing, process, dynamics, forces, deformation, cutting, modulation, optimization, factors.

I. Introduction

In modern mechanical engineering, due to high requirements for the accuracy and quality of machine parts processing, there is often a need to create new progressive processing methods and special cutting tools that provide high quality of the processed surface, along with increased tool life and process productivity [1-5]. One of these processing methods is the rotary honing method, which provides a roughness of the processed surface within 0.63-2.5 μm, accuracy of 9-10-th quality, and an increase in productivity by 1.5-1.9 times. The widespread use of this process is currently limited by a number of circumstances, in particular, by the relatively small amount of study of the process. The recommendations in the technical literature on choosing the optimal parameters for rotary honing are too general and cannot be extended to all types of processing. The possibilities of rotary honing in the processing of low-rigidity thin-walled parts such as bushings have not been studied at all.

Rotary honing has a number of advantages over other processing methods. These include the corrective ability of the process, high productivity, ensuring high quality and accuracy of processed surfaces, stability of the operational properties of parts, tool durability, etc.

The state of the problem of rotary honing, along with the known advantages, is also characterized by increased cutting forces, which can negatively affect the geometric accuracy of non-rigid thin-walled parts. In this regard, there is an obvious need to study the influence of the main design and technological parameters of the process on the cutting forces, with the aim of optimizing these parameters in relation to ensuring processing with extremely small deformations of parts.

II. Purpose of the work

Research of dynamic characteristics of rotary honing process during processing of high-precision non-rigid thin-walled parts. Modeling and optimization of the process for determination of its rational parameters, providing the least components of cutting forces.

III. Solution tasks

The total error of mechanical processing, as is known, is determined by the combined effect of a number of factors that generate primary elementary errors.

When processing thin-walled, relatively low-rigid parts such as bushings, the accuracy of processing is significantly affected by elastic movements of the elements of the technological system and, in particular, the workpiece under the action of cutting forces. In addition, the accuracy of the parameters of thin-walled parts can be affected by other force factors.

The article examines some issues of calculating the forces acting on the inner surface of bushings, as well as the influence of the main parameters ($P_{sp.}$, 3, $V_{rec.}$, $V_{per.}$) of rotary honing on the components of the cutting force.

To solve the specified problem, thin-walled bushings are considered as shells.

We calculate the concentrated forces affecting the inner surface (Fig. 1).

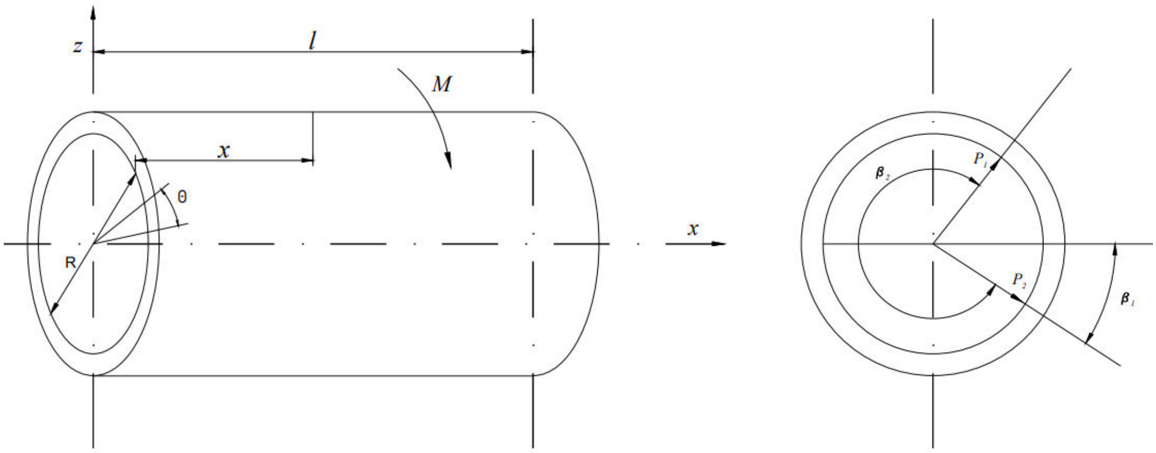

Figure 1: *Scheme for determining concentrated forces acting on an elementary section of the shell surface*

We assume that one end of the shells is fixed. In this case, a concentration of force is applied to a certain area.

We will determine the stress and strain state of the shell for the specified case (2).

In this case, the deformation equations will have the form

$$\frac{\partial^4\varphi}{\partial x^4} + 2\frac{\partial^4\varphi}{\partial x^2\partial y^2} + \frac{\partial^4\varphi}{\partial y^4} = \frac{E\delta}{R}\frac{\partial^2\omega}{\partial x_2^2}\frac{1}{R}\frac{\partial^2\varphi}{\partial x^2} + D\left(\frac{\partial^4\omega}{\partial x^4} + 2\frac{\partial^4\varphi}{\partial x^2\partial y^2} + \frac{\partial^4\varphi}{\partial y^4}\right) = qz \tag{1}$$

We will seek the solution of these equations in the form of double trigonometric series

$$\omega_1 = \sum\sum A_{1mn}\sin\frac{m\pi x}{l}\sin n\theta$$

$$\varphi_1 = \sum\sum B_{1mn}\sin\frac{m\pi x}{l}\sin n\theta$$

These functions satisfy the following boundary conditions:

$$\left.\begin{array}{r}\omega=0\\ M_x=0\end{array}\right\}\quad \begin{array}{l}x=0\\ x=l\end{array}$$

$$\left.\begin{array}{r}V=0\\ N_x=\dfrac{\partial^2\varphi}{R\partial\theta^2}=0\end{array}\right\}\quad \begin{array}{l}x=0\\ x=l\end{array}$$

In addition, at $\theta=0$, the deflection and stress functions, as follows from the nature of the loading, vanish and are odd functions of the angle θ.

To determine the coefficients A_{1mn} and B_{1mn}, it is necessary to substitute the expressions ω_1 and φ_1 into equations (1). But first, we will expand the external acting load into a double trigonometric series by the sought functions. In this case, the external load is represented as a concentrated moment, which is statically equivalent to a pair of forces with a shoulder.

$$d=[2\pi-\beta_2]+\beta_1 R$$

Therefore, we can write

$$P_1=\frac{0{,}5M}{R\beta_1},\ P_2=\frac{0{,}5M}{(2\pi-\beta_2)^2}$$

Thus, in the case under consideration, the external load is represented in the form of two concentrated forces

$$P_1=P_2$$

To reduce this load to the dimension of distributed pressure q_z, it is necessary to represent it in the form

$$q_z=\frac{P_1}{\Delta F}$$

Where $\Delta F=\Delta S_1\Delta X_1$ is a small area on which the force is applied;
ΔS, ΔX - are the dimensions of this area in the circumferential and axial directions.
Then

$$q_z=\frac{P_1}{\Delta S_1\Delta X_1}=\sum_n\sum_m C_{mn}\sin\frac{m\pi x}{l}\sin n\theta$$

Let's multiply the right and left sides of this expression by

$$\sin\frac{m\pi x}{l}\sin n\theta d\theta dx$$

and integrate the right side over X from 0 to l and over θ from 0 to 2π, and the left side over X from the value of X to X + ΔX and from the value of β_1 to $\beta_1+\Delta\beta_1$. Solving the equation C_{mn} obtained after this integration, we determine that

$$C_{mn}=\frac{2\dfrac{P_1}{\Delta S_1\Delta X_1}}{\pi Rl}\frac{l}{\pi m}\left[\cos\frac{\pi m(X_1+\Delta X)}{l}-\cos\frac{m\pi x_1}{l}\right]\cdot\cdot\frac{R}{n}[\cos n\,(\beta_1+\Delta\beta_1)-\cos n\beta_1]$$

Passing to the limit as $\Delta S \to 0$, $\Delta X_1 \to 0$
(where $\Delta\beta_1 = \frac{\Delta S_1}{R}$, $\beta_1 = \frac{S_1}{R}$) we obtain

$$C_{mn} = \frac{2P_1}{\pi_{mn}^2} \cdot \lim_{\Delta x_1 \to 0} \frac{\cos\frac{\pi m(\Delta X + X_1)}{l} - \cos\frac{m\pi x_1}{l}}{\Delta X_1} \cdot \lim_{\Delta S_1 \to 0} \frac{\cos\frac{n(S_1 + \Delta S_1)}{R} - \cos\frac{nS}{R}}{\Delta S_1}$$

or

$$C_{mn} = \frac{2P_1}{\pi R l} \sin\frac{m\pi x_1}{l} \sin n\beta_1$$

and

$$q_z = \frac{2P_1}{\pi R l} \sum_n \sum_m \sin\frac{m\pi x_1}{l} \sin n\beta_1 \sin\frac{m\pi x}{l} \sin n\theta \tag{2}$$

Here X_1, β_1 - are the coordinates of the point of application of force P_1, taking into account the corresponding derivatives of the function φ_1 and ω_1 and the value of the external load q_z, we obtain:

$$B_{1mn}\left[\left(\frac{m\pi R^2}{l}\right) + n^2\right] = -E\delta R A_{1mn}\left(\frac{m\pi R}{l}\right)^2 -$$
$$-\frac{B_{1mn}}{R^3}\left(\frac{m\pi R}{l}\right)^2 + \frac{DA_{1mn}}{R^4}\left[\left(\frac{m\pi R^2}{l}\right) + n^2\right]^2 = \frac{2P_1}{\pi R l} \sin n\beta_1.$$

Solving the obtained equations with respect to the parameters A_{1mn} and B_{1mn}, we determine

$$A_{1mn} = \frac{2P_1 R\left[\left(\frac{m\pi R^2}{l}\right) + n^2\right] \sin\frac{mpx_1}{l} \sin n\beta_1}{\pi E\delta l\left\{\frac{D}{E\delta R^2}\left[\left(\frac{m\pi R}{l}\right)^2 + n^2\right]^4 + \left(\frac{m\pi R}{l}\right)^4\right\}}$$

$$B_{1mn} = \frac{2P_1 R^2\left(\frac{m\pi R}{l}\right)^2 \sin\frac{m\pi x_1}{l} \sin n\beta_1}{\pi l\left\{\frac{D}{E\delta R^2}\left[\left(\frac{m\pi R}{l}\right)^2 + n^2\right]^4 + \left(\frac{m\pi R}{l}\right)^4\right\}}$$

By entering the force values into these expressions using the formula $p_1 = \frac{0.5\mathcal{M}}{R\beta_1}$, we obtain

$$A_{1mn} = \frac{\mathcal{M}\left[\left(\frac{m\pi R^2}{l}\right) + n^2\right]^2 \sin\frac{m\pi x_1}{l} \frac{\sin n\beta_1}{\beta_1}}{\pi E\delta l\left\{\frac{D}{E\delta R^2}\left[\left(\frac{m\pi R}{l}\right)^2 + n^2\right]^4 + \left(\frac{m\pi R}{l}\right)^4\right\}}$$

$$B_{1mn} = \frac{MR\left(\frac{m\pi R}{l}\right)^2 \sin\frac{m\pi x_1}{l} \frac{\sin n\beta_1}{\beta_1}}{\pi l\left\{\frac{D}{E\delta R^2}\left[\left(\frac{m\pi R}{l}\right) + n^2\right]^4 + \left(\frac{m\pi R}{l}\right)^4\right\}}$$

Where A_{1mn} - is the amplitude coefficient of the sine wave when solving trigonometric series;
B_{1mn} - is the amplitude coefficient of the cosine series when solving trigonometric series.
For the force P_2 we obtain similar expressions, but with opposite signs and replacing β_1 with β_2 and $n\beta_1$ with $n(2\pi - \beta_2)$, i.e.

$$A_{2mn} = \frac{M\left[\left(\frac{m\pi R}{l}\right)^2 + n^2\right]^2 \sin\frac{m\pi x_1}{l_1}\frac{\sin n\beta_2}{2\pi - \beta_2}}{\pi E\delta l\left\{\frac{D}{E\delta R^2}\left[\left(\frac{m\pi R}{l}\right)^2 + n^2\right]^4 + \left(\frac{m\pi R}{l}\right)^4\right\}}$$

$$B_{2mn} = \frac{MR\left(\frac{m\pi R}{l}\right)^2 \sin\frac{m\pi x_1}{l}\frac{\sin n\beta_2}{2\pi - \beta_2}}{\pi l\left\{\frac{D}{E\delta R^2}\left[\left(\frac{m\pi R}{l}\right)^2 + n^2\right]^4 + \left(\frac{m\pi R}{l}\right)^4\right\}}$$

Passing in the obtained expressions for A_{1mn}, B_{1mn}, A_{2mn}, B_{2mn} to the limit $\beta_1 \to 0$ and $\beta_2 \to 2\pi$, we have

$$A_{1mn} = \frac{Mn\left[\left(\frac{m\pi R}{l}\right)^2 + n^2\right]^2 \sin\frac{m\pi x}{l}}{\pi E\delta\left\{\frac{D}{E\delta R^2}\left[\left(\frac{m\pi R}{l}\right)^2 + n^2\right]^4 + \left(\frac{m\pi R}{l}\right)^4\right\}}$$

$$A_{2mn} = \frac{Mn\left[\left(\frac{m\pi R}{l}\right)^2 + n^2\right]^2 \sin\frac{m\pi x_1}{l}}{\pi E\delta l\left\{\frac{D}{E\delta R^2}\left[\left(\frac{m\pi R^2}{l}\right)^2 + n^2\right]^4 + \left(\frac{m\pi R}{l}\right)^4\right\}}$$

$$B_{1mn} = -\frac{MRn\left(\frac{m\pi R}{l}\right)^2 \sin\frac{m\pi x_1}{l}}{\pi l\left\{\frac{D}{E\delta R^2}\left[\left(\frac{m\pi R^2}{l}\right)^2 + n^2\right]^4 + \left(\frac{m\pi R}{l}\right)^4\right\}}$$

$$B_{2mn} = -\frac{MRn\left(\frac{m\pi R}{l}\right)^2 \sin\frac{m\pi x_1}{l}}{\pi l\left\{\frac{D}{E\delta R^2}\left[\left(\frac{m\pi R^2}{l}\right)^2 + n^2\right]^4 + \left(\frac{m\pi R}{l}\right)\right\}}$$

The complete solution to the problem can be found by adding up the solutions obtained.

Let us calculate the distributed forces acting on the inner surface of the shell. Let us consider the shell (Fig. 2) loaded with a flow of tangential forces transmitted as a result of the action of the torque $M_{to.}$, in section "b", in order to determine the value of P, taking into account the elementary arc d_s, allocated on the cross-section of the shell

$$\omega = \omega_1 + \omega_2 = \frac{2M}{\pi E\delta l}\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\frac{n\left[\left(\frac{m\pi R}{l}\right)^2 + n^2\right]^2 \sin\frac{m\pi x_1}{l}\sin\frac{m\pi x}{l}\sin n\theta}{\frac{D}{E\delta R^2}\left[\left(\frac{m\pi R}{l}\right)^2 + n^2\right]^4 + \left(\frac{m\pi R}{l}\right)^4} \tag{3}$$

$$\varphi = \varphi_1 + \varphi_2 = \frac{2M}{\pi l}\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\frac{n\left(\frac{m\pi R}{l}\right)^2 \sin\frac{m\pi x_1}{l}\sin\frac{m\pi x}{l}\sin n\theta}{\frac{D}{E\delta R^2}\left[\left(\frac{m\pi R}{l}\right)^2 + n^2\right]^4 + \left(\frac{m\pi R}{l}\right)^4} \tag{4}$$

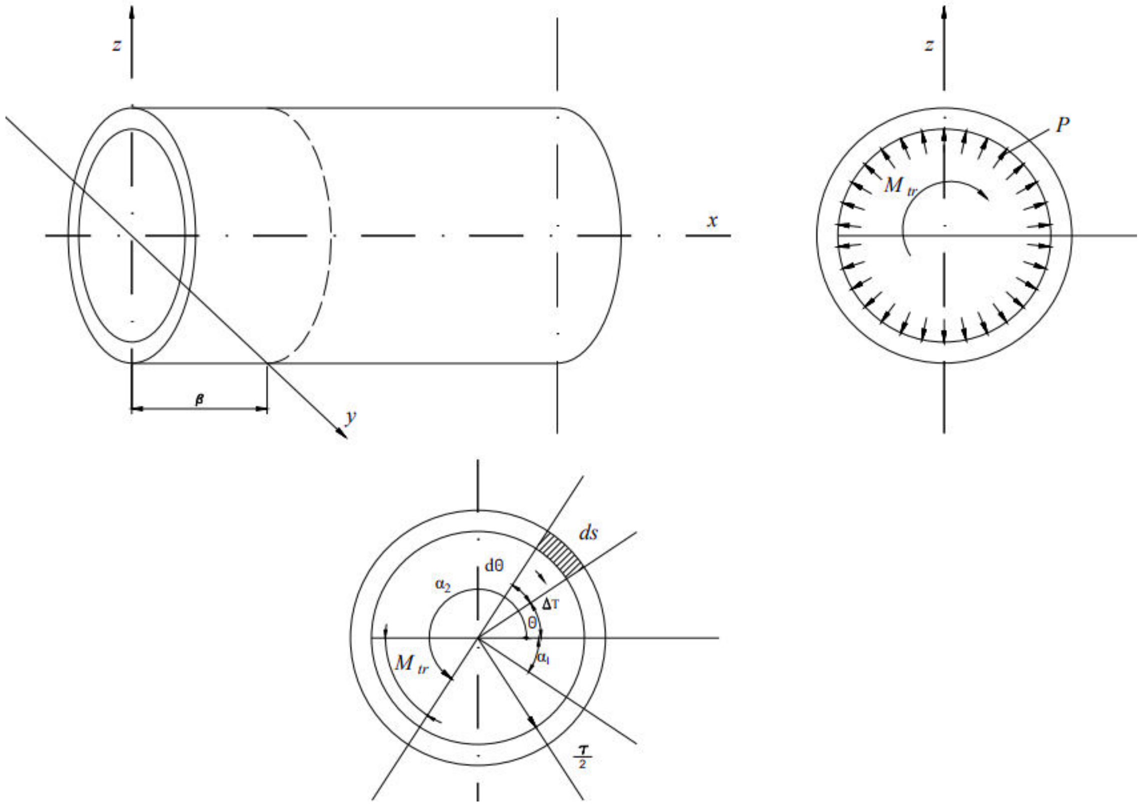

Figure 2: *Scheme for determining concentrated forces acting on the inner surface of shells*

The elementary force dT, acting along the arc d_s, will be equal to

$$dT = pd_s b = prd\theta b(x) \tag{5}$$

Then

$$T = \int_{\alpha_1}^{\alpha_2} prb(x)d\theta = prb(x)(\alpha_2 + \alpha_1) \tag{6}$$

The moment causing the force is equal to

$$M_{torq.} = T \cdot r = pr^2 b(x)(\alpha_2 + \alpha_1) \tag{7}$$

Where

$$P = \frac{M_{to.}}{r^2 b(x)(\alpha_2+\alpha_1)} \tag{8}$$

Substituting (8) into (4) and multiplying by d, we obtain the elementary moment of the tangential load

$$dM = dT \cdot r = \frac{M_{to.} \cdot r \cdot b(x) d\theta}{r \cdot b(x)(\alpha_2+\alpha_1)} = \frac{M_{to.} \cdot d\theta}{(\alpha_2+\alpha_1)} \tag{9}$$

Or section $\theta E[-\beta_1, 2\pi - \beta_2]$

$$M = \int_{-\beta_1}^{2\pi-\beta_2} \frac{M_{to.} d\theta}{(\alpha_2+\alpha_1)} = \frac{M_{to.}}{(\alpha_2+\alpha_1)}(2\pi - \beta_2 + \beta_1). \tag{10}$$

Using the solutions obtained in (2) and (3), taking into account equation (10), we obtain the value of the displacement,

$$\omega = \omega_1 + \omega_2 = \frac{2M_{to.}(2\pi - \beta_2 + \beta_1)}{\pi E\delta l(\alpha_2 + \alpha_1)} \cdot \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} \frac{n\left[\left(\frac{m\pi R}{l}\right)^2 + n^2\right]\sin\frac{m\pi x_1}{l}\sin\frac{m\pi x}{l}\sin\theta}{\frac{D}{E\delta R^2}\left[\left(\frac{m\pi R}{l}\right)^2 + n^2\right]^4 + \left(\frac{m\pi R}{l}\right)^4} \quad (11)$$

$$\varphi = \varphi_1 + \varphi_2 = -\frac{2RM_{to.}(2\pi - \beta_2 + \beta_1)}{\pi l(\alpha_2 + \alpha_1)} \times \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} \frac{n\left(\frac{m\pi R}{l}\right)^2 \sin\frac{m\pi x_1}{l}\sin\frac{m\pi x}{l}\sin n\theta}{\frac{D}{E\delta R^2}\left[\left(\frac{m\pi R}{l}\right)^2 + n^2\right]^4 + \left(\frac{m\pi R}{l}\right)^4} \quad (12)$$

Having the expressions of displacement and stress functions, it is possible to obtain all the internal force factors arising in the shell from

$$M_x = \frac{\partial^2\varphi}{R^2\partial\theta^2},\ N_y = \frac{\partial^2\varphi}{\partial x^2},\ N_{x\,y} = \frac{\partial^2\varphi}{R\partial\theta\partial x}$$

$$M_x = D(\chi_x + \mu\chi_y)$$

$$M_y = D(\chi_y + \mu\chi_x)$$

As is known, the accuracy of the characteristics of machine parts, along with other force factors, largely depend on the components of the cutting forces that arise during their mechanical processing. This circumstance is especially evident when force technological processes are used in the processing of non-rigid thin-walled parts, such as rotary honing.

Rotary honing, along with its known advantages, is also characterized by increased cutting forces, which can negatively affect the geometric accuracy of non-rigid thin-walled parts. In this regard, there is an obvious need to study the influence of the main design and technological parameters of rotary honing on the components of the cutting force, with the aim of optimizing these parameters in relation to ensuring processing with extremely low forces.

The study was conducted according to the methodology described in work (1) using second-order orthogonal planning. As a result of calculations for coded values of factors, the following mathematical model was obtained, characterizing the influence of specific pressure $P_{sp.}$, grain size of diamond stones 3, reciprocating speed $V_{rec.}$ and peripheral speed $V_{per.}$ on the peripheral $P_{per.}$ cutting force.

$$\begin{gathered} Y_{P_{per.}} = 117{,}41 + 5{,}42X_1 + 3{,}22X_2 - 1{,}91X_3 - 1{,}51X_4 - \\ -0{,}08X_1X_2 - 0{,}07X_1X_3 + 0{,}44X_1X_4 - 0{,}21X_2X_3 - \\ -0{,}07X_2X_4 + 0{,}21X_3X_4 + 0{,}47X_1^2 + 0{,}99X_2^2 + 0{,}46X_3^2 + 0{,}42X_4^2 \end{gathered} \quad (13)$$

The reproducibility of the experiments was checked using the Cochran criterion, the significance of the regression coefficients using the Student criterion, and the adequacy of the model for the significance level $\alpha = 0{,}05$ ($F_P < F_T$) using the Fisher criterion.

For natural values of factors, equation (13) has the form:

$$\begin{gathered} P_{per.} = 97{,}51 + 25{,}41P_{sp.} + 6{,}31\,3 - 4{,}23V_{rec.} - 2{,}11V_{per.} + \\ +1{,}21P_{sp.}3 + 1{,}02P_{sp.}V_{rec.} - 1{,}21P_{sp.}V_{per.} + 0{,}91\,3V_{rec.} - \\ -1{,}01\,3V_{per.} - 2{,}1V_{rec.}V_{per.} + 12{,}41P_{sp.}^2 + 4{,}04\,3^2 - 3{,}11V_{rec.}^2 - 1{,}22V_{per.}^2 \end{gathered} \quad (14)$$

As a result of the calculations, the minimum value of the circumferential cutting force was determined, $P_{per.} = 121{,}12N$, with optimal values of the rotary honing parameters: $P_{sp.} = 0{,}6MPa$, $3 = 160/125\ mkm$; $V_{rec.} = 0{,}16\ m/s$; $V_{per.} = 0{,}51\ m/s$.

The mathematical model of the rotary honing process, characterizing the influence of $P_{sp.}$, 3, $V_{rec.}$, $V_{per.}$ on the axial cutting force $P_{a.f.}$ for coded values of the factors is written in the form

$$\begin{gathered} Y_{P_{a.f.}} = 75{,}62 + 6{,}11X_1 + 3{,}27X_2 - 2{,}67X_3 - 2{,}05X_4 - \\ -1{,}21X_1X_2 - 2{,}14X_1X_3 + 1{,}23X_1X_4 + 1{,}41X_2X_3 - \\ -2{,}12X_2X_4 - 1{,}13X_3X_4 - 3{,}14X_1^2 - 3{,}21X_2^2 + 2{,}16X_3^2 + 1{,}02X_4^2 \end{gathered} \quad (15)$$

For natural values of factors, the mathematical model (15) has the following form

$$\begin{gathered} P_{a.f.} = 61{,}43 + 21{,}12P_{sp.} + 3{,}24\,3 - 4{,}14V_{rec.} - 2{,}18V_{per.} - \\ -3{,}21P_{sp.}3 - 2{,}41P_{sp.}V_{rec.} - 2{,}56P_{sp.}V_{per.} + 1{,}27\,3V_{rec.} - \\ -3{,}11\,3V_{per.} - 2{,}46V_{rec.}V_{per.} - 4{,}21P_{sp.}^2 - 4{,}56\,3^2 + 3{,}71V_{rec.}^2 + 2{,}16V_{per.}^2 \end{gathered} \quad (16)$$

The minimum value of the axial cutting force $P_{a.f.}$ at optimal values of the parameters of the rotary honing process ($P_{sp.} = 0{,}6MPa,\ 3 = 160/125\,mkm;\ V_{rec.} = 0{,}16\,m/s;\ V_{per.} = 0{,}51\,m/s.$) is $P_{a.f.} = 87{,}42N$.

IV. Conclusions

Using the developed mathematical models, it is possible to obtain different graphical dependencies characterizing the influence of the parameters of the rotary honing process on the components of the cutting force $P_{per.}$ and $P_{a.f.}$.

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