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CROSSING AXES OF WORKPIECE AND TOOL AT GRINDING OF THE CIRCULAR TROUGH WITH VARIABLE PROFILE

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Abstract: In the article the method of grinding with crossed axes of the tool and the workpiece got further developed. The work discloses a method of processing details having an external surface with a profile in the form of an arc of a circle of variable radius (for example, rolls of pipe rolling mills). The particular three-dimensional geometric models of the processing, shaping and profiling of abrasive wheels have been developed. A method for controlling the grinding process, which ensures the removal of allowances along equidistant curves has been offered. The developed method of grinding provides a constant depth of cutting according to the coordinate of profile processing. This is achieved at the expense of the synchronous inclination of the wheel and its insertion by the size of the allowance. The diameter of grinding wheel affects on the maximum angle of orientation of the wheel has been proven. It has been shown that increasing the diameter of the abrasive wheel has led to a slight decrease in value orientation angle.

Key words: Circular Trough, Grinding, Equidistant Curves, Cutting Edge, Abrasive Surface, Abrasive Materials, Crossed Axes, Abrasive Wheel, Orientation Angle, Grinding Performance

1. INTRODUCTION

Details having the shape as bodies of rotation with a profile in the form of a circular arc or spiral surface are widespread in modern engineering. As examples of the ring bearings, spindles, rollers of the tube mills, the mandrel cold rolling tubes. To working surfaces of these details there are high demands on the geometrical accuracy and surface quality (Grabchenko et al., 2016). Finishing profiles of these details are carried by grinding.

The most efficient method of grinding surfaces of rotation with a profile in the form of a circular arc shaping is by copying. This method is characterized by high efficiency and simplicity of shaping movements. But this method has several disadvantages:

- Uneven specific load and thickness of the cutting layer along the profile of the abrasive tool, which results in uneven wear (Abidi et al., 2013; Anderson et al., 2011);
- Variable processing capacity in the process of infeed, maximum value of filing per rotation is determined at the time of forming the center point of the profile (Cong Sun et al., 2018);
- The temperature at the area of processing edge portions of part profile is a limiting factor, because the ratio of the thickness of the cutting layer az to the radius of cutting edge ρ does not exceed 0.1, which leads to increased friction. For example, when processing the bearing rings, the edge portions of the profile have a large inclination with respect to the rotation axis of a detail, for them, the contact arc at processing is more than the initial arc. Contact is carried throughout the profile length (Peng et al., 2016; Kalchenko et al., 2016);
- infeed length $l = \delta / cos\theta_{max}$ greater than allowance for processing δ and depends on the maximum angle of ascent profile forming θ_{max} (Tian et al., 2015).

Using method-oriented processing tool which further changes the angular orientation relative to the detail, can eliminate these shortcomings. Material removal is done by lateral movement of the wheel and its rotation in the plane in which the axis of wheel rotation and detail are located.

Consider the process of form-building processing roll rolling for manufacturing thin-walled seamless tubes, which has a profile in the form of a circle arc and requires high geometric accuracy and quality of processing.

Thin-walled seamless tubes are made by cold rolling at tube mills. In order to get high quality tubes it has to be ensured with high accuracy of form-building elements of states. The basic elements – is a tube-roll which has an annular trough, which forms a tube directly. The working part of the trough consists of a pressing area and a calibrating area. The tube is deformed on pressing area, which has a variable profile (Stepien, 2009; Kalpana, Arunachalam. 2018). The calibration roll trough section has a constant radius of a form-building surface. No matter what area is that, the center of trough profile has a constant radius centered on the axis of the roll rotation (Grabchenko et al., 2016).

Finishing roll trough is performed by grinding. Rolls are made of alloy tool steel and tempering to the hardness of HRC 58-62. To produce high-quality thin-walled tubes, trough profile deviation on calibrating area should be within 0,01-0,03 mm and roughness should be Ra 0,63-0,32 μm. The allowance for final polishing should not exceed 0.3-0.5 mm (Grabchenko et al., 2016).

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At the present stage for processing of variable troughs profile mainly are used two basic techniques: rounding and touch.

For grinding by a method of rounding the processing is performed by grinding wheel that has a profile in a shape of arc of a grinding wheel, which center moves on equidistance to the profile. The shaping occurs with parallel axis of the roll and grinding wheel which lies in one plane. The main disadvantage of this method is the shaping of the contact point of the grinding wheel and workpiece, which significantly reduces the processing performance. This method of processing is implemented on grinding machines.

The method of the touch is realized by using special constructions of machines that allow the tool to rotate around a vertical axis. The radius of axial profile of grinding wheel is equal to the radius of calibration area of trough. Therefore, the shaping of this area is carried out by a method of copying with a contact line, which increases productivity and the quality finishes. The shape crimping area that has a variable trough profile is carried out by rounding point of a contact, which reduces the performance compared to processing trough with a constant radius of the profile (Grabchenko et al., 2016; Li, Axinte 2016).

The analysis of existing methods showed that at this stage there is no way for grinding rolls with a variable profile which would allow the process by copying not only the calibrating area which has a constant radius of a profile but also crimping.

All these ways of grinding trough variable profile are carried out within two operations. This leads to the formation of the transition that reduces the quality of a shaping tube. This error specifically impacts the roll at the calibration area.

Thus, the aim of this work is to develop a method of grinding, which increases the accuracy of the roll shaping and processing performance through the use of a method of copying on crimping and calibration trough sections with a linear contact of instrument and workpiece. It is necessary to develop modular 3D models of profiling of abrasive grinding wheel, shaping and removal allowance that provide the processing by the equidistant curves.

2. DEVELOPMENT OF THE TROUGH MODEL

The mathematical description of nominal workpiece surface can be performed by spherical module:

$$\overline{r}_w = S^{w}_{\theta\cdot y_w\cdot\varphi_w\cdot y_p}\cdot e^{-4}, \qquad (1)$$

where: $\overline{r}_w$ – is the radius vector of the surface of the ring trough with variable profile of rolling roll; $S^{w}_{\theta\cdot y_w\cdot\varphi_w\cdot y_p}$ – spherical module is a matrix of switching from the starting point in a coordinate system of the workpiece; $e^{-4} = (0,0,0,1)^T$ – radius vector of starting point (Grabchenko et al., 2016; Kacalak et al., 2013, Kacalak W., Budniak Z., 2015; Uhlmann et al., 2016).

Spherical module of workpiece is a product of one-coordinate matrix M_2 - moves along the axis *OY*, M_6 and M_4 - turns about *OZ* and *OX* axes, respectively:

$$S^{w}_{\theta\cdot y_w\cdot\varphi_w\cdot y_p} = M_6(\theta_w)\cdot M_2(y_w)\cdot M_4(\varphi_w)\cdot M_2(y_p),$$

where θ_w – is the angle of rotation around the axis of the workpiece rotation (Fig. 2); y_w – is the distance from the center of the profile to the axis of the workpiece rotation; φ_w – is the angle of rotation around the axis of *OX*; $y_p = \rho$ – is the radius profile of the workpiece. Parameters of the matrices y_w, φ_w, y_p for pressing section of the roll are variables and the functions of the independent parameter θ_w. On the calibration area, where profile is unchanged, they become constant.

$$M_2(y_w)=\begin{pmatrix}1&0&0&0\\0&1&0&y_w\\0&0&1&0\\0&0&0&1\end{pmatrix}, M_2(y_p)=\begin{pmatrix}1&0&0&0\\0&1&0&y_p\\0&0&1&0\\0&0&0&1\end{pmatrix},$$

$$M_4(\varphi_w)=\begin{pmatrix}1&0&0&0\\0&cos\varphi_w&-sin\varphi_w&0\\0&sin\varphi_w&cos\varphi_w&0\\0&0&0&1\end{pmatrix},$$

$$M_6(\theta_w)=\begin{pmatrix}cos\theta_w&-sin\theta_w&0&0\\sin\theta_w&cos\theta_w&0&0\\0&0&1&0\\0&0&0&1\end{pmatrix}.$$

The calculation of the models (1) in the MathCAD allowed to simulate graphic representation of a trough which is a subject to processing. Initial data of processing: trough diameter $D_w = 2R_w = 80$ *mm*, radius of the profile on the calibrating area ρ = 12 mm, tolerance *0.02 mm*, sector angle ξ = *140º*, difference of the radii on the crimping area is ΔR = *2.5 mm*, surface roughness *Ra = 1.25* microns, the material of workpiece - alloy steel, hardness *HRC = 58 ... 62*, allowance for processing *0.4 mm*. The parameters of the grinding wheel: diameter *150 mm*, grain 40, bunch of ceramic.

The tool radius vector in a modular kind is described through the form of details and transition matrix:

$$\overline{r_t} = M_{tw}\cdot\overline{r}_w, \qquad (2)$$

where: M_{tw} – is the transition matrix from the coordinate system of the workpiece to the coordinate system of the tool.

The matrix of transition (2) is the product of two spherical modules:

$$M_{tw} = S^{\varphi_t}_{\theta_t\cdot y_c}\cdot S^{O}_{\psi}, \qquad (3)$$

where: $S^{\varphi_t}_{\theta_t\cdot y_c}$ – is the module of the shape-building of a tool; S^{O}_{ψ} – is the module of the angular orientation of the tool relative to the details.

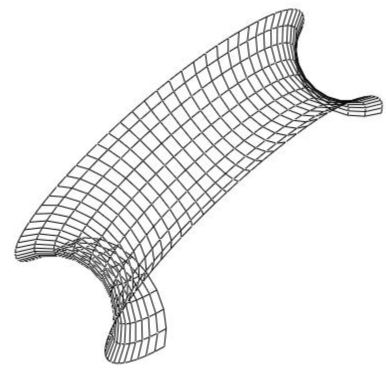

Fig. 1. Model of trough

Orientation module (3) is performed by the matrices of relative rotation:

$$S^{\varphi_t}_{\theta_t\cdot y_c} = M_6(\theta_t)\cdot M_2(y_c), \qquad (4)$$

where: θ_t – is the angle of rotation of the workpiece coordinate system relative to the axis of rotation of the tool; y_c – is the distance between the axes of rotation of the tool 1 and workpiece 2 (Fig. 2).

The module of orientation (3) is presented by the matrix of relative rotations:

$$S_{\psi}^{O} = M_5(\psi), \quad (5)$$

where: ψ – is the angle of rotation grinding wheel 1 about the axis which is perpendicular to the axis of rotation of workpiece and tools, and passing through the center of the profile of the

radius ρ, $M_5 = \begin{pmatrix} cos\psi & 0 & sin\psi & 0 \\ 0 & 1 & 0 & 0 \\ -sin\psi & 0 & cos\psi & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$. (6)

In processing an annular trough by copying, there occurs a necessity of displacement of grinding wheel in the vertical direction *Δh* which is ensured by a vertical feed *Sv* (Fig. 2). It is caused by a variable radius of the profile on the crimping area of the roll. The shift is made so that the surface of trough and wheel in the central point of contact lines has a common normal line. Therefore, the center of rotation of the wheel *Ot*, the central point of the line of contact *K* and radius center of curvature of the ridge trough *Owj* must lie on one line. On the calibration area where the radius of the curvature bottom of trough is constant and coincides with the axis of rotation of the roll *Ow*, offset value *Δh = 0.*

The final shaping of a pipe is on the calibration area of the roll where the trough radius is the smallest. The tool surface is determined by the condition of the touch wheel with trough on the calibration area. The radius of the axial section of the tool *ρk* must be less than the radius of the workpiece *ρ*. Thus, from now on, the radius vector of the tool $\overline{r_t}$ will be considered for the roll calibration areas where modular model parameters are constant, except the rotation angle of workpiece θ_w.

3. DETERMINATION OF THE TOOL PROFILE

For profiling of the tool it is necessary to make the equation that defines the line of the contact

$$\overline{V} \cdot \overline{n} = 0, \quad (7)$$

where: $\overline{n}$ – is the unit vector of normal line to the workpiece surface; $\overline{V}$ – is the vector of the velocity of the relative motion of the surface in the coordinate system of the tool (Grabchenko et al., 2016; Anderson 2011).

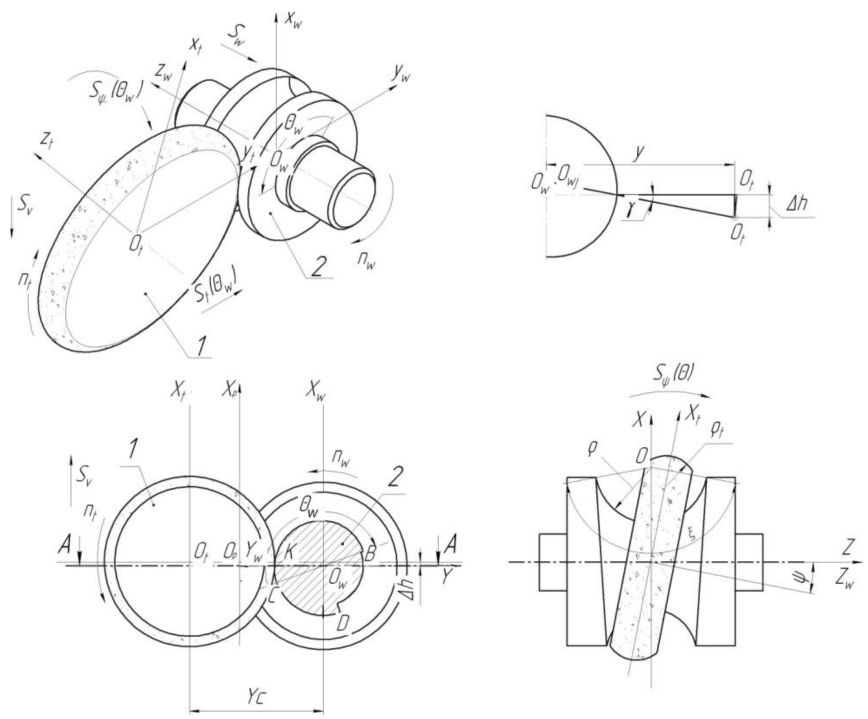

Fig. 2. Scheme of the trough processing with variable profile of roll rolling

The vector of the normal, as we know, can be found as the vector product of vectors tangent to the surface (Chi, Li. 2012; Yanlong et al., 2013; Rabiey, Zhi Wei. 2018). There is a need to differentiate the normal radius vector of the workpiece surface on both parameters.

During the one-parametric rounding (Grabchenko et al., 2016; Kalchenko et al., 2017) relationship between the parameters ψ_w, θ and τ_w equal to zero of a mixed product of three vectors that are derived of the vector $\overline{r_t}$.

$$\left(\frac{\partial\overline{r_t}}{\partial\psi_w} \times \frac{\partial\overline{r_t}}{\partial\theta}\right) \cdot \frac{\partial\overline{r_t}}{\partial\tau_w} = 0, \quad (8)$$

where: $\left(\frac{\partial\overline{r_t}}{\partial\psi_w} \times \frac{\partial\overline{r_t}}{\partial\theta}\right) = \overline{n}$ – is the vector normal to the surface of the workpiece at the point with curvilinear coordinates ψ_w, θ. The value ψ_w is determined from the condition of tangency the surface of the tool with the workpiece surface, and is the maximum value of ψ.

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$\frac{\partial \overline{r_t}}{\partial \tau_w} = \overline{V}$ – is the vector of velocity of relative motion of the surface in the coordinate system of the tool; τ_w – is the time of moving the workpiece, while turning it at the angle θ_t in the opposite motion an axis OtZt of the wheel.

The velocity of the workpiece regarding the wheel determined by a matrix of transition from the workpiece coordinate system in the tool coordinate system:

$$\frac{\partial \overline{r_t}}{\partial \tau_w} = \frac{\partial M_6(\theta_w)}{\partial \theta_w} \cdot \frac{\partial \theta_w}{\partial \tau_w} \cdot M_{tw}, \quad (9)$$

where: $\frac{\partial \theta_w}{\partial \tau_w} = \overline{\omega_{tw}}$ is the angular velocity of the workpiece rotation relative to the axis of the wheel.

The radius vector $\overline{r_t}$ describes a set of tool surfaces. The choice of a rational surface is carried on the analysis of the geometric parameters of the outer surface of the workpiece and allowance, which is removed (Fig. 2).

The radius vector of the tool can be presented by a spherical module that is similar to the same module of the workpiece (1), but with its own parameters

$$\overline{r}_t = S^t_{\theta_t \cdot y_t \cdot \varphi_t \cdot y_{pt}} \cdot e^{-4}, \quad (10)$$

$$S^t_{\theta_t \cdot y_t \cdot \varphi_t \cdot y_{pt}} = M_6(\theta_t) \cdot M_2(y_t) \cdot M_4(\varphi_t) \cdot M_2(y_{pt}),$$

where: $\overline{r}_t$ – is the radius vector of the surface of the wheel; $S^t_{\theta_t \cdot y_t \cdot \varphi_t \cdot y_{pt}}$ – is the spherical module, that is a matrix of transition from the starting point to the coordinate system of the tool; θ_t – is the angle of turning around the axis *OtZt* of rotation of the tool; $y_t = R_t$ – is the distance from the center of the profile of the tool to its axis of rotation; φ_t – is angle of rotation around the axis *OtXt*; $y_{pt} = \rho_t$ – is the radius wheel profile (Fig. 3).

Model (10) provides the possibility to determine the coordinates of the profile wheel, which is shown in Fig. 3.

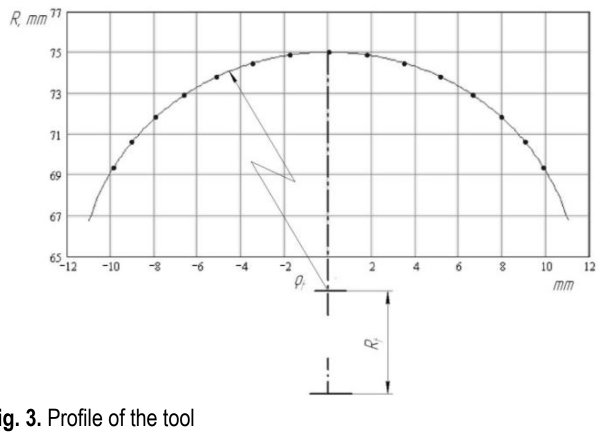

Fig. 3. Profile of the tool

In processing the crimping area, the angle of the wheel is constantly changing with the change of the radius of the trough, reaching a maximum inclination of at the beginning of the crimping area of the roll. The angle at each point of the ridge is determined according to the condition of a minimum deviation of the radius projection of the line of contact on the axial plane from the radius of profile trough.

Fig. 4 shows a sweep of lines of the contact of the tool and the workpiece for various angles of the wheel while processing trough with the parameters listed above.

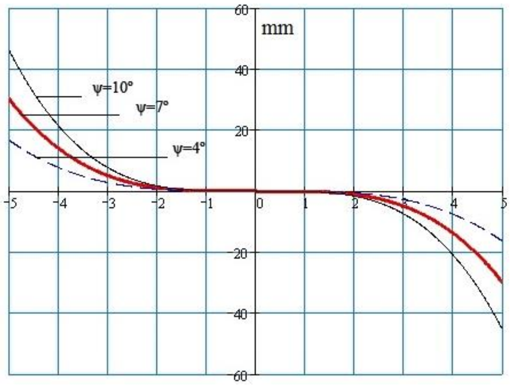

Fig. 4. The contact line of the wheel and the workpiece while grinding by the oriented tool

The radius vector of an annular trough rolling with a variable profile of the roll that is formed after processing by the tool that is described by model (5) can be presented by two spherical modules and the radius vector of the tool:

$$\overline{r_{wt}} = S^{\varphi}_{\theta_w \cdot y} \cdot S^{O}_{\psi \cdot x} \cdot \overline{r_t}, \quad (11)$$

where: $S^{\varphi}_{\theta_w \cdot y} = M_6(\theta_w) \cdot M_2(-y_c + a \cdot \theta - t \cdot k)$ – is the shaping module of details; θ_w – is the angle of rotation coordinate system of the tool around the axis of rotation of the workpiece; $y = -y_c + a \cdot \theta - t \cdot k$ – the current coordinate interaxal distance of the tool and workpieces; $a = \frac{t}{2\pi}$ – is the constant of Archimedean spiral, which moves in relative motion wheel when removing of the allowance; t – is the value of traverse wheel in the direction perpendicular to the axis OwZw of workpiece rotation on each of its turnover; k – is the number of working moves required to remove the allowance; $S^{O}_{\psi \cdot x} = M_5(\pm\psi) \cdot M_1(x)$ – is the module of the angular orientation of the tool relative to the workpiece.

Processing of crimping area of the trough will be conducted with an error that is caused by a mismatch of the radii of the trough profile and projection of the contact line on the axial plane that passes through the point of the contact at the bottom of the trough. Thus, trough profile processing will be carried out by successive clarifying: the maximum error of processing will be expressed at the beginning of the crimping area of the roll Δ and will gradually decrease in the direction of the calibration area (area F1) and will reach the zero value (Fig. 5). It should be noted that regardless of the plot which is processed, the bottom of trough is formed without an error. The value of the error Δ is determined by the method of least squares and must lie within the tolerance of processing.

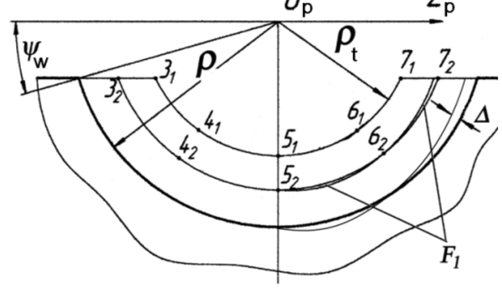

Fig.5. The scheme of the trough profile clarifying

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During the processing (Fig. 6) the bottom of the trough 1, the wheel 3 moves along the equidistant relative motion of the tool center 2. The normal 4 passes through the center wheel, the point of contact at the bottom of trough and the center of the radius curvature.

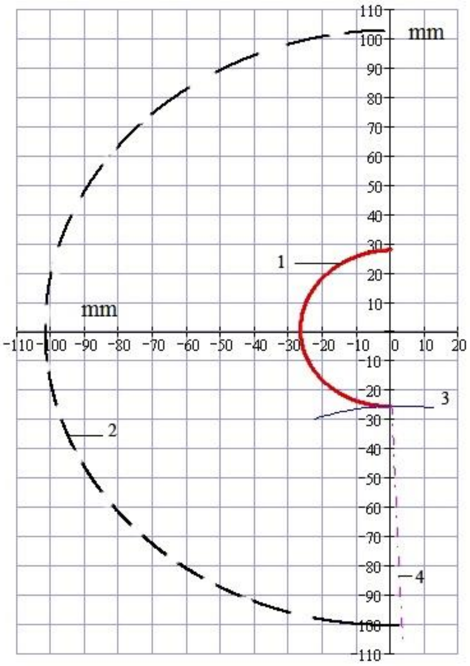

Fig .6. The scheme of the trough processing

4. CONCLUSIONS

The 3D module models of allowance removal, shaping and profiling tools have been developed. New method of grinding by copying with a linear contact of the wheel and workpiece on calibration and crimping areas of trough roller, based on the analysis of these models, which significantly increases processing performance, has been developed.

Based on the analysis of models the method of managing the process of grinding, which provides for removal allowance by equidistantly curves has been proposed. The constant cutting depth profile of the coordinate processing is achieved by simultaneous cutting and turning wheel by the amount of allowance processing, which improves the performance of grinding.

The diameter of the grinding wheel affects the maximum value of the orientation angle ψ. By increasing the diameter of the grinding wheel the value ψ slightly decreased.

Increasing the central angle θ leads to a significant decrease of the orientation angle ψ. Thus the profile of the tool approaches the workpiece profile.

The developed modular models can be used to determine:
- the efficiency of processing by the oriented tool;
- the optimal crossing angle during the cutting;
- other parameters of forming curved surfaces of the revolution;
- thickness of the layer, which is cut off by cutting edge.

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