This paper reports the spatial modeling of the dressing process of grinding wheels with a conical calibration area to enable two-sided end grinding of cylindrical parts. Components with cylindrical end surfaces are common in the industry, for example, bearing rollers, crosses, piston fingers, and others. High requirements are put forward for the accuracy and quality of the end surfaces. The most efficient is to machine them simultaneously on a double-sided face grinding machine. To improve the quality, grinding is carried out by oriented wheels. The wheel's angle of rotation in the vertical plane is chosen subject to the uniform distribution of the allowance along a working surface; this makes it possible to reduce the temperature in the cutting zone and improve machining conditions. To improve the accuracy, grinding wheels are provided with a conical calibration area whose rectilinear generatrix is in the plane passing through the axis of wheel rotation and is perpendicular to the end of the part. The minimum permissible length of the calibration area depends on the diameter of the parts being machined; that makes it possible to utilize the work surface more efficiently. Two wheels are dressed simultaneously using diamond pencils that are symmetrically installed in a part feed drum. The angular velocity when dressing the rough area of the wheel is constant, which ensures its different development, and it gradually decreases when dressing the calibration area to provide for its constant roughness. In general, this prolongs the resource of grinding wheels and the quality of machining. The wheels are given axial movement to ensure the straightness of the cone calibration area. The dressing technique reported here can be used on machines equipped with a numerical software control system and without it. It could also be applied in the machining of parts with non-round ends

Keywords: double-sided grinding, crossed axes, wheel dressing, conical calibration area, diamond pencil

BUILDING A MODEL OF THE PROCESS OF SHAPING TAPERED CALIBRATING AREAS OF WHEELS AT THE TWO-SIDED GRINDING OF ROUND ENDS

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1. Introduction

Ever-increasing requirements for the accuracy and quality of articles as a prerequisite for their uninterrupted long-term operation stimulate industrial advancements. More attention is paid to the design and implementation of high-quality and high-performance equipment as a means of achieving competitiveness. In addition, the modern market requires sufficient flexibility [1]. Rapid reorientation of production is often achieved by using more versatile equipment with numerical control systems. Of significance is to develop not only new equipment that requires significant initial contributions but also to devise new methods and technologies based on existing ones.

Increasing the durability of articles is achieved in various ways. One of which is to design new structural materials with predetermined properties [2]. Tool engineering is being actively developed, offering more high-performance and accurate cutting tool designs and tool materials [3].

The final stage in parts manufacturing is their finishing on grinding and polishing machines [4]. It is these operations that provide the final accuracy of the dimensions and the required quality of surfaces.

Such components with high-precision end surfaces are widespread, for example, as bearing rollers, crosses of cardan shafts, piston fingers, springs, and others. The most productive technique is a simultaneous two-sided grinding of the ends of such parts. At the same time, in addition to the improved productivity, the accuracy of the mutual arrangement of end surfaces also increases. However, with the classic two-sided grinding with parallel axes of grinding wheels and a falling device, all allowance is removed when the part enters the machining area. As a result, there is significant wear of wheels and there is a need for frequent adjustment of their profile. More progressive machining schemes with crossed axes of the tool and part provide a uniform distribution of allowance and prolong the resource of grinding wheels. However, the machining scheme itself introduces a geometric error in the accuracy of the ends.

Therefore, devising new schemes of double-sided end grinding of round parts, for example, bearing rollers, piston fingers, and others, as well as methods for dressing grinding wheels, is an important scientific and technical task. Addressing this issue would improve the accuracy of machining and prolong the operational period of tools.

Modern metalworking machinery is equipped with numerical control systems, which improves its flexibility to perform various types of work. To describe the trajectories and speeds of movement of the machine bodies, special control programs are set. Their mathematical basis is the spatial models of the process of removing allowance and shaping.

Therefore, the construction and investigation of modular spatial mathematical models of the dressing process of a grinding wheel with conical calibration areas for double-sided machining of the ends of round parts is a relevant task.

2. Literature review and problem statement

A significant share in the market of grinding machines belongs to Junker Group [5]. It offers a number of double-sided grinding machines for different types of articles. In the machining area, parts are fed through the rotational movement of the falling drum into whose special holes blanks are pre-installed. The design of the machine provides for the possibility of machining with parallel axes of the tool and part or oriented wheels. It is also possible to periodically dress the working surfaces of tools.

The task to choose the dressing tool is tackled in work [6], which considers different types of diamond pencils and investigates dressing schemes and related equipment. However, there are no proposals and methods for improving existing schemes. Study [7] considers the shape of grinding wheels and their texture. The expediency of performing active and passive areas on the working surface of the grinding wheel has been proven. At the same time, active areas enable the removal of the allowance and shaping of the grinding process. The passive ones increase the space for removing chips from the machining area. The use of such grinding wheels improves the quality of machining.

In work [8], it is proposed to pre-dress the grinding wheels with double-sided end grinding. It is shown that predetermining the shape of the working surface affects the quality of the first parts of the batch, significantly reducing the time for the wheels to adjust. However, the hyperbolic shape of the wheel profile, which is proposed to be used in the cited work, could not provide high accuracy of surfaces as a result of curvature. Paper [9] reports measurement schemes for the kinematic, dynamic, and force parameters of double-sided grinding. The influence of various parameters on the quality of manufactured parts is proved; the control of the machining process is proposed. However, there are no practical recommendations on their optimal values.

In work [10], it is proposed to dress the periphery of the grinding wheel with a variable axial feed. This ensures different development of the working profile and improves the conditions in the machining area. Additionally, the cited work reports mathematical modeling of the dressing process, it is proposed to use a common modular model of the dressing tool. However, the shape of the diamond is described in the form of tetrahedra, which requires its orientation in space. Thus, at some angles of rotation, the faces of the working surface of the pencil would come out of contact. In addition, the cited work describes the formation of only the peripheral part of the grinding wheel. No features of dressing the end surface were considered.

Work [11] considers the impact of the quality of the machined surface of bearing rollers on the durability of their work. Study [12] reports methods for improving the quality of the surface layer of bearing rollers and shows that its condition significantly increases the life of units. The authors of [13] performed mathematical modeling of the process of double-sided end grinding of various parts with a round profile, as well as components with different diameters of the ends. They provided the notation of the mathematical models of the process of removal of allowance and shape formation, as well as studied the accuracy of the resulting end surfaces. However, when considering the dressing of the grinding wheel, the rotational movement of the dressing tool was not taken into consideration. Work [14] proposes a scheme for dressing the tool for double-sided end grinding of round parts. On the end surface of the grinding wheel, it is proposed to execute a calibration area but it is not defined how its dimensions and location should be determined. Mathematical models of tool dressing and double-sided grinding process have been built. It is shown that in the presence of conical calibration areas, there is no geometric error of the ends of the part. However, when describing the models of dressing, the functional dependence of the axial movement of the grinding wheel is not given, depending on the angle of rotation of the dressing tool. That makes it virtually impossible to write a control program and provide the necessary geometry of wheels.

The task to improve the quality of the surface layer of the ends of parts, as well as enhance their accuracy, can be solved by dressing grinding wheels with the formation of straight-line conical areas on them. The construction of spatial mathematical models could make it possible to consider and analyze in more detail the process of formation of the working end surface of the wheel at dressing. In addition, they would create a mathematical basis for compiling programs for machines with numerical control.

3. The aim and objectives of the study

The purpose of this study is to spatially model the process of shaping the conical calibration areas of wheels at the double-sided grinding of round ends. This would make it possible to determine the trajectory and angular speed of movement of the diamond pencil, which is a mathematical basis for writing control programs. Dressing grinding wheels with the formation of rectilinear conical calibration areas would improve the accuracy of double-sided end grinding while changing the angular speed of the wheel feed drum could ensure uniform development of the calibration area. This additionally improves the quality of machined ends and prolongs the resource of grinding wheels.

To accomplish the aim, the following tasks have been set:
– to determine the minimum permissible length of the calibration area;
– to build a spatial model of the dressing tool with a spherical work surface;
– to construct the spatial mathematical models of the process of removing allowance and shape formation when dressing a wheel;
– to determine the trajectory and angular velocity of relative movement of the diamond pencil and grinding wheel.

4. The study materials and methods

The object of this study is the process of removing the allowance and shaping when dressing an abrasive tool with the formation of a straight-line conical calibration area. Determining the general appearance and position of the calibration area is based on the use of the run-in method when shaping parts. The calculation of its minimum permissible length involves the basic geometric dependences from the mathematical software package Mathcad (United States of America).

Grinding wheels are dressed using a diamond pencil with a spherical work surface. The radius of rounding at its top is about 0.1 mm and can increase as a result of wear to 0.4...0.5 mm. The size of the radius of the diamond pencil is limited by the necessary development of the profile of the grinding wheel and its characteristics.

The working surface of the dressing tool and the grinding wheel is mathematically notated using three basic modules – rectangular, cylindrical, and spherical. Each of them determines the position of the point in space in the corresponding coordinate system. In this case, the working surface of a diamond pencil is described by a spherical tool module. And the surface of the grinding wheel is cylindrical. In general, the following modules are distinguished: instrumental, orientation, formation. To describe them, six $M1$, $M2$... $M6$ matrices with a dimensionality of 4×4 are applied, which determine the movement of a single point in the coordinate system. The analysis of modules and the calculation of specific geometric values were carried out in the Mathcad software, in which logical calculation blocks were additionally developed, using built-in functions.

5. Results of studying the dressing of conical calibration sections of wheels at the two-sided grinding of the ends of round parts

5. 1. Calculation of the minimum permissible length of the calibration area

Simultaneous machining of the ends of round parts is proposed to be carried out by oriented wheels with conical calibration areas on a double-sided face grinding machine (Fig. 1). Round parts 1 with radius R_p are installed in feed drum 2. They enter the machining area along the arc R_b, with a constant angular velocity ω_b. Machining is carried out by two grinding wheels 3 and 4, with a maximum radius $R_{w1}=R_{w2}$, which rotate at speed $\omega_{w1}=\omega_{w2}$. The axes of rotation of the drum that feeds articles and grinding wheels are previously in the same horizontal plane at distance L_c. In order to evenly distribute the allowance along the working surface of the wheels, they are rotated at angle $\alpha_{w1}=\alpha_{w2}$ in the vertical plane. The position of the calibration area is determined by the orientation of the tool in the horizontal plane $\beta_{w1}=\beta_{w2}$. At the same time, the general angle of orientation of grinding wheels δ_Σ can be determined as the geometric sum of the angles of rotation:

$$\delta_\Sigma = \sqrt{\alpha_{w1}^2 + \beta_{w1}^2} = \sqrt{\alpha_{w2}^2 + \beta_{w2}^2}. \tag{1}$$

The structure of the face grinding machines makes it possible to orient the wheels together with the grinding headstock. In this case, the rotation is carried out using special hinge 5, which is located in the conditional center of the coordinate system of the grinding headstock O_{gh}. The displacement of the coordinate system, for example, the right-hand wheel $O_{w1}X_{w1}Y_{w1}Z_{w1}$ relative to the coordinate system of grinding headstock 6 $O_{gh1}X_{gh1}Y_{gh1}Z_{gh1}$ is determined by the X_{gh1} and Z_{gh1} coordinates.

To exclude the geometric error of the end of the part during the double-sided grinding with oriented wheels, it is proposed to execute conical calibration areas on the end tool surface. They should be located in a plane that passes through the axis of rotation of the wheel and is perpendicular to the end of the machined part. In order to make the most of the working surface of the grinding wheel, it is desirable to provide for the minimum permissible length. In this case, the draft allowance will be removed by a larger area of the wheel, which will reduce its instantaneous value and, accordingly, reduce the heat resistance of machining. The scheme for determining the minimum permissible length of the calibration area is shown in Fig. 1, c; it corresponds to the view from side A. To simplify and visualize the diagram, the article feed drum is not given while only the radius R_b of the location of blanks 1 is shown. And, accordingly, the trajectory of their movement in the grinding process.

The maximum radius of the calibration area of the grinding wheel is taken equal to the radius of the tool $R_{k\max}=R_w$. To determine the minimum length of the calibration area, consider the two positions of a machined workpiece. Position I: the cylindrical workpiece enters the calibration grinding zone; position II – it exits the machining area. The condition of shape formation is determined by the equality to zero of the product of the velocity and guide vector ($n{\times}V=0$). Thus, the endpoint A_2 of the calibration area is found as the intersection point of the profile of the part in position II and the line tangent to it, passing through the center of the grinding wheel. Thus, the plane to which the calibration area belongs is at angle θ_k to the horizontal plane $O_{w1}Y_{w1}Z_{w1}$:

$$\theta_k = \theta_{wex} - \Delta\theta, \tag{2}$$

where θ_{wex} is the angle of rotation of the radius line of the tool, connected to the center of the part, when it leaves the machining area, rad; $\Delta\theta$ is the angle between the radius lines passing through the center of the part and tangent to its surface.

These angles can be calculated from the following dependences:

$$\theta_{wex} = a\cos\left(\frac{L_c^2 + R_w^2 - R_b^2}{2 \cdot L_c \cdot R_w}\right), \tag{3}$$

$$\Delta\theta = a\cos\left(\frac{2 \cdot R_w^2 - R_p^2}{2 \cdot R_w^2}\right), \tag{4}$$

where L_c is the distance between the centers of the grinding wheel and the article feed drum, mm; R_w is the grinding wheel radius, mm; R_b is the feed drum radius, mm; R_p is the radius of the machined part, mm.

The equation of the straight line containing the calibration area in the coordinate system of the wheel is as follows:

$$x_k(y_k) = \text{tg}(-\theta_k) \cdot y_k, \tag{5}$$

where $\text{tg}(-\theta_k)$ is the angular coefficient of inclination of the line containing the calibration area; y_k is the current coordinate along the $O_{w1}Y_{w1}$ axis, mm.

To determine the beginning of the calibration area, it is necessary to find the coordinates of point A_1. That is, the points of contact of the cylindrical surface of the part moving along the arc of the wheel R_b, with a defined straight line.
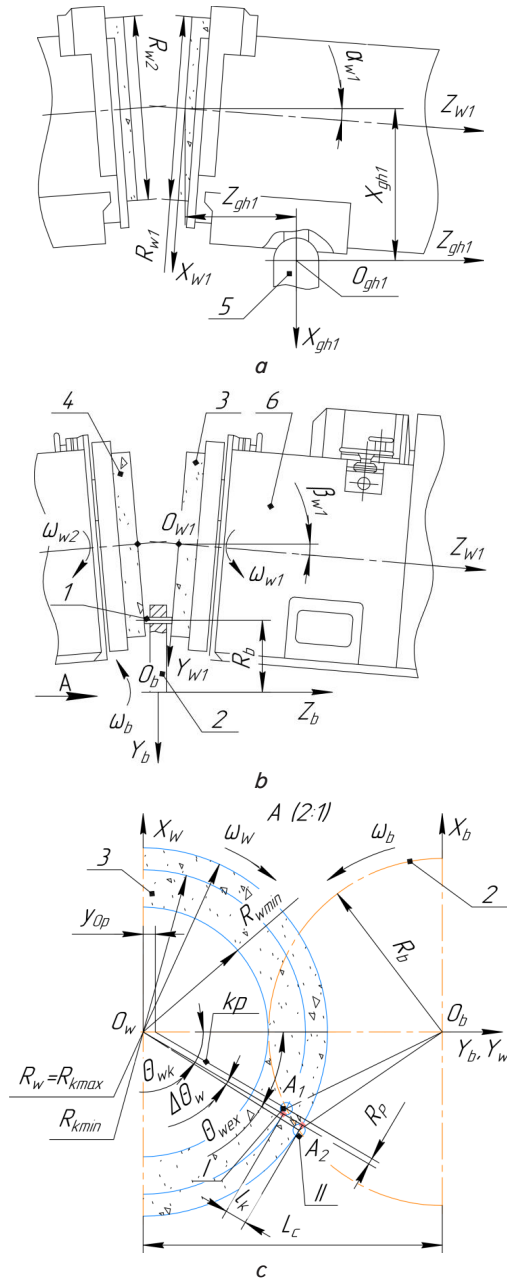
Fig. 1. Schematic showing the double-sided grinding of the ends of round parts using wheels with conical calibration areas: *a* — front view; *b* — view from above; *c* — enlarged view *A*

Let us write the equation of the line *kp*, which is parallel to the calibration area and is at a distance from it equal to the radius of the machined part:

$$x_{kp}\left(y_{kp}\right) - x_{0p} = \mathrm{tg}\left(-\theta_k\right) \cdot \left(y_{kp} - y_{0p}\right), \quad (6)$$

where y_{kp} is the current coordinate along the $O_{w1}Y_{w1}$ axis, mm; y_{k0}, x_{k0} are the coordinates of the intersection of the straight line *kp* with the $O_{w1}Y_{w1}$ axis, mm.

Fig. 1 shows that:

$$x_{0p} = 0,$$

$$y_{0p} = \frac{R_p}{\sin\theta_k}. \quad (7)$$

Given (7), the straight-line equation (6) takes the form:

$$x_{kp}\left(y_{kp}\right) = \mathrm{tg}\left(-\theta_k\right) \cdot y_{kp} - \mathrm{tg}\left(-\theta_k\right) \cdot \frac{R_p}{\sin\theta_k}. \quad (8)$$

The equation of the arc along which blanks move in the coordinate system of the grinding wheel is as follows:

$$x_b\left(y_b\right) = -\sqrt{R_b^2 - \left(y_b - L_c\right)^2}, \quad (9)$$

where y_b is the current coordinate of the arc point of the center of the workpiece along the $O_{w1}Y_{w1}$ axis, mm.

The coordinates of the center of a part (x_{cI}, y_{cI}) when it enters the calibration zone (position I) can be found as coordinates of the intersection point of lines (8) and (9):

$$\mathrm{tg}\left(-\theta_k\right) \cdot y_{cI} - \mathrm{tg}\left(-\theta_k\right) \cdot \frac{R_p}{\sin\theta_k} =$$
$$= -\sqrt{R_b^2 - \left(y_{cI} - L_c\right)^2} \Rightarrow y_{cI}, \quad (10)$$

$$x_{cI} = -\sqrt{R_b^2 - \left(y_{cI} - L_c\right)^2}. \quad (11)$$

The perpendicular, drawn from the center of a part (x_{cI}, y_{cI}) to the straight line containing the calibration area, takes the form:

$$x_{kper}\left(y_{kper}\right) = \frac{1}{\mathrm{tg}\left(\theta_k\right)} \cdot \left(y_{kper} - y_{cI}\right) + x_{cI}, \quad (12)$$

where x_{kper}, y_{kper} are the current coordinates of the points of the line that is perpendicular to the calibration area and passes through the center of the part when it enters the calibration zone in the coordinate system of the wheel $O_{w1}X_{w1}Y_{w1}$, mm.

The coordinates of the beginning of the calibration area are defined as the point of intersection of the line, described by equality (5) and perpendicular to (12), that is,

$$\mathrm{tg}\left(-\theta_k\right) \cdot y_{A1} = \frac{1}{\mathrm{tg}\left(\theta_k\right)} \cdot \left(y_{A1} - y_{cI}\right) + x_{cI} \Rightarrow y_{A1}, \quad (13)$$

$$x_{A1} = -\sqrt{R_b^2 - \left(y_{A1} - L_c\right)^2}. \quad (14)$$

The radius of the beginning of the calibration area in a working plane is equal to:

$$R'_{k\min} = \frac{y_{A1}}{\cos\theta_k}. \quad (15)$$

Given the total angle of rotation of the grinding wheel, the radius of the beginning of the calibration area in the end plane is smaller by:

$$R_{k\min} = R'_{k\min} \cdot \cos\delta_\Sigma. \quad (16)$$

Thus, the coordinates of the point A_1 (x_{A1}, y_{A1}), that is, the beginning of the calibration area, for a certain size of the machine, depend only on the radius of a workpiece being machined. Accordingly, the length of the calibration area also depends only on the size of the part and does not depend on the allowance that is removed.

For example, when grinding ($R_w = 225$ mm) the ends of rollers ($R_p = 7.5$ mm), which move in the feed drum in a circle with radius $R_b = 212$ mm, and $L_c = 365$ mm, $\delta_\Sigma = 0.123$ rad, the radius of the beginning of the calibration area $R_{k\,min} = 208.785$ mm. And the minimum permissible length of the calibration area, which would ensure a zero geometric error of the ends, is 16.215 mm.

5. 2. Building a spatial model of the dressing tool with a spherical work surface

As a tool for dressing a working surface of the grinding wheel with conical calibration areas, we take a diamond in the frame. In order to conduct modular spatial modeling of the dressing process, let us notate a mathematical model of the working surface of the diamond. One of the most common options for describing the shape of a diamond is its representation in the form of a cone with a rounded vertex. At the same time, it is the top of the diamond that mainly participates in work, that is, a spherical area with a radius of ρ (Fig. 2, *a*). Its mathematical description is:

$$\bar{r}_d(\varphi,\theta) = M6(\theta) \cdot M5(\varphi) \cdot M3(\rho) \cdot \bar{e}4, \qquad (17)$$

where ρ is the radius of rounding the top of the diamond, mm; φ is the current angle of rotation of a single point around the $O_d Y_d$ axis, $\varphi = 0...\varphi_k$ rad; φ_k is the angle that determines the transition from the spherical section of the top of the diamond to its cone part, $\varphi_k = 0.5 \cdot \psi$ rad; θ is the current angle of rotation of a single point around the $O_d Z_d$ axis, $\theta = 0...2 \cdot \pi$ rad.

A cone straight section of the diamond tool is described by the following equality:

$$\bar{r}_d(\varphi,\theta) = M6(\theta) \cdot M1(h(\varphi)) \times$$
$$\times M3(-h(\varphi)) \cdot M5(\varphi_k) \cdot M3(\rho) \cdot \bar{e}4, \qquad (18)$$

where φ is the current angle of rotation of a single point around the $O_d Y_d$ axis, $\varphi = \varphi_k...\pi$ rad; $h(\varphi) = \sin(\pi/4) \cdot \rho \cdot \tan(\varphi - \varphi_k)$ is the function that sets the current coordinates of the point of the rectilinear section of the diamond tool along the $O_d X_d$ and $O_d Z_d$ axes, depending on a change in the current angle φ, mm.

A general model of the dressing instrument (Fig. 2, *b*) can be described by combining equations (17), (18) through the introduction of a Heaviside function.
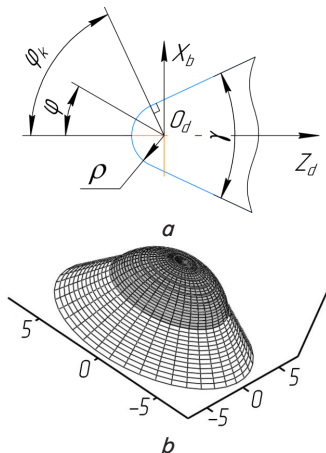

Fig. 2. A working part of the dressing tool:
a — estimation scheme; *b* — mathematical model

In the process of modeling the dressing of the wheel, one can use a simplified model of the diamond tool (17) considering a small amount of removable material. In addition, by changing the radius of rounding the top of the diamond ρ, the wear of the dressing tool is taken into consideration.

5. 3. Construction of spatial mathematical models of the process of removing allowance and shaping when dressing a wheel

We propose that the grinding wheels with conical calibration areas should be dressed at the double-sided grinding of the ends of round parts by using two diamond tools. In this case, diamond pencils are installed in article feed drum 2 (Fig. 1) symmetrically relative to the central plane $O_b X_b Y_b$. In order to form a rectilinear conical calibration area, grinding wheels 3 and 4 are additionally moved along the $O_{w1} Z_{w1}$ and $O_{w2} Z_{w2}$ axes, respectively. To ensure the constant development of the end working surface on the calibration area, the article feed drum moves at a variable angular speed.

A general mathematical model of shaping the end working surface of wheels can be described by the equation:

$$\bar{r}_w(\varphi,\theta) = C^F_{\theta_w,z_w} \cdot S^O_{\alpha_w,\beta_w} \cdot P^T_{x_{gh1},L_c,z_{gh1}} \cdot C^T_{\theta_b,R_b} \cdot \bar{r}_d(\varphi,\theta), \qquad (19)$$

where $C^T_{\theta_b,R_b}$ is the cylindrical module of transition from the coordinate system of the diamond tool to the coordinate system of the feed drum; $P^T_{x_m,y_m,z_m}$ – rectangular module of transfer to the coordinate system of the machine, to describe the orientation of the wheels; $S^O_{\alpha_w,\beta_w}$ – spherical orientation module; $C^F_{\theta_w,z_w}$ – cylindrical shape formation module at dressing.

Equation (19) can be rewritten as:

$$\bar{r}_w(\theta_w,z_w,\theta_b,\varphi,\theta) = M6(\theta_w) \cdot M3(z_w) \cdot M4(\beta_w) \times$$
$$\times M5(\alpha_w) \cdot M3(z_{gh1}) \cdot M2(L_c) \cdot M1((x_{gh1}) \times$$
$$\times M6(\theta_b) \cdot M2(R_b) \cdot \bar{r}_d(\varphi,\theta), \qquad (20)$$

where R_b is the radius of movement of the top of the diamond pencil in the feed drum, mm; θ_b is the current angle of rotation of the feed drum, rad; L_c – the distance between the center of the feed drum and the axis of rotation of the grinding wheel along the coordinate line $O_{w1} Y_{w1}$, mm; x_{gh1}, z_{gh1} – the distance from the beginning of the coordinate system of the wheel to the rotary hinge, mm; α_w, β_w are the angles of orientation of the grinding wheel relative to the $O_w Y_w$ and $O_w X_w$ axes, respectively, rad; z_w – displacement of the grinding wheel along the $O_w Z_w$ axis, mm; θ_w – the current angle of rotation of the grinding wheel, rad.

The mathematical model of the end surface of the grinding wheel (20) includes five variables. In this case, the parameters φ and θ determine the working surface of the dressing tool. The angle of drum rotation θ_b must be set in the form of functional dependence on the angle of rotation of the grinding wheel θ_w: this would ensure the constant development of the calibration area. The axial movement z_w should be functionally dependent on the angle of rotation of the feed drum θ_b in order to form a rectilinear conical area.

5. 4. Determining the trajectory and angular velocity of the relative movement of the diamond pencil and grinding wheel

Consider in more detail the formation of a cone calibration area of the right-hand grinding wheel 3 (Fig. 1). As noted above, the position and length of the calibration area are deter-

mined by the total orientation angle of the tool and the diameter of the parts being machined. According to the proposed method, it is necessary to create a curve on the calibration area, which by nature would correspond to the Archimedes spiral with the constant step S_a. To this end, it is necessary to change, namely, reduce the angular speed of rotation of the feed drum when moving to the machining of the calibration area.

With the minimum length of the calibration area, the radius of its beginning corresponds to the value of R_{kmin}, and the end – R_{kmax}. However, when machining parts with some radius R_p, when crossing the arc of movement of articles in the feed drum R_b with a minimum radius of R_{kmin}, the endpoint of the part touches the calibration line. Then, in the case of dressing with a diamond pencil, with a relatively small radius of rounding the vertex ρ, when crossing the arc of its feed with the radius of R_{kmin}, it is at a distance from the point A_1, A_1A_1' (Fig. 3). Given that this is a conical surface of the rotation the point A_1' is to be located somewhat lower, and, to ensure the straightness of the calibration area, it is necessary to give the wheel an additional axial movement z_w. The only point at which $z_w=0$ is point A_0 – the intersection of the arc of motion of the diamond pencil R_b with a calibration area. We shall consider this point basic and determine axial movements relative to it. The coordinates of pole A_0 can be defined as the coordinates of the intersection point of the line containing the calibration area (5) and the arc of the feed drum (9):

$$\operatorname{tg}\left(-\theta_k\right)\cdot y_{A0} = -\sqrt{R_b^2 - \left(y_{A0} - L_c\right)^2} \Rightarrow y_{A0}, \tag{21}$$

$$x_{A0} = -\sqrt{R_b^2 - \left(y_{A0} - L_c\right)^2}, \tag{22}$$

where x_{A0}, y_{A0} are the coordinates of point A_0 in the coordinate system of the grinding wheel, mm.

The radius of placement of the A_0 pole on the end surface of the grinding wheel:

$$R_{A0} = y_{A0} \cdot \frac{\cos\delta_\Sigma}{\cos\theta_k}. \tag{23}$$

The current angle of rotation of the feed drum with a diamond pencil when forming the pole A_0:

$$\theta_{bA0} = a\cos\left(\frac{L_c^2 + R_b^2 - R_{A0}^2}{2\cdot L_c \cdot R_b}\right). \tag{24}$$

Determine the necessary axial movements and the corresponding angles of rotation of the feed drum and grinding wheel during the formation of points of the calibration area corresponding to the current radius of the wheel to the pole and after it.

Consider the part of the calibration area that lies below the A_0 point, that is, the A_0A_2 segment. We assume that by the time of dressing the point A_0, the grinding wheel has executed N revolutions and its current position angle is $2\pi N+\theta_{wk}$ or $2\pi N+\theta_{wA0}$. At the same time, the feed drum rotated at angle θ_{bA0}. To form a certain roughness in increments S_a on the calibration area, it is necessary to ensure compliance with the angle of rotation of the feed drum θ_{bi_afA0} and the axial movement of the grinding wheel z_{wi_afA0} with the angle of tool rotation θ_{wi_afA0}.

In this case, the radius of a certain i-th point on the grinding wheel is determined as:

$$R_{i\_afA0} = R_{A0}+i\cdot S_a, \tag{25}$$

where i is the serial number of the point under consideration, $i=1,2...$

Then the angle of rotation of the grinding wheel and the feed drum:

$$\theta_{bi\_afA0} = a\cos\left(\frac{L_c^2 + R_b^2 - R_{i\_afA0}^2}{2\cdot L_c \cdot R_b}\right). \tag{26}$$

$$\theta_{wi\_afA0} = 2\cdot\pi\cdot N + i\cdot 2\cdot\pi + a\cos\left(\frac{L_c^2 + R_{i\_afA0}^2 - R_b^2}{2\cdot L_c \cdot R_{i\_afA0}}\right) =$$
$$= 2\cdot\pi\cdot\left(N+i\right)+a\cos\left(\frac{L_c^2 + R_{i\_afA0}^2 - R_b^2}{2\cdot L_c \cdot R_{i\_afA0}}\right). \tag{27}$$

To determine the axial movement of the grinding wheel, we draw a perpendicular from the point of A_{i_afA0} to the calibration line and find the point of its intersection with the arc of the diamond pencil movement.
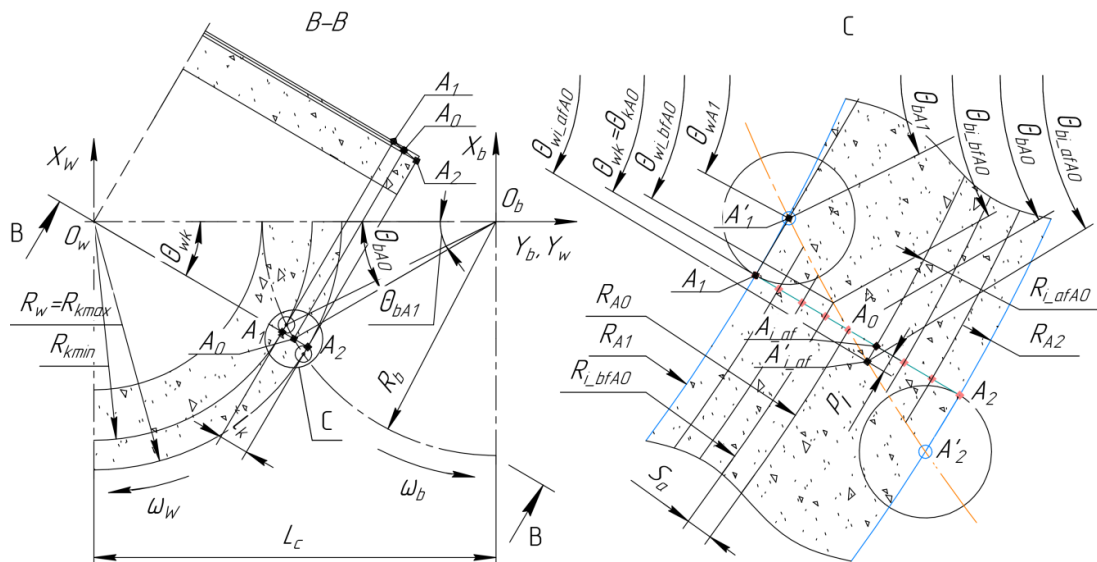

Fig. 3. Diagram for determining the axial movement of the grinding wheel

Coordinates of the point A_{i_afA0}:

$$x_{i\_afA0} = \frac{R_{i\_afA0}}{\sin\theta_{wi\_afA0}},$$

$$y_{i\_afA0} = \frac{R_{i\_afA0}}{\cos\theta_{wi\_afA0}}. \tag{28}$$

The equation of the perpendicular drawn from the point A_{i_afA0}:

$$x_{kpi\_afA0}\left(y_{kpi\_afA0}\right) =$$
$$= \frac{1}{tg(\theta_k)} \cdot \left(y_{kpi\_afA0} - y_{i\_afA0}\right) + x_{i\_afA0}, \tag{29}$$

where x_{kpi_afA0}, y_{kpi_afA0} are the current coordinates of points lying on a straight line perpendicular to the calibration area and passing through the point A_{i_afA0}, mm.

The coordinates x_{pi_afA0}, y_{pi_afA0} of the intersection of the drawn perpendicular with the arc of motion of the dressing diamond:

$$\frac{1}{tg(\theta_k)} \cdot \left(y_{pi\_afA0} - y_{i\_afA0}\right) + x_{i\_afA0} =$$
$$= -\sqrt{R_b^2 - \left(y_{pi\_afA0} - L_c\right)^2} \Rightarrow y_{pi\_afA0}, \tag{30}$$

$$x_{pi\_afA0} = -\sqrt{R_b^2 - \left(y_{pi\_afA0} - L_c\right)^2}. \tag{31}$$

The length of the resulting section:

$$p_i = \sqrt{\left(x_{i\_afA0} - x_{pi\_afA0}\right)^2 - \left(y_{i\_afA0} - y_{pi\_afA0}\right)^2}. \tag{32}$$

The machining of the conical surface, in contrast to flat, predetermines some spatial curvature. Thus, when drawing an arc with a radius of R_{i_afA0}, it will cross the curve of movement of the diamond pencil at a point located at some distance from the previously drawn perpendicular. This distance is the amount of additional axial movement of the grinding wheel. To determine it, we find the length of the chord of the circle with a radius of R_{i_afA0}, which is limited by the angles θ_{wA0} and θ_{wi_afA0}:

$$h_i = \sqrt{2 \cdot R_{wi\_afA0}^2 - 2 \cdot R_{wi\_afA0}^2 \cdot \cos\left(\theta_{wi\_afA0} - \theta_{wA0}\right)}. \tag{33}$$

Knowing the length of the perpendicular p_i, the chord h_i, and the angle that is opposite to the chord $\psi_i = 90 - \theta_{wi\_afA0} + \theta_{wA0}$ in the triangle $p_i h_i z_{wi\_afA0}$, the instantaneous movement of the grinding wheel can be determined from the following expression:

$$z_{wi\_afA0} = p_i \cdot \cos\psi_i + 0.5 \cdot \sqrt{4 \cdot p_i^2 \cdot \cos^2\psi_i - 4 \cdot \left(p_i^2 - h_i^2\right)}. \tag{34}$$

Thus, equations (26), (27), and (34) determine the relationship between the angle of rotation of the feed drum, the axial movement, and the angle of rotation of the grinding wheel when dressing the calibration area within the section between points A_0 and A_2. Equations for determining the corresponding dependences when dressing the section $A_0 A_1$, which is located above the pole, are determined similarly.

Each subsequent point A_{i_bfA0} is selected in the direction of reducing the diameter in a step of S_a. At the same time, unlike the previous case, the radius of the current point would decrease:

$$R_{i\_bfA0} = R_{A0} - i \cdot S_a. \tag{35}$$

Given the reverse order of calculation, the angle of rotation of the grinding wheel also decreases:

$$\theta_{wi\_afA0} = 2 \cdot \pi \cdot (N - i) + a\cos\left(\frac{L_c^2 + R_{i\_afA0}^2 - R_b^2}{2 \cdot L_c \cdot R_{i\_afA0}}\right). \tag{36}$$

The procedure of calculating the angle of rotation of the feed drum (26) and the value of the axial movement of the grinding wheel (34) remains unchanged.

Therefore, the calculated current values of the angular coordinates of the feed drum and grinding wheel, as well as the linear movement of the wheel, are the input data for writing the control program of dressing. The exclusion of the loop parameter i and the transformation of the calculation results of equations (26), (27), (34), (36) into functional dependences of the type $\theta_b(\theta_w)$ and $z_w(\theta_w)$ can be carried out by standard means of the Mathcad software. Substituting them in the mathematical model of the process of dressing the end surface of the grinding wheel (20) leaves only three independent parameters. The variables φ and θ forming the tool surface of the diamond and the current angle of rotation of the grinding wheel θ_w. Thus, the mathematical model of the process of removal of allowance and shaping at dressing (20) becomes fully defined, which makes it possible to conduct research into the characteristics of the cutting process.

6. Discussion of results of studying the process of dressing wheels with the formation of conical calibration areas

The proposed scheme for dressing grinding wheels (Fig. 1) ensures the simultaneous formation of two wheels and can be used not only on machines equipped with CNC systems but also without them. Due to the simultaneous dressing of two wheels, the time of preparation for work is reduced by 50 % and, accordingly, the overall productivity of the equipment increases.

We calculated the minimum permissible length of the calibration area (16), which is in the plane passing through the axis of rotation of the grinding wheel and perpendicular to the end of the part. The use of a minimum-sized calibration area allows for better utilization of the working area of the grinding wheel and increases its resource. The angle of rotation of wheels in the vertical plane is selected subject to the uniform distribution of allowance along the rough part of the wheel. The orientation angle in the tool in the horizontal plane determines the position of the calibration area.

When dressing rough and finishing areas, the angular speed of the feed drum is constant; this ensures the formation of different roughness along the radius line and improves the conditions in the cutting zone. In the case of dressing the calibration area, the angular velocity gradually decreases (36); this ensures the constant development of this part of the

surface. That improves the quality of grinding ends, unlike known methods where the tool is dressed at constant feeding.

We have built modular mathematical models of the tool surface of a diamond pencil (18) (Fig. 2) and the process of removing the allowance and shaping at dressing (20). The use of a simplified model of the dressing tool is proposed, which is advisable given the small thickness of the cut layer. In addition, the mathematical model of the diamond pencil takes into consideration its wear, by changing the radius at the top.

We have established the dependence of the axial movement of the grinding wheel (34) on the angle of rotation of the feed drum at dressing in order to form a straight-line calibration area. The presence of a calibration area of a certain shape eliminates the occurrence of a geometric error of the end of the part, which increases the overall accuracy of machining. This distinguishes our result from the standard methods of dressing where the dressing tool moves only along the arc of the wheel; that leads to the following: the resulting calibration area is in the form of a fourth-order curve, which makes it impossible to obtain a flat end and causes an error in shape. Th reported dependences and modular models are the mathematical basis for writing control programs.

However, this work did not examine the minimum length of the calibration area for machining the ends of non-round parts. In addition, it is advisable to perform additional calculations for the machining of parts that rotate in the process of double-sided grinding.

7. Conclusions

1. We have determined the minimum permissible length of the calibration section of the grinding wheel during the two-sided machining of the ends of round parts. It has been shown that its length depends only on the diameter of the articles machined and does not depend on the amount of allowance that is removed. The execution of a calibration part with minimal dimensions makes it possible to better utilize the working surface of the grinding wheel and increase its resource. In addition, it reduces the amount of allowance that is removed per unit of time, as a result of which the heat intensity of the process decreases while the quality of the surface layer of the machined parts is increased.

2. A general model of the dressing tool has been built, with the main working part in the form of a sphere whose radius is equal to the radius of the rounding of the diamond pencil and an additional cone part that participates in work in the case of an increase in the allowance for dressing. The proposed model takes into consideration the wear of the dressing tools by adjusting the radius of the sphere.

3. The general modular spatial models of adjustment of grinding wheels for double-sided grinding of ends of round parts, such as bearing rollers, piston fingers, and others have been proposed. On the end surface of the grinding wheels, one forms a calibration area in the form of a straight line, which lies in the plane passing through the axis of rotation of the wheel and is perpendicular to the end of the part. To improve the quality of machining, the calibration area is dressed with a change in the angular speed of the diamond pencil; this ensures its uniform development. In this case, the feed of the drum at the dressing of the rough area is greater in value and constant in time. Thus, the variable roughness of the wheel is formed, which facilitates the removal of chips during rough and finishing grinding and improves the quality of machining.

4. We have determined the instantaneous axial movements of the grinding wheel depending on the angle of rotation of the feed drum, which form a rectilinear calibration area. The relationship between the angular velocity of the grinding wheel and the dressing tool was found. This makes it possible to achieve the same development of the working surface of the calibration area, which increases the quality of grinding the ends of round parts. Applying the established dependences makes it possible to record the control program of the dressing process.

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