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INVESTIGATION OF GEOMETRICAL PARAMETERS IN SCREW SURFACES WHIRLING PROCESS

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Summary. *The investigation of the parameters in screw surfaces whirling process is presented. The equation of the trajectory of relative movement of the workpiece and the cutter in parametric form taking into account the movement of the whirling ring along the workpiece is obtained. Appropriate graphs are plotted, which allow to make the conclusion that increasing the rotational speed of the whirling ring results the decrease in the thickness of the metal layer, which is cut during one period of contact between the workpiece and the cutter. It is also show on the graphs that the ratio between the rotational speeds of the whirling ring and the workpiece is decisive. The greater this ratio, the smaller the thickness of the cut layer. The obtained equations make it possible, using the appropriate application software, to determine and predict the shape and thickness of the material cut layers in the cylindrical workpiece by each cutter in whirling ring based on plotted graphs, visually observe the change of trajectory movement when changing cutting conditions and machined surface parameters.*

Key words*: screw surface, trajectory, whirling process, whirling ring.*

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Statement of the problem. Whirling cutting of screw surfaces is a high-performance process providing high quality of the machined surface, which does not form burrs, as it occurs in the milling process, and does not form folds, as it is observed in the rolling process. This process is especially important for machining screw surfaces on long parts with low rigidity and small diameter, in the formation of deep and multi-thread screws with variable pitch. During screw surfaces whirling cutting, not perfect cylindrical surface on the inner diameter is formed, but polygonal one like in milling, while during conventional turning cylindrical surface is formed. However, the maximum distance between the points of the polygon and the cylindrical surface of the inner diameter is up to 0.1 μm, which is much less than with conventional milling. Therefore, in order to predict and control the parameters of the accuracy in such process there is a need to investigate the trajectory of mutual movement of cutters and workpieces depending on the cutting modes for the determination of the material cut layers thickness and protrusions of the formed polygon.

Analysis of available investigation results. The process of machining and strengthening of screw surfaces on lathes using several cutting tools is widely discussed in numerous scientific publications [1, 2, 3, 4], but such processes are different from the whirling cutting of screw surfaces.

It is reasonable to use the process of whirling cutting of screw surfaces for medium-scale production. In general, this process makes it possible to cut screw surfaces up to 10,000 mm long and from 4 mm to 200 mm in diameter and it is widely used in the medical equipment manufacturing [5, 6].

The process of whirling cutting of screw surfaces can be performed on the conventional equipment with special installation or on CNC machines. Quite often in the literature this process is associated with milling, taking into account parameters of such process [7, 8]. The speed of workpiece rotation is from 3 rpm to 30 rpm, while the whirling head rotates at the speed from 1000 rpm to 10,000 rpm. The main processing time is 3–4 times less than during the usual milling method, and during long shafts processing can be 9 times less.

Due to the size of the formed chips, the heat released during cutting is dissipated mainly through chips, thus reducing the need for cooling and lubrication of cutting tools, and the specific energy of the cutting process is lower than in conventional turning [9, 10, 11, 12]. The temperature of the workpiece remains low after the cutting process. It is also recommended to coat the cutting inserts with titanium and aluminum nitride to prevent build-up on the cutting edge and to remove heat quickly. The investigation is also aimed at establishing the qualitative parameters of the formed screw surfaces [13, 14, 15].

The objective of the paper is to investigate the trajectory of mutual movement of the cutters on the whirling head and workpiece with derivation of equations in parametric form, which determine the dependence of geometric parameters of the machined screw surface on the modes of whirling cutting for the determination of the thickness of the cut material layers of and protrusions of the formed polygon.

Statement of the task. One of the progressive ways of forming screw surfaces is the process of whirling cutting (Fig. 1), which provides the formation of screw surfaces on the outer cylindrical surface in one pass on the lathe, using several cutters. During cutting, you can adjust the thickness of the metal layer, cut with one cutter by changing the rotational velocity of the workpiece and whirling head.

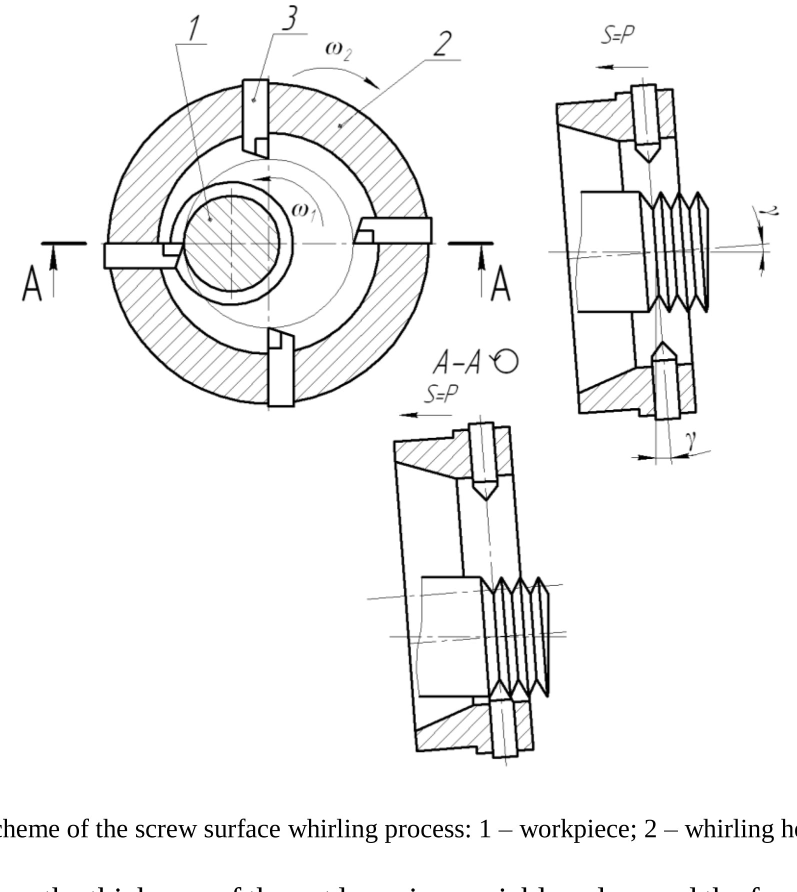

Figure 1. Scheme of the screw surface whirling process: 1 – workpiece; 2 – whirling head; 3 – cutter

In this case the thickness of the cut layer is a variable value, and the formed chips consist of individual particles, which is important in the processing of plastic materials, where the continuous chips are formed during conventional turning.

The scheme of the process of screw surface whirling cutting is shown in Figure 1, where four cutters 3 are evenly placed in a circle on the whirling head 2. They sequentially touch the machine part and cut the material on workpiece 1.

Here the workpiece 1 rotates at low velocity in the opposite direction or in the direction of high-speed rotation of whirling head 2. The whirling head 2 is inclined at angle γ relatively to the workpiece axis corresponding to the angle of the cut screw surface and shifted relatively to the center of workpiece rotation. In addition, the whirling head 2 is fed along the workpiece axis with feed *S* equal to the pitch of the screw surface *P*.

The main geometric parameters of the screw surface whirling process are presented in the calculation scheme in Figure 2.

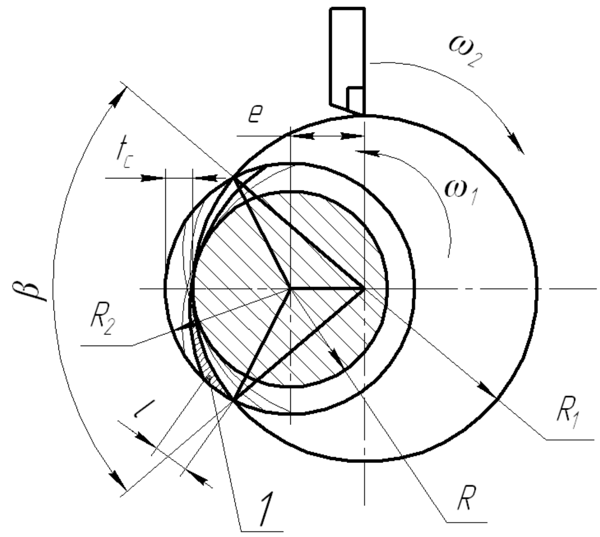

Figure 2. Calculation scheme of geometrical parameters in the screw surface whirling process: 1 - the layer of metal cut during one period of contact between the workpiece and the cutter

From the calculation scheme shown in fig. 2 on the basis of the cosine theorem we determine the contact angle β between the cutter and the workpiece

$$\beta = 2\arccos\left(\frac{R_1^2 + e^2 - R^2}{2R_1 e}\right), \tag{1}$$

where R_1 is the radius of cutter trajectory, mm;
e is the displacement of whirling head rotation centre relatively to the centre of workpiece rotation, mm;
R is the screw surface inner radius mm.

Results of the investigation

In the process of screw surface whirling cutting there is mutual movement of the workpiece and the cutter, resulting in the formation of the machined surface, which is determined by a certain geometric curve. The distance between successive turns of the curve within the workpiece determines the thickness of the metal layer, cut during one period of contact between the workpiece and the cutter. In order to find the trajectory of the mutual movement of the workpiece and the cutter, let us consider the calculation scheme shown in Figure 3.

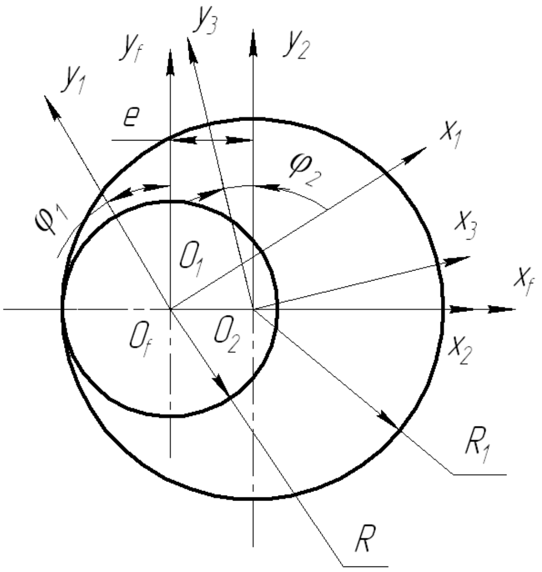

Figure 3. Calculation scheme for determining the trajectory of mutual movement of the workpiece and the cutter in the screw surface whirling process

The relative motion is considered in the scheme shown in Fig. 3, thus the workpiece is assumed to be stationary, and the whirling head rotates around its own axis and the workpiece axis, while the speed of whirling head rotation velocity around the workpiece axis is equal to the velocity of workpiece rotation.

Coordinate system $y_1O_1x_1$ is given the rotational motion around the center of the workpiece O_1. Coordinate system $y_fO_fx_f$ is assumed to be stationary and attached to the machine frame on the axis between the front and rear center. Coordinate system $y_3O_2x_3$ rotates around the center of the whirling head O_2, where coordinate system $y_2O_2x_2$ is shifted relatively to coordinate system $y_fO_fx_f$ by value e of the whirling head rotation center relatively to the workpiece rotation center and moves along axis z_2.

Vector $\overrightarrow{p_1}$ of the cutter tip in coordinate system $y_2O_2x_2$ is presented in parametric form:

$$\vec{p}_1 = \begin{bmatrix} 0 & -R_1 & 0 & 1 \end{bmatrix}^T. \qquad (2)$$

The equation of the trajectory of mutual movement of the workpiece and the cutter in coordinate system $y_fO_fx_f$ is determined by the formula:

$$\vec{p}_2(\varphi) = \vec{p}_1 \cdot \overrightarrow{M_{f3}} \cdot \overrightarrow{M_{f1}}, \qquad (3)$$

where $\overrightarrow{M_{f3}}$ is the transition matrix determining the displacement of the center of whirling head rotation relatively to the center of workpiece rotation along x_f axis in coordinate system $y_fO_fx_f$ from the origin of coordinate system O_2 and the whirling head rotation around z_2 axis;

$\overrightarrow{M_{f1}}$ is the transition matrix determining the rotational motion of the whirling head relatively to z_f axis with the workpiece rotation velocity.

The transition matrix determining the rotational motion of the whirling head relatively to z_f axis.

$$\overrightarrow{\mathrm{M}}_{f1} = \begin{bmatrix} \cos\varphi_1 & -\sin\varphi_1 & 0 & 0 \\ \sin\varphi_1 & \cos\varphi_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{4}$$

where φ_1 is the angle of coordinate system $y_1O_1x_1$ rotation relatively to z_f axis.

Vector between the origin of the whirling head and fixed coordinate system $y_fO_fx_f$ on the plane is as follows:

$$\overrightarrow{O_f O_2} = \begin{bmatrix} -e & 0 & 0 & 1 \end{bmatrix}^T . \tag{5}$$

Accordingly, the transition matrix determining the displacement of the center of the whirling head rotation relatively to the center of the workpiece rotation along x_f axis in coordinate system $y_fO_fx_f$ from the origin O_2 and the whirling head rotation around z_2 axis has is (taking into account that the whirling head rotates in the opposite direction of the workpiece rotation):

$$\overrightarrow{\mathrm{M}}_{f3} = \begin{bmatrix} -\cos\varphi_2 & \sin\varphi_2 & 0 & -e \\ -\sin\varphi_2 & -\cos\varphi_2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{6}$$

where φ_2 is the angle of coordinate system $y_3O_2x_3$ relatively to z_2 axis.

We obtain the resulting matrix as the product of matrices (4) and (6):

$$\overrightarrow{\mathrm{M}}_{31} = \overrightarrow{\mathrm{M}}_{f3} \cdot \overrightarrow{\mathrm{M}}_{f1};$$

$$\overrightarrow{\mathrm{M}}_{31} = \begin{bmatrix} -\cos\varphi_1\cos\varphi_2 + \sin\varphi_1\sin\varphi_2 & \cos\varphi_1\sin\varphi_2 + \sin\varphi_1\cos\varphi_2 & 0 & -e\cos\varphi_1 \\ -\sin\varphi_1\cos\varphi_2 - \cos\varphi_1\sin\varphi_2 & -\cos\varphi_1\cos\varphi_2 + \sin\varphi_1\sin\varphi_2 & 0 & -e\sin\varphi_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \tag{7}$$

Let us determine the trajectories of mutual motion of the workpiece and the cutter in coordinate system $y_fO_fx_f$ as the product of the resulting matrix (7) and vector $\overrightarrow{p_1}$ of the cutter tip in the coordinate system $y_2O_2x_2$ (2)

$$\vec{p}_2(\varphi) = \begin{bmatrix} -R_1\left(\cos\varphi_1\sin\varphi_2 + \sin\varphi_1\cos\varphi_2\right) - e\cos\varphi_1 \\ -R_1\left(-\cos\varphi_1\cos\varphi_2 + \sin\varphi_1\sin\varphi_2\right) - e\sin\varphi_1 \\ 0 \\ 1 \end{bmatrix}. \tag{8}$$

The angles of coordinate systems rotation are determined by the following formulas:

$$\varphi_1 = \omega_1 t; \tag{9}$$

$$\varphi_2 = \omega_2 t \,, \tag{10}$$

where ω_1 is the workpiece rotation velocity rad/s;

ω_2 is the whirling head rotation velocity rad/s.

Then we obtain the equation of the trajectory of mutual motion of the workpiece and the cutter in coordinate system $y_f O_f x_f$ in parametric form

$$x_f(t) = -R_1\left(\cos(\omega_1 t)\sin(\omega_2 t) + \sin(\omega_1 t)\cos(\omega_2 t)\right) - e\cos(\omega_1 t)\,; \tag{11}$$

$$y_f(t) = -R_1\left(-\cos(\omega_1 t)\cos(\omega_2 t) + \sin(\omega_1 t)\sin(\omega_2 t)\right) - e\sin(\omega_1 t)\,.$$

In this case the inner radius of the screw surface is determined by equation

$$R = R_1 - e\,. \tag{12}$$

Based on equation (11), graphs of the trajectory of mutual movement of the workpiece and the cutter (Figures 4 and 5) for different speeds of rotation of the workpiece and the whirling head are constructed. Figures 4 and 5 show that the increase of the rotation velocity of whirling head results in the decrease of the thickness of metal layer, cut during one period of contact between the workpiece and the cutter. The graphs also show that the ratio between the rotational velocity of the whirling head and the workpiece is decisive. The greater this ratio, the smaller the thickness of the cut layer. In Figure 4, the thickness of the cut layer is 0.4 mm at $\omega_2 = 50$ rad/s, and in Fig. 5 it is 0.2mm at $\omega_2 = 100$ rad / s.

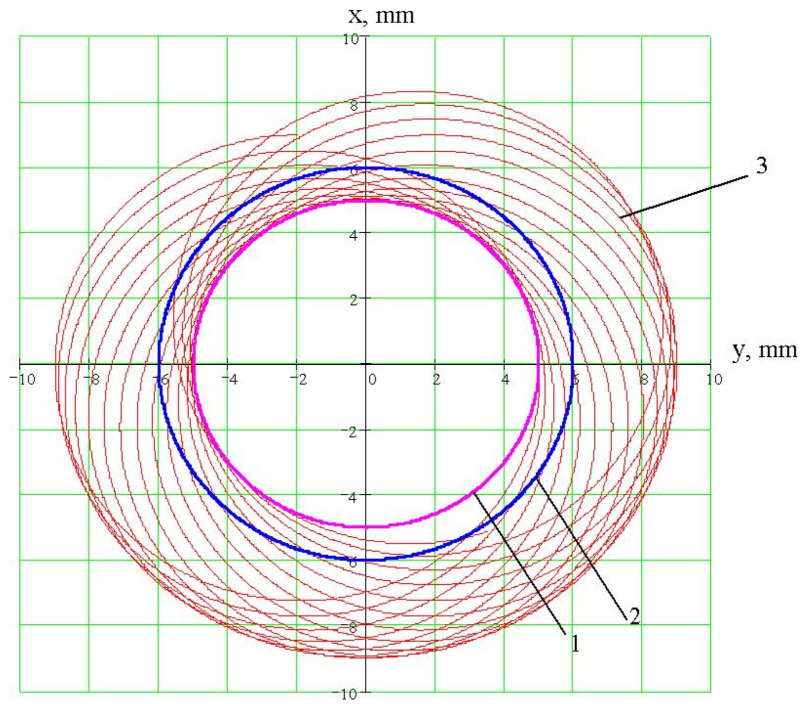

Figure 4. Graphs of the trajectory of relative movement of the workpiece and the cutter R_1 = 7 mm, e = 2 mm, ω_1 = 2 rad/s, ω_2 = 50 rad/s, t=2 s.: 1 – the circle of screw surface inner radius; 2 – the circle of screw surface outer radius; 3 – the cutter trajectory

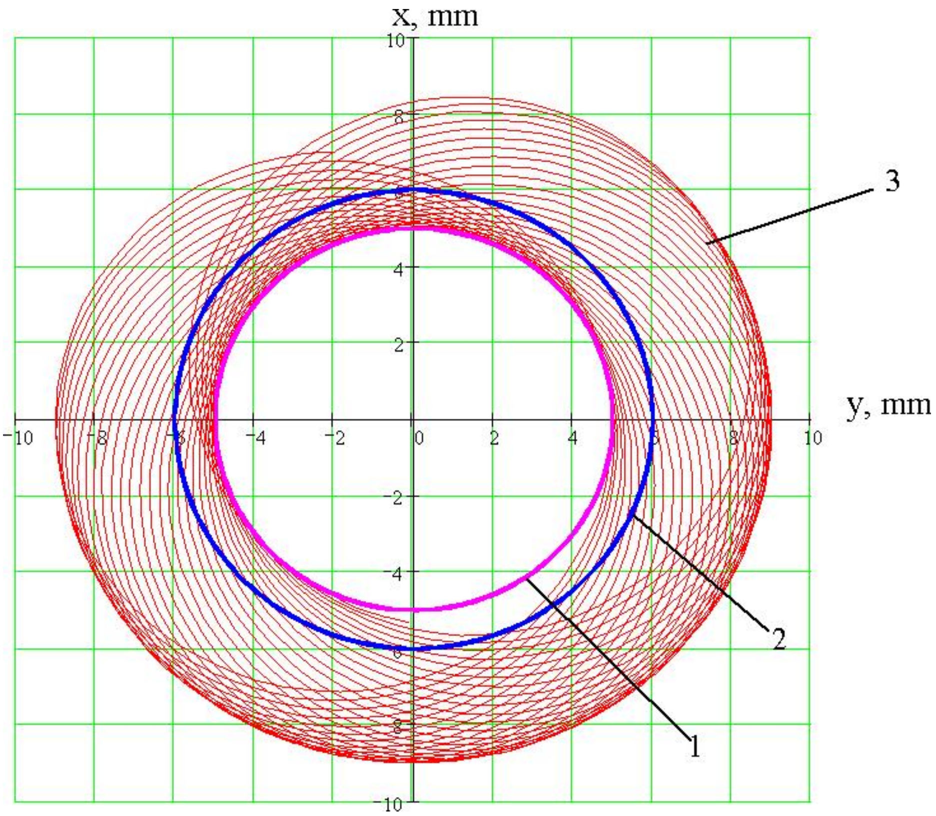

Figure 5. Graphs of the trajectory of relative movement of the workpiece and the cutter $R_1 = 7$ mm, e=2mm, $\omega_1 = 2$ rad/s, $\omega_2 = 100$ rad/s, t = 2 s.: 1 – the circle of the screw surface inner radius; 2 – the circle of the screw surface outer radius; 3 – the cutter rajectory

If we take into account the movement of the whirling head along the workpiece, then the vector between the origin of the whirling head and fixed coordinate system $y_fO_fx_f$ on the plane is written as follows:

$$\overrightarrow{O_f O_2} = \begin{bmatrix} -e & 0 & \frac{P\varphi_1}{2\pi} & 1 \end{bmatrix}^{\mathrm{T}}. \tag{13}$$

Performing transformations similar to the previous ones, we obtain the equation of the trajectory of mutual movement of the workpiece and the cutter in the coordinate system $y_fO_fx_f$ in parametric form, taking into account the movement of the whirling head along the workpiece

$$x_f(t) = -R_1\left(\cos(\omega_1 t)\sin(\omega_2 t) + \sin(\omega_1 t)\cos(\omega_2 t)\right) - e\cos(\omega_1 t);$$

$$y_f(t) = -R_1\left(-\cos(\omega_1 t)\cos(\omega_2 t) + \sin(\omega_1 t)\sin(\omega_2 t)\right) - e\sin(\omega_1 t); \tag{14}$$

$$z_f(t) = \frac{P\omega_1 t}{2\pi}.$$

Based on the parametric equation (14), the graph of the trajectory of mutual movement of the workpiece and the cutter is constructed, taking into account the movement of the whirling head along the workpiece (Fig. 6). The graph shows that during the mutual movements of the whirling head and the workpiece is formed by cutting the screw surface.

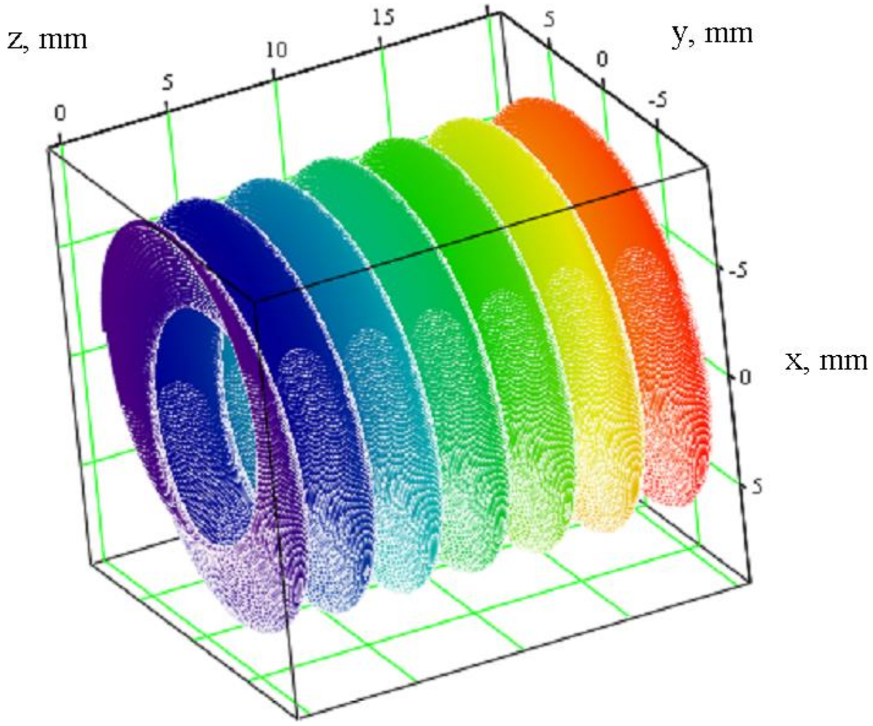

Figure 6. Graph of the trajectory of relative movement of the workpiece and the cutter taking into account the movement of the whirling hrad along the workpiece

Conclusions. The investigation of the parameters of the process of screw surface whirling cutting is presented. The equation of the trajectory of mutual motion of the workpiece and the cutter in parametric form taking into account the movement of the whirling head along the workpiece, using multiplication of the vector of the cutter tip on the transition matrix, determining the displacement of the vortex is obtained. Appropriate graphs are constructed, making it possible to come to the conclusion that the increase of the speed of the whirling head results in the decrease of the thickness of the metal layer, cut during one period of contact between the workpiece and the cutter. The graphs also shows that the ratio between the rotational velocity of the whorling head and the workpiece is decisive. The greater this ratio, the smaller is the cut layer thickness. The obtained equations make it possible, using the appropriate application software, to determine and predict the shape and thickness of the material cut layers of the cylindrical workpiece with each whirling head cutter based on the constructed graphs, visually observe the change of trajectory while changing cutting modes and surface parameters of the machined surface.

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ДОСЛІДЖЕННЯ ГЕОМЕТРИЧНИХ ПАРАМЕТРІВ ПРОЦЕСУ ВИХРОВОГО НАРІЗАННЯ ГВИНТОВИХ ПОВЕРХОНЬ

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Резюме *Розкрито, що одним із прогресивних способів формоутворення гвинтових поверхонь є процес вихрового нарізування, що дозволяє формувати гвинтові поверхні на зовнішній циліндричній* *поверхні за один прохід на токарному верстаті, використовуючи кілька різців. Під час різання можна регулювати товщину шару металу, що зрізується одним різцем за рахунок зміни частот обертання заготовки та вихрової головки. В процесі вихрового нарізування гвинтової поверхні відбувається взаємний рух заготовки та різця, що призводить до формування обробленої поверхні, яка визначається певною геометричною кривою. Відстань між послідовними витками кривої в межах заготовки визначає товщину шару металу, що зрізується за один період контакту між заготовкою та різцем. Представлено дослідження параметрів процесу вихрового нарізування гвинтових поверхонь. Отримано рівняння траєкторії взаємного руху заготовки та різця у параметричній формі з урахуванням переміщення вихрової головки вздовж заготовки, використовуючи множення вектора вершини різця на матриці переходу, що визначають зміщення центру обертання вихрової головки відносно центру обертання заготовки, обертового руху вихрової головки та переміщення вихрової головки вздовж заготовки. Побудовано відповідні графіки, які дозволяють зробити висновок, що підвищення частоти обертання вихрової головки призводить до зменшення товщини шару металу, що зрізується за один період контакту між заготовкою та різцем. Також графіки показали, що визначальним є співвідношення між частотами обертань вихрової головки та заготовки. Чим більше таке співвідношення, тим меншою є товщина зрізаного шару. Отримані рівняння дозволяють, використовуючи відповідне прикладне програмне забезпечення, визначати й прогнозувати форму й товщину зрізаних шарів матеріалу циліндричної заготовки кожним різцем вихрової головки на основі побудованих графіків, візуально спостерігати зміну траєкторії руху різця при зміні режимів різання та параметрів обробленої поверхні.*

Ключові слова: *гвинтова поверхня, траєкторія, процес вихрового нарізування, вихрова головка.*

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