

Проведено тривимірне геометричне моделювання процесу формоутворення циліндричних деталей при шліфуванні зі схрещеними осями її та круга. Шліфування валів, які широко використовуються у автомобілебудуванні, верстатобудуванні, та валків стрічкопрокатних станів здійснюється за один установ орієнтованим широким абразивним кругом. На базі отриманої просторової моделі формоутворення та зняття припуску досліджено розподіл припуску вздовж різальної ділянки інструмента при шліфуванні орієнтованим інструментом. Показано, що на периферійній різальній ділянці шліфувального круга суміщаються чорнова, чистова обробки та калибрування.

Розроблена модульна тривимірна модель правки периферійної ділянки шліфувального круга однокристалним алмазним інструментом при шліфуванні зі схрещеними осями інструмента та деталі з використанням уніфікованих модулів правлячого інструмента, орієнтації та формоутворення. На базі поданої моделі проведені дослідження геометричної точності формоутворення периферійної ділянки інструмента після його правки. З метою отримання необхідної мікрогеометрії та різальних властивостей абразивних кругів відповідно до особливостей процесу обробки валків стрічкопрокатних станів орієнтованим інструментом пропонується правка із зменшеною подачею правлячого інструмента до калибрувальної ділянки. При цьому величина подачі правлячого однокристалного інструмента залежить від величини припуску. Різна подача правлячого інструмента забезпечує різну розвиненість різальної периферійної ділянки інструмента. Це, в свою чергу, збільшує інтервали між правками шліфувального круга, який працює у режимі затуплення. А отже, підвищується стійкість та зменшується собівартість обробки. Впровадження запропонованого способу правки кругів при однопрохідному шліфуванні зі схрещеними осями інструмента та циліндричної деталі забезпечить високоточність, якість оброблених поверхонь, а також значно підвищить ефективність та продуктивність процесу обробки. Розроблений спосіб правки може бути застосований для процесів круглого шліфування зі схрещеними осями оброблюваної деталі та абразивних кругів

**Ключові слова:** двостороннє торцеве шліфування, схрещені осі, правка кругів, розвиненість поверхні круга, циліндричні деталі

## DEVELOPMENT OF A MODEL OF TOOL SURFACE DRESSING WHEN GRINDING WITH CROSSED WHEEL AND CYLINDRICAL PART AXES

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### 1. Introduction

In the conditions of the formation of a new type of economy [1], a special role is played by the machine-building

industry, which ensures the economic growth of the country and increases its international competitiveness. Therefore, the products of this industry are required to ensure high accuracy and quality. Cylindrical shaft-type parts are widely

used in modern mechanical engineering, in particular automotive, metal-cutting and rolling machine tools. Ensuring high accuracy of machining is carried out using finishing operations on grinding machines.

In the known methods of cylindrical parts circular grinding, their processing is usually carried out on the same machine with the same abrasive wheel. The main metal layer is cut off by the front part of the wheel. The other part of the tool is finished. In this case, the forming point occupies an unstable position due to the uneven wear of the wheel. This, in turn, reduces the accuracy of the dimensions and geometric shape of parts.

The use of the grinding method with crossed axes of the wheel and part makes it possible to fix the abrasive tool forming part. This ensures an even distribution of the allowance along the profile of the wheel, its more uniform wear and increases the processing productivity.

To ensure high processing performance, it is necessary to take into account the peculiarities of its further work when dressing the wheel.

Therefore, the development and study of spatial models of tool surface dressing in circular grinding with crossed axes of the wheel and cylindrical part is an urgent task. Because it will increase processing productivity, product accuracy and tool stability and ensure high competitiveness in various fields of mechanical engineering.

**2. Literature review and problem statement**

In the existing multi-pass grinding methods by the periphery of the cylindrical wheel, there is an uneven tool surface wear [2]. In the process of machining part 1 (Fig. 1), not the entire height  $B$  of the grinding wheel 2 is involved, but only the part equal to the feed rate of the part per revolution of the wheel  $s_0$  [3]. Therefore, the height  $h_i$  of the tool worn section  $I$  at each point of its working surface depends on the feed rate  $s_0$  and the height of the allowance  $t_i$ . Tool wear occurs on one or both sides, depending on the method of processing.

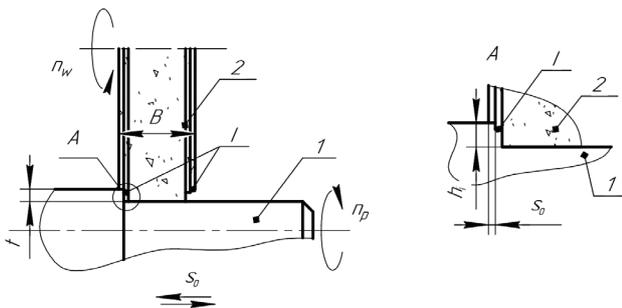


Fig. 1. Method of multi-pass grinding by the periphery of a cylindrical wheel

The decrease in machining productivity in this method is due to the work in the process of grinding not the entire height of the wheel, but only its small parts, and the location of the forming point is unknown.

The method of high-speed grinding with crossed axes of the wheel 2 and part 1 [4, 5] was performed by Junker on Quickpoint 1000, Quickpoint 3000, Quickpoint 5,000 machines [6]. Elbor or diamond grinding wheels with a height of 4–6 mm and a coating width  $h$  of several millimeters at

speeds of the grinding wheel up to 140 m/s and the part rotation up to 12,000 rpm are used.

In this method, the fixation of the forming point  $B$  of the wheel 2 (Fig. 2) is carried out by rotating the tool at an angle  $\alpha$  relative to the axis of rotation of part 1.

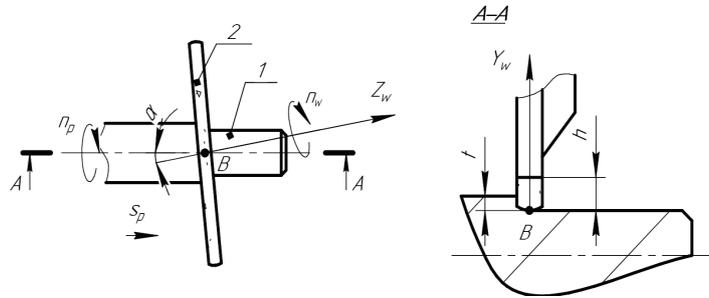


Fig. 2. Grinding method with crossed axes of the tool and part of the Yunker company

This ensures an even distribution of the allowance along the tool profile. Much of the allowance falls on the wheel end. The amount of material removed in one pass is divided into several parts. This allows you to unload the wheel periphery and select some calibration area, which will ensure the processing ultimate accuracy.

However, in single-pass finishing grinding of shafts with cutting depths of about 0.3–0.5 mm, the initial machining accuracy is insufficient. And the use of diamond and Elbor wheels becomes economically unprofitable due to their high cost and low development of the relief of the work surface.

For example, abrasive wheels with diameters of 700–1,080 mm and a height of 50–150 mm are used in the processing of rolling mill rolls [7]. It is necessary to ensure high accuracy (IT6-8) and roughness ( $Ra=0.4-1.6 \mu m$ ) of working surfaces [8] and to withstand the tolerance for the deviation of the barrel roundness and necks – 0.010–0.015 mm and the forming rolls error – 5–10  $\mu m$ .

It is possible to provide high indicators of dimensional accuracy, low roughness and undulation of the processed surfaces in the course of grinding wheels work in the blunting mode [9]. The cutting and deforming grains are firmly held by a bond in the tool, which makes it possible to preserve the tool profile that is formed during dressing.

Since the entire periphery of the tool is involved in cross-axis grinding, the allowance is distributed along the roughing, semi-finishing, finishing and calibration sections of the grinding wheel. Accordingly, the development of the tool working surface in these areas should be different. It should be maximum during the rough grinding to ensure high processing productivity; it should be lower for semi-finished and finished treatments to obtain low surface roughness.

Therefore, there is a need to develop such an adjustment of the wheel, which would provide the ability to control the relief of its working surface in accordance with the allowance distribution for grinding with crossed axes of the wheel and part.

In [10], the use of textured grinding wheels, which have both specially designed active and passive grinding sections on their geometrically active surfaces, is proposed. The core allows you to perform the processing. The passive area, where there is no grain, provides more space to remove chips. This increases the development of the wheel surface.

In [11], the researches of dressing accuracy increase of grinding wheels have been carried out. It is determined that

the dressing force is a key parameter in determining the number of passes required to achieve high process efficiency. Therefore, it is possible to reduce the dressing duration and the governing instrument cost. And in [12], in order to improve the processing accuracy, a contactless method of measuring the grinding wheel wear has been presented.

Experimental studies of the grinding wheel dressing process, described in the paper [13], showed that the grinding wheel roughness is influenced by the speed ratio, cross-feed and roller profiles.

However, the existing methods of grinding wheel dressing [10–13] do not consider the issue of ensuring different relief development of the tool working surface.

There is a need to develop a method of wheel dressing when grinding cylindrical parts with crossed axes of it and the part, which would provide different cutting properties of the tool working surface in accordance with the machining process characteristics.

This problem can be solved by developing modular three-dimensional models of the processes of allowance removal and abrasive tools shaping during dressing. The analysis of models will promote the development of abrasive wheel dressing with the maintenance of different development of the tool working surface relief when grinding with crossed axes of the tool and part.

of the allowance, and the tool end part does not participate in the processing. The intersection of the tool and part axes ensures the operation of the entire wheel periphery, and the displacement of the  $O_w Y_w$  axis provides the presence of a calibration section of length  $C$ , which increases the initial accuracy of the cylindrical roller.

At a constant feed rate  $s_p$  of wheel 2 per rotation of part 1, the value of the allowance  $t$  from the initial point  $i_1$  on the wheel profile to the turning point  $A$  gradually decreases: at point  $i_1$  the value of allowance  $t$ , at point  $i_2-t_1$ , at point  $i_k-t_2$ . In this case, the forming point  $A$  is the beginning of the calibration section of the tool periphery, where the allowance is almost zero.

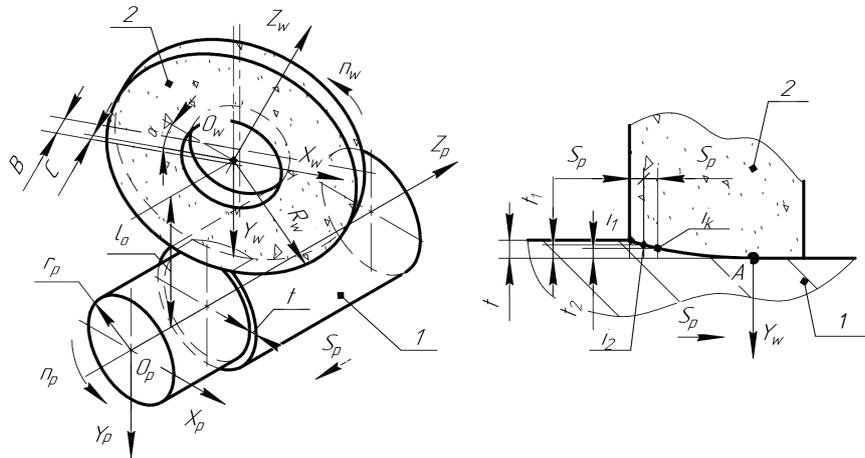


Fig. 3. Grinding of a cylindrical shaft by the periphery of the oriented tool

### 3. The aim and objectives of the study

The aim of the research is to develop a spatial model of dressing the tool surface during circular grinding with crossed axes of the wheel and cylindrical part. This will increase the accuracy of shaping and processing productivity.

To achieve this goal, the following tasks were set:

- to investigate the features of the grinding process with crossed axes of the tool and cylindrical part in terms of the allowance distribution along the cutting section of the wheel;
- to develop a modular three-dimensional model of dressing the peripheral section of the grinding wheel on the basis of unified modules: tool, orientation and shaping;
- to investigate the development of the wheel working surface after dressing;
- to propose a method of dressing abrasive wheels when grinding cylindrical parts with crossed axes of it and the part, which would provide different development of the tool working surface in accordance with the characteristics of the machining process.

### 4. Investigation of the grinding process of shafts with crossed axes of the tool and cylindrical part

When grinding shafts 1 (Fig. 3), the abrasive wheel 2 is fed to the entire depth of cut  $t$  (Fig. 3) and moves along the  $O_p Z_p$  axis of the part coordinate system with the feed rate of  $s_p$ . The tool is rotated around the  $O_w Y_w$  axis, which is located at a distance  $C$  from the end of the tool [14]. The majestic angle  $\alpha$  of the tool orientation depends on the height

To develop a model of the grinding process, it is necessary to mathematically describe the tool surface, the workpiece and the molding process during grinding with crossed axes of the tool and part.

Models for grinding with crossed axes of the roller and grinding wheel were built in the MathCAD software package.

The radius vector of the tool surface  $\overline{GW}(z, \varphi)$  is given by the cylindrical shaping module:

$$\overline{GW}(z, \varphi) = MC_{z, \varphi, R_w}^w \cdot \bar{e}4 = M3(z) \cdot M6(\varphi) \cdot M2(R_w) \cdot \bar{e}4, \quad (1)$$

where  $MC_{z, \varphi, R_w}^w$  is the cylindrical module for shaping the tool surface, represented as a matrix of the radius vector transition of the starting point in the tool coordinate system;  $M1...M6$  are the matrices of displacements and rotations relative to the coordinate axes;  $R_w = 700$  mm is the grinding wheel radius;  $z = 0...B$  is the linear coordinate on the wheel periphery, varies from 0 to the height of the tool  $B = 60$  mm;  $\varphi = 0...360^\circ$  is the angular coordinate of the grinding wheel profile.

The surface  $\bar{P}$  of the processed cylindrical shaft is given by the tool surface radius vector, the transition matrix and the grinding wheel orientation module in the part coordinate system:

$$\begin{aligned} \bar{P} &= M^{tr} \cdot MC_{\gamma}^{or} \cdot \overline{GW} = \\ &= M1(-l_o) \cdot M6(-\gamma) \cdot M3(-B+C) \cdot \overline{GW}, \end{aligned} \quad (2)$$

where  $M^{tr} = M1(-l_o)$  is the transition matrix from the wheel coordinate system to the part coordinate system;

$l_o = R_w + r_p$  is the distance between the tool and part axes;  $MC_{\gamma}^{or} = M6(-\gamma) \cdot M3(-B+C)$  is the cylindrical module of tool orientation;  $\gamma$  is the angle of the grinding wheel rotation;  $C$  is the length of the wheel calibration section.

The nominal profile of the cylindrical roller treated surface is described by the cylindrical forming module  $C_{\gamma_p}^{sh}$ :

$$MC_{\gamma_p}^{sh} = M3(\gamma_p \cdot p_z) \cdot M6(\gamma_p), \quad (3)$$

where  $\gamma_p$  is the current angle of the part rotation around its own axis;  $\gamma_p$  is the helical line pitch;  $s_p$  is the part axial feed.

Finally, the nominal part surface, taking into account equations (1)–(3), can be described:

$$\begin{aligned} \bar{P}(z, \gamma_p, \gamma) &= MC_{\gamma_p}^{sh} \cdot M^r \cdot MC_{\gamma}^{or} \cdot MC_{z\Phi R_w}^w \cdot \bar{e}4 = \\ &= M3(\gamma_p \cdot p_z) \cdot M6(\gamma_p) \cdot M1(-l_o) \cdot M6(-\gamma) \times \\ &\times M3(-B+C) \cdot M3(z) \cdot M6(\varphi) \cdot M2(R_w) \cdot \bar{e}4. \end{aligned} \quad (4)$$

To determine the machined surface profile of the roller, we use the profiles contact condition, which determines the contact line of the part and the tool surface:

$$\bar{v} \cdot \bar{n} = \left( \frac{\partial \bar{P}(z, \gamma_p, \gamma)}{\partial z} \times \frac{\partial \bar{P}(z, \gamma_p, \gamma)}{\partial \gamma} \right) \cdot \frac{\partial \bar{P}(z, \gamma_p, \gamma)}{\partial \gamma_p} = 0, \quad (5)$$

where  $\bar{n}$  is the unit vector of the normal to the wheel surface, found as a differential of the radius vector  $\bar{P}(z, \gamma_p, \gamma)$  for two independent parameters  $z$  and  $\gamma$ ;  $\bar{v}$  is the speed vector of the wheel relative motion in the roller coordinate system (differential of the radius vector  $\bar{P}(z, \gamma_p, \gamma)$  for the parameter  $\gamma_p$ , which simulates the rotation angle of the treated surface per unit time).

You can find the contact line between the tool and the processed roller using the following calculation block:

$$\text{Line} = \left\{ \begin{array}{l} \gamma \leftarrow 0, \\ \text{for } j \in 0..N_i \\ z \leftarrow z_{\min} + \frac{z_{\max}}{N_i} \cdot j, \\ \gamma \leftarrow \text{root} \left( \left( \frac{\partial \bar{P}(z, \gamma_p, \gamma)}{\partial z} \times \frac{\partial \bar{P}(z, \gamma_p, \gamma)}{\partial \gamma} \right) \cdot \frac{\partial \bar{P}(z, \gamma_p, \gamma)}{\partial \gamma_p}, \gamma \right), \\ M^{(j+1)} \leftarrow \begin{pmatrix} z \\ \gamma \end{pmatrix}, \\ M^T. \end{array} \right. \quad (6)$$

where  $z_{\min}=0$ ,  $z_{\max}=B$  are the smallest and largest coordinates of points on the wheel profile, respectively;  $N_i$  is the number of points on the wheel periphery;  $\gamma$  is the angular coordinate of the contact point on the tool surface;  $M$  is the coordinate matrix of the contact line points.

The obtained geometric three-dimensional models of the roll surfaces 1 (Fig. 4), the tool 2 and the area of their contact are bounded by lines: 3 – contact; 4 – the intersection of the tool and the workpiece end; 5 – section of the outer workpiece cylinder and the grinding wheel. As can be seen from Fig. 4, the entire periphery of the grinding wheel 2 is involved in the process of allowance removing. The intersec-

tion of the tool and part axes provides unloading of the wheel finishing and calibration sections, which account for the lowest allowance values. Consequently, their wear is minimal, which has little effect on the part forming accuracy.

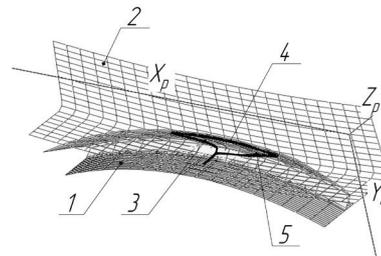


Fig. 4. Contact spot when grinding the shaft 1 with the oriented wheel 2, bounded by lines: 3 – contact line; 4 – line of intersection of the tool and workpiece end; 5 – line of intersection of the workpiece outer cylinder and grinding wheel

From the obtained graph of the projection of the contact line 3 on the plane (Fig. 5), it is seen that the allowance  $t$  along the wheel periphery decreases evenly from the rough ( $50 < z < 20$ ) to the finishing and calibration sections ( $20 < z < 0$ ).

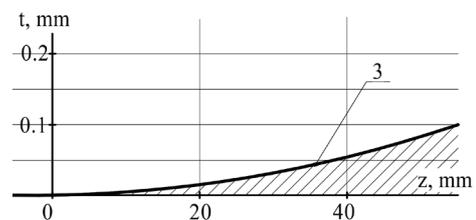


Fig. 5. Distribution of allowance  $t$  along the contact line 3 of the grinding wheel and part when grinding with the oriented tool:  $z$  – grinding wheel height

From the coordinate  $z$  (Fig. 5), which corresponds to the grinding wheel height  $B$ , to the coordinate  $z=0$  (the calibration section beginning), the allowance (shaded area under the contact line 3) gradually decreases and is almost zero on the calibration section.

Therefore, on the periphery of the grinding wheel, roughing, semi-finishing, finishing and calibration are combined. Uneven wear of the grinding wheel does not affect the shaping accuracy, because the intersection of the tool and part axes provides unloading of the wheel finishing and calibration sections and their minimum wear.

### 5. Three-dimensional modeling of the abrasion wheel periphery dressing with a single-crystal diamond tool

In order to ensure the development of the rough, semi-finished, finishing and calibration sections of the wheel periphery, which is appropriate for processing, it is necessary to model the process of tool surface dressing.

Dressing of the abrasive wheel 1 (Fig. 6) is carried out with a single-crystal diamond pencil 2 with a cutting grain of the octahedron shape.

The diamond pencil must be applied at an angle  $\gamma_{or}$  to the processed surface of the grinding wheel. This arrangement of

the dressing tool ensures the operation of the diamond grain faces, which have not yet blunted during processing.

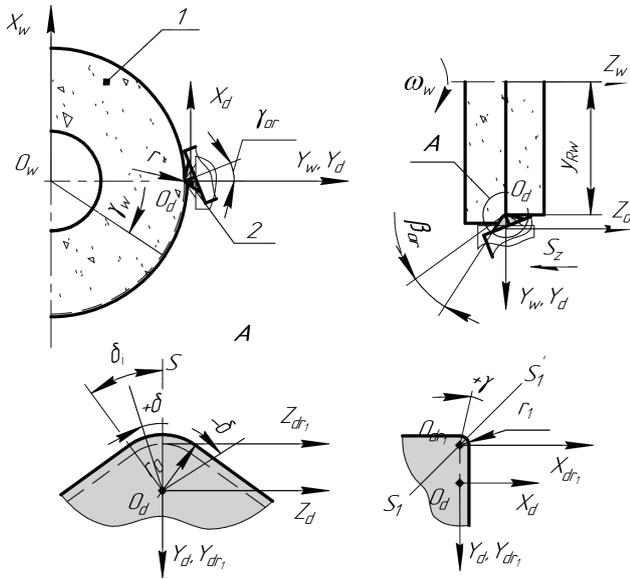


Fig. 6. Scheme of dressing the abrasive wheel with a diamond pencil

To develop a general three-dimensional model of allowance removal and shaping accuracy of the abrasive wheel peripheral area during its dressing, it is necessary to describe the tool surface of the diamond pencil 2 (Fig. 6, A).

The radius vector  $\vec{r}_d$  of the cutting surface points of the diamond pencil is given by the spherical module  $MS_{\delta_0, \gamma, r_1}^d$  of its shaping:

$$\overline{RD} = MS_{\delta_0, \gamma, r_1}^d \cdot \bar{e}4 = M4(\delta) \cdot M2(r_0 - r_1) \cdot M6(\gamma) \cdot M2(r_1), \quad (7)$$

where  $r_1$  is the radius that determines the position of the diamond pencil top (Fig. 6, A);  $\delta$  is the angle of rotation around the  $O_d X_d$  axis (Fig. 6, A), which specifies the radius  $r_0$  of the pencil rounding edge;  $\gamma$  is the angular coordinate that specifies the radius  $r_1$  of the cutting edge rounding. The radius vector  $\overline{RD}(\delta, \gamma)$  of the tool cutting surface is set in the form of two rectilinear sections and a spherical part (Fig. 6, A):

$$\begin{aligned} \overline{RD}(\delta, \gamma) = & MS_{\delta_0, \gamma, r_1}^d \cdot \bar{e}4 \cdot \Phi(|\delta|) - \\ & MS_{\delta_0, \gamma, r_1}^d \cdot \bar{e}4 \cdot \Phi(|\delta| - \delta_i) + \\ & M2(h|\delta|) \cdot MS_{\delta_0, \gamma, r_1}^d \cdot \bar{e}4 \cdot \Phi(\delta - \delta_i) + \\ & M2(-h|\delta|) \cdot MS_{\delta_0, \gamma, r_1}^d \cdot \bar{e}4 \cdot \Phi(-\delta - \delta_i), \end{aligned} \quad (8)$$

where  $\delta_i$  is the angle that determines the spacing of the radial edge relative to the symmetry line of the plate  $O_d S$  (Fig. 6, A);  $h(\delta) = (r_0 - r_1) \cdot \text{tg}(\delta - \delta_i)$  is the function that determines the coordinate of the point location along the conical sections of the pencil cutting surface;  $\Phi(\delta)$  is the Heaviside function, with a positive argument equal to one, with a negative – zero.

Fig. 7 shows the spatial model of the diamond pencil cutting surface with an angle at the apex  $\delta_i = \pi/4$  and rounding radii  $r_0 = 1.5$  mm,  $r_1 = 0.2$  mm.

This graph (Fig. 7) is a mathematical representation of the diamond pencil surface, which, thanks to the developed equations, can be changed depending on the parameters of the working tool. The mathematical model of the tool surface allows to model a geometrical profile of the processed surface of the part.

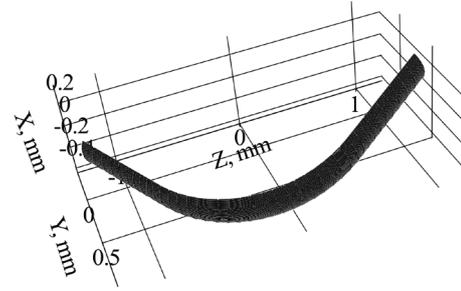


Fig. 7. Cutting edge of the diamond pencil surface

Let's describe the nominal surface of the grinding wheel 1 (Fig. 6):

$$\begin{aligned} \overline{R}_{GW}(\delta, \gamma, \gamma_w) = & MC_{p_z, \gamma_w, y_{Rw}}^{sh} \cdot MS_{\beta_{or}, \gamma_{or}, \chi_{or}}^{or} \cdot \overline{RD} = \\ = & M3(\gamma_w \cdot p_z) \cdot M2(-y_{Rw}) \times \\ & \times M6(\gamma_{or}) \cdot M4(\beta_{or}) \cdot M5(\chi_{or}) \cdot \overline{RD}, \end{aligned} \quad (9)$$

where  $MS_{\beta_{or}, \gamma_{or}, \chi_{or}}^{or}$  is the orientation modulus of the diamond pencil in the wheel coordinate system;  $MC_{p_z, \gamma_w, y_{Rw}}^{sh}$  is the cylindrical module that sets the movement of the diamond pencil relative to the grinding wheel;  $R_w$  is the wheel radius after dressing;  $t$  is the allowance for the wheel dressing;  $\gamma_{or}$ ,  $\beta_{or}$ ,  $\chi_{or}$  are the angles of tool surfaces inclination relative to the  $O_d Z_d$ ,  $O_d X_d$ ,  $O_d Y_d$  axes, respectively;  $y_{Rw}$  is the displacement of the tool coordinate system to the part coordinate system (radius of the grinding wheel cylindrical surface after dressing);  $\gamma_w$  is the rotation angle of the wheel treated surface around its own axis;  $p_z$  is the helical motion parameter of the pencil cutting blade along the wheel surface,  $p_z = s_z / 2\pi$ ;  $s_z$  is the feed per revolution in the appropriate direction (Fig. 6).

This is the final equation of the grinding wheel treated surface, taking into account models (8) and (9):

$$\overline{R}_{GW}(\delta, \gamma, \gamma_w) = MC_{p_z, \gamma_w, y_{Rw}}^{sh} \cdot MS_{\beta_{or}, \gamma_{or}, \chi_{or}}^{or} \cdot MS_{\delta_0, \gamma, r_1}^d \cdot \bar{e}4. \quad (10)$$

The contact line between the wheel and the diamond pencil is determined from equation (11) similarly to (5):

$$\bar{n} \cdot \bar{v} = \left( \frac{\partial \overline{R}_{GW}(\delta, \gamma, \gamma_w)}{\partial \delta} \times \frac{\partial \overline{R}_{GW}(\delta, \gamma, \gamma_w)}{\partial \gamma} \right) \cdot \frac{\partial \overline{R}_{GW}(\delta, \gamma, \gamma_w)}{\partial \gamma_w} = 0, \quad (11)$$

where  $\bar{n}$  is the unit vector of the normal to the diamond pencil surface;  $\bar{v}$  is the speed vector of the pencil relative movement in the wheel coordinate system.

To find the angles  $\gamma_{min}$ ,  $\gamma_{max}$ , which determine the location of the contact line on the forming face of the diamond pencil, we use the calculation block similar to the block (6):

$$Ang = \begin{cases} \lambda \leftarrow 0, \\ \text{for } i \in 0..k \\ \delta \leftarrow \delta_{min} + \frac{\delta_{max}}{k} \cdot j, \\ \gamma \leftarrow \text{root}(n(\delta, \gamma, 0) \cdot v(\delta, \gamma, 0), \gamma), \\ M^{(j+1)} \leftarrow \begin{pmatrix} \gamma \\ \delta \end{pmatrix}, \\ M^T. \end{cases} \quad (12)$$

Equations (10) and (11) describe a modular three-dimensional model of the shaping of the grinding wheel peripheral section during dressing.

**6. Investigation of the peripheral cutting area microrelief of the abrasive wheel after dressing**

On the basis of the modular three-dimensional model of the grinding wheel surface shaping when dressing by the diamond pencil, the grinding wheel peripheral surface after its dressing is obtained (Fig. 8). Grinding wheel radius  $R_w=600$  mm; height  $h=50$  mm, angle at the diamond pencil top  $\gamma_f=\pi/4$ , feed rate  $s_z=0.1$  mm/rev.

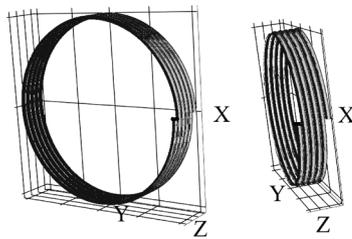


Fig. 8. Spatial model of the grinding wheel periphery surface after dressing with a single-crystal diamond pencil

As can be seen from Fig. 8, as a result of dressing the grinding wheel with a single-crystal diamond pencil on the grinding wheel periphery, a geometric roughness in the form of helical grooves is formed. The height of the grooves depends on the value of allowance and feed rate of the dressing tool. At a constant feed rate  $s_z$  per revolution, the dimensions of the grooves are the same, which ensures the same development of the grinding wheel working surface.

**7. Method of dressing abrasive wheels when grinding with crossed tool and cylindrical part axes**

When grinding with crossed axes of the tool and part, there is a geometric roughness  $Rz$  (Fig. 9), the value of which is defined as the distance from the nominal surface of the part to the point  $N$  of intersection of two consecutive positions 1 and 2 of projections of contact lines on the plane.

As can be seen from Fig. 9, changing the feed rate from  $s_{z1}$  to  $s_{zi}$  provides the ability to control the development of the relief and cutting properties of the grinding wheel peripheral section.

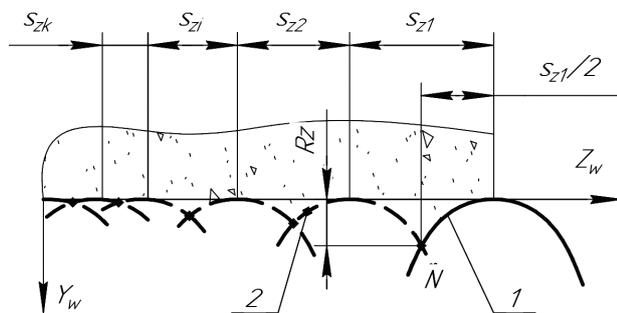


Fig. 9. Formation of the geometric roughness  $Rz$  on the abrasive wheel surface when dressing with a single-crystal dressing tool with different feed rates  $s_z$

Thus, when grinding rolls of belt rolling mills with crossed axes of the tool and part, the value of allowance along the contact line is constantly changing. On the grinding wheel peripheral section, roughing, finishing and calibration are combined (Fig. 5).

In order to ensure high precision machining of the rolls when grinding with a wide oriented abrasive wheel, it is proposed to adjust its periphery with different feed rates of the single-crystal dressing tool. Thus, rough and semi-finished areas of the wheel periphery are dressed with higher feed rates  $s_{z1}, s_{z2}=0.3-0.5$  m/min (Fig. 9), clean – with feed rates  $s_{zi}=0.15-0.25$  m/min, and calibration – with feed rates  $s_{zk}=0.05-0.1$  m/min. As you approach the finish area of the wheel periphery, the feed rate of the dressing tool gradually decreases, and the calibration area must be adjusted with the same feed rate to ensure high accuracy of the roll surface. The feed rate of the diamond pencil depends on the allowance.

**8. Discussion of the results of the study of the accuracy of wheel dressing when grinding with crossed axes of the tool and part**

The presented grinding method with crossed axes of the tool and cylindrical part provides fixation of the wheel forming part and uniform reduction of the allowance along its periphery from the rough to the finishing and calibration sections (Fig. 5). This increases the productivity of processing in comparison with existing methods [2, 3], which involves not the entire wheel height, but only its small parts, and the location of the area that provides the formation is unknown.

The developed modular three-dimensional model of dressing the grinding wheel peripheral site (Fig. 8), obtained by means of equations (10) and (11), gives the chance to consider the features of its rough and finishing sites when grinding by the oriented tool.

Since when grinding with crossed axes, the allowance is distributed along the rough, semi-finished, finished and calibration sections of the grinding wheel (Fig. 5), respectively, the development of the tool working surface in these areas should be different.

In contrast to the existing methods of editing grinding wheels [10–13], the presented method provides different development of its peripheral surface due to different feed rates of the dressing tool (Fig. 9). Thus, on the wheel rough section, the main allowance is removed when dressing, larger grooves provide more space for the removal of chips, preventing it from sticking and vibration. This increases the machining accuracy of the part to IT 6-7. And the finishing and calibration sections of the periphery, which have small values of allowance, provide low geometric surface roughness of the rolls ( $Ra=0.32-1.25$   $\mu\text{m}$ ) due to lower values of geometric roughness.

This method of dressing also increases the period between dressing processes (45 min) due to the presence of different configuration grooves on the rough and clean sections of the grinding wheel in combination with the peculiarities of the machining process with the oriented tool. Machining productivity when grinding with crossed axes of the abrasive wheel, the peripheral part of which is dressed in this way, and roll increases by 10 % due to the possibility of using higher machining modes.

Because the oriented wheel is subjected to different dressing methods on its roughing, finishing and calibration

sections, this method imposes restrictions on the length of these sections. Therefore, this method of dressing cannot be used when dressing narrow wheels, as well as diamond and Elbor. The three-dimensional model of grinding wheel dressing makes it possible to obtain only its geometric profile, taking into account the influence of the diamond pencil profile, depth of cut and feed rate. However, the obtained model of the wheel profile does not take into account the influence of system rigidity and vibration.

In the future, the dressing model can be applied to the methods of grinding not only cylindrical, but also stepped and curved surfaces of rotation with an oriented tool.

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## 9. Conclusions

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1. Investigations of the grinding method of cylindrical parts by the oriented tool periphery, which have been conducted on the basis of spatial models of the wheel, roller, processes of allowance removal and shaping, showed the pos-

sibility of allowance uniform reduction to the finishing and calibration areas along the cutting surface. This increases the accuracy to IT 6-7 and processing performance by dividing the tool periphery into rough, finishing and calibration areas.

2. A modular spatial model of dressing abrasive wheels with a single-crystal dressing tool has been developed, using the equations of which the wheel geometric profile is obtained at different input parameters (dressing tool profile, depth of cut and feed rate). This makes it possible to analyze the processes of allowance removal and shaping of grinding tools.

3. A method of dressing the abrasive wheel peripheral section with different feed rates of the dressing tool in accordance with the features of the grinding process with crossed axes of the wheel and part has been proposed. Due to the different development of the tool working surface on its rough, clean and calibration areas, dressing for wheels operating in the blunting mode has been presented.

4. The proposed method of tool dressing can be used for grinding methods with crossed axes of wide abrasive wheels and cylindrical, stepped and curved surfaces of rotation.

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## References

1. Shkarlet, S., Kholiavko, N., Dubyna, M., Zhuk, O. (2019). Innovation, Education, Research Components of the Evaluation of Information Economy Development (as Exemplified by Eastern Partnership Countries). *Marketing and Management of Innovations*, 70–83. doi: <https://doi.org/10.21272/mmi.2019.1-06>
2. Nadolny, K., Słowiński, B. (2011). The Effects of Wear upon the Axial Profile of a Grinding Wheel in the Construction of Innovative Grinding Wheels for Internal Cylindrical Grinding. *Advances in Tribology*, 2011, 1–11. doi: <https://doi.org/10.1155/2011/516202>
3. Kalchenko, V. I., Kalchenko, V. V., Yeroshenko, A. M., Sira, N. M. (2016). Investigation of the method for grinding of the rolls of rolling mills with crossed axes of the tool and workpiece. *Visnyk Cherkaskoho derzhavnogo tekhnolohichnoho universytetu*, 4, 80–87. Available at: [http://visnyk.chdtu.edu.ua/images/tech/4\\_2016/14.pdf](http://visnyk.chdtu.edu.ua/images/tech/4_2016/14.pdf)
4. Li, C. H., Qi, L. Y., Zhao, H. Y. (2011). Application and Development of High-Efficiency Abrasive Finishing. *Advanced Materials Research*, 189-193, 3113–3116. doi: <https://doi.org/10.4028/www.scientific.net/amr.189-193.3113>
5. Hou, Y., Li, C., Zhou, Y. (2010). Applications of High-Efficiency Abrasive Process with CBN Grinding Wheel. *Engineering*, 02 (03), 184–189. doi: <https://doi.org/10.4236/eng.2010.23026>
6. Quickpoint. Flexible high-performance grinding machine (2015). Available at: [https://www.junker-group.com/fileadmin/user\\_upload/Prospekte/JUNKER\\_QUICKPOINT\\_en.pdf](https://www.junker-group.com/fileadmin/user_upload/Prospekte/JUNKER_QUICKPOINT_en.pdf)
7. Technical solutions for roll grinding (2019). Norton Saint-Gobain. Available at: [https://www.nortonabrasives.com/sga-common/files/document/ROLL%20GRINDING%20BROCHURE\\_apr2019.pdf](https://www.nortonabrasives.com/sga-common/files/document/ROLL%20GRINDING%20BROCHURE_apr2019.pdf)
8. Permyakov, A. A., Zhizhev, A. A. (2011). Improving the rough grinding technology for mill rolls by restoration of the grinding wheel cutting capacity without dressing. *Visnyk SevNTU. Seriya: Mashynopryladobuduvannia ta transport*, 118, 113–118. Available at: [http://lib.sevsu.ru:8080/xmlui/bitstream/handle/123456789/4928/118\\_19.pdf?sequence=1&isAllowed=y](http://lib.sevsu.ru:8080/xmlui/bitstream/handle/123456789/4928/118_19.pdf?sequence=1&isAllowed=y)
9. Shakhbazov, Y. O., Shyrokov, V. V., Shyrokov, O. V., Palamar, O. O. (2018). Grinding process technology support. *Printing and Publishing*, 1 (75), 75–81. doi: <https://doi.org/10.32403/0554-4866-2018-1-75-75-81>
10. Li, H. N., Axinte, D. (2016). Textured grinding wheels: A review. *International Journal of Machine Tools and Manufacture*, 109, 8–35. doi: <https://doi.org/10.1016/j.ijmachtools.2016.07.001>
11. Young, H.-T., Chen, D.-J. (2005). Online dressing of profile grinding wheels. *The International Journal of Advanced Manufacturing Technology*, 27 (9-10), 883–888. doi: <https://doi.org/10.1007/s00170-004-2271-8>
12. Fan, K.-C., Lee, M.-Z., Mou, J.-I. (2002). On-Line Non-Contact System for Grinding Wheel Wear Measurement. *International Journal of Advanced Manufacturing Technology*, 19 (1), 14–22. doi: <https://doi.org/10.1007/pl00003964>
13. Kundrák, J., Fedorovich, V., Markopoulos, A. P., Pyzhov, I., Kryukova, N. (2014). Improvements of the Dressing Process of Super Abrasive Diamond Grinding Wheels. *Manufacturing Technology*, 14 (4), 545–554. Available at: <https://www.researchgate.net/publication/269129723>
14. Kalchenko, V., Kolohoida, A., Kuzhelnyi, Y., Morochko, V. (2018). Single pass finishing grinding with crossed axes tool and cylindrical part. *Technical sciences and technologies*, 4 (14), 9–17. doi: [https://doi.org/10.25140/2411-5363-2018-4\(14\)-9-17](https://doi.org/10.25140/2411-5363-2018-4(14)-9-17)