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New Calculation Methodology of the Operations Number of Cold Rolling Rolls Fine Grinding

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Abstract: This article considers the methods of calculating the number of operations for the fine grinding of cold rolling rolls which allows one to ensure the least labor-intensive processing of the part. Based on the analysis of the patterns in the operation of single abrasive grains, the dependence of the productivity of the fine-grinding process on the grain size of the wheel, the grinding allowance, the grinding mode, the size of the workpiece, and the wheel, is proposed. To analyze the productivity of the finishing grinding processes, a productivity indicator, independent of the size of the wheel and the workpiece, is analyzed, and the impact on the productivity indicator of the number of finishing grinding operations, as well as the following sequence of their optimization, is established. To simplify the calculation of the optimal number of operations, graphs and a nomogram are constructed. According to the proposed methodology, the calculation of the number of finishing operations of cold rolling rolls of various sizes was carried out. Experimental verification of the proposed theoretical dependencies and methods for calculating the optimal number of grinding operations was also carried out.

Keywords: fine-grained wheels; grinding; operation; performance indicator; the least labor intensity of processing; grinding mode

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1. Introduction

One of the high-performance methods of finishing parts is grinding them with fine-grained wheels. Circular external grinding with fine-grained wheels can provide parts with a processing accuracy of five accuracy standards, with a surface roughness of $Ra = 0.02 - 0.01$ microns [1]. The productivity of the process is higher than the productivity of such widespread finishing methods as superfinishing and semi-mechanical finishing [2–7].

Grinding of parts with fine-grained wheels is used in the ball bearing, machine tool, and instrument-making industries, as well as in the processing of cold rolling rolls in the metallurgical industry [8]. In recent years, models of high- and especially high-precision circular grinding machines have been developed and mastered, and manufacturing technology and formulations of fine-grained wheels have also been developed. All of these are prerequisites for the wider introduction of grinding with fine-grained wheels into the industry as a progressive finishing method.

The main issues in the development of technological processes for grinding parts to obtain a surface roughness of $Ra = 0.02$ and surface accuracy according to the fifth quality are: determining the number of grinding operations of parts, choosing the characteristics of grinding wheels, and assigning grinding modes [9–12].

Recommendations on these issues are diverse [12]. For example, for the case of grinding the rolls of cold rolling machines to obtain $Ra = 0.02 - 0.01$ microns, various recommendations suggest carrying out finishing in one, two, three, four, or more operations [10]. The variety of recommendations for grinding with fine-grained wheels is explained not only by the multiplicity of factors affecting the process, but also by the lack of methods for optimizing the process.

The use of fine-grained wheels makes it possible to provide a given roughness of $Ra = 0.04 - 0.02$ microns for the surface of the rolls; however, the complexity of their processing increases sharply, and intensive wear of the abrasive tool is observed [13]. Attempts to intensify the process lead to a deterioration in the output quality indicators; that is, it is not possible to obtain a part with a given surface roughness. It is possible to solve this problem by optimizing the number of technological operations. Similarly to other process parameters, the optimal number of operations when grinding parts with fine-grained wheels should be determined on the basis of a technical and economic analysis. The complexity of processing the part can be taken as a parameter reflecting a variable share of the cost of the process. With an increase in the number of finishing operations, the auxiliary time increases, due to the additional costs of rearranging the part and the wheel, and the machine processing time of the part decreases, since larger-grained wheels are used for intermediate operations, providing greater productivity [12]. When constructing technological processes of grinding in one, two, three, or more operations, each option must ensure that the part is obtained with a given surface roughness, a given accuracy, and the required quality of surface layers. The optimal one can be taken as the one that provides the least complexity in processing the part [13].

Thus, the object of research is the process of the fine grinding of cold rolling rolls.

The subjects of the study are the regularities of determining the optimal number of operations that ensures the roughness of the surface of cold rolling rolls is $Ra = 0.04 - 0.02$ microns with the least complexity of processing the part.

The present work aims, based on theoretical and experimental study of the grinding process with fine-grained wheels, to develop a methodology for calculating the number of operations for the fine grinding of cold rolling rolls in order to obtain a surface roughness of $Ra = 0.04 - 0.02$ microns, which allows for the least labor-intensive processing of the part.

2. Mathematical Derivation of Applied Relationships

The complexity of finishing the part T_K during the grinding process in one, two, three, or more operations can be calculated according to the generally accepted formula [14]:

$$T_K = T_M + T_B + T_{eq} + T_{nn} + \frac{T_{nc}}{n_{pp}} \tag{1}$$

where T_M is machine part processing time, min; T_B is auxiliary time, min; T_{eq} is time for organizational and technical maintenance of the workplace, min; T_{nn} is time for rest and natural needs, min; T_{nc} is preparatory and final time, min; n_{pp} is the number of parts in the package. Values T_B, T_{eq}, T_{nn}, and T_{nc} can be found according to the normative data, and the machine grinding time of the part can be determined by the equation:

$$T_M = f/Q_\Omega \tag{2}$$

where f is the surface area to be processed, in mm^2; Q_Ω is the grinding performance by processing area, mm^2 ·min^{-1}.

Grinding performance with fine-grained wheels on the area processed per unit of time Q_Ω, can be expressed in terms of the grinding performance with regard to the volume of metal removed per unit of time, Q_M, by the formula:

$$Q_\Omega = Q_M/\Omega \tag{3}$$

where Ω is the radial allowance for grinding, in mm.

During grinding, the metal is removed from the workpiece by single abrasive grains, so the grinding performance, Q_M, depends on the number of slices and the volume of metal removed during a single slice, which are determined by the shape and size of the slice. The most typical cuts in finishing grinding processes are segmented cuts [14].

Figure 1 shows a diagram of a single mark applied to a polished surface, where S_1 and S_2 are areas of bulk formed on the surface of the material due to plastic deformation by its abrasive grain, in μm^2. At the accepted coordinates, the elementary volume of one-quarter of the segmented mark is determined by the equation:

$$dV_p' = \phi(y,z)dydz \tag{4}$$

where $\phi(y,z)$ is the equation of the surface limiting the volume of the mark.

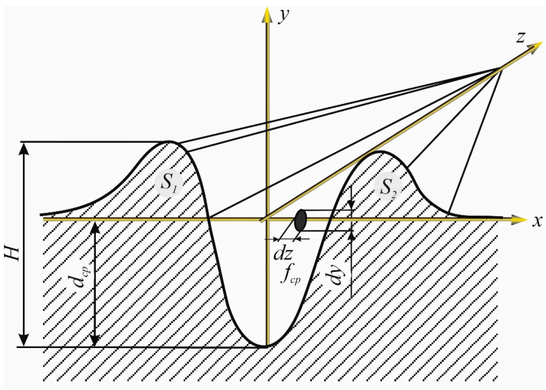


Figure 1. Diagram of a single mark applied by a diamond cone to the polished surface of a steel sample.

Integrating Equation (4) and multiplying the result by four, we obtain the full volume of the segmented mark, dV_p:

$$dV_p = \int_0^y \int_0^z \phi(y,z)dydz \tag{5}$$

The number of single slices per minute N can be determined by the equation:

$$N = \Psi \cdot B \cdot V_K \cdot n_g \tag{6}$$

where n_g is the number of grains located on a single site in 1 mm^2 of the wheel surface, Ψ is the scale factor (during processing with fine-grained wheels, $\Psi = 6 \times 10^4$), B is wheel height, and V_K is the circumferential speed of the wheel.

It is shown in [15–17] that the abrasive grains on the surface of the wheel are located at different levels, and therefore are embedded in the processed metal at different depths. On a single site perpendicular to the radius of the wheel, the distribution of vertices can be expressed by the dependence:

$$dn_g = f(y)dy \tag{7}$$

where dn_g is the number of grains enclosed between the surface of the wheel in depth y and $y + dy$ in the direction of the radius; and $f(y)$ is the function of the distribution of the vertices of abrasive grains in depth.

The volume of metal removed per minute by grains enclosed in a layer dy, taking into account Equations (5)–(7), is determined by:

$$dQ_M = 2.4 \cdot 10^5 \cdot B \cdot V_K \left[f(y) \int_0^y \int_0^z \phi(y,z)dydz \right] dy \tag{8}$$

Integrating and substituting the value (8) into Equation (3) we obtain:

$$Q_{\Omega} = \frac{2.4 \cdot 10^5 \cdot B \cdot V_K \left[f(y) \int_0^y \int_0^z \phi(y,z) dy dz \right] dy}{\Omega} \quad (9)$$

To use Equation (9), it is necessary to know the function of the distribution of abrasive grains in depth and the equation of the surface that limits the volume of the mark.

According to the data of [1], in the first approximation, it is quite acceptable to consider a segmented structure as two equal pyramids with a common base. In this case, the volume of a single mark can be determined by the equation:

$$V_p = \frac{2 \cdot 10^{-6}}{3} \cdot f_{cp} \cdot L \quad (10)$$

where f_{cp} is the median cross-sectional area of the mark, in μm^2; L is half of the contact area with a segmented cut, equal to the contact arc with a comma cut, in mm.

According to Maslov [14], the length of the contact area, L, during circular external grinding can be determined by the equation:

$$L = 3.16 \cdot 10^{-2} \cdot \left(1 \pm \frac{V_W}{60 \cdot V_K} \right) \cdot \sqrt{\frac{D \cdot d \cdot a_{cp}}{D + d}} \quad (11)$$

where D is the diameter of the grinding wheel, in mm; a_{cp} is the average depth of embedding of the abrasive grain into the processed metal, in mm; V_W is the circumferential speed of the workpiece; and m·s^{-1}; d is the diameter of the workpiece, in mm.

The middle area of the mark, neglecting the elastic deformations of the metal, can be determined by the geometry of the vertex of the abrasive grain [1].

For the case when the thickness of the slice lies within $a_{cp} \backslash \rho \leq 0.29$ the median cross-sectional area can be calculated using an approximate dependence:

$$f_{cp} = 1.8 \cdot a_{cp} \cdot \sqrt{\rho \cdot a_{cp}} \quad (12)$$

The dependence (12) is obtained by processing mathematical tables of the segment area at different values of the arrow height. The radius of an abrasive grain, ρ, depends on the grain size and grain material [12].

In the works of Bogomolov [1], Vakser [18], and Novoselov [12], it is shown that the volume of marks formed is always greater than the volume of metal actually removed from the part. Part of the metal is displaced from the volume of the mark, forming bulk along its edges. The ratio of the volume of metal removed, V_M, during the formation of marks and the volume of the mark, V_P, can be considered as a first approximation by the ratio of bulk areas to the area of the mark in the middle section (Figure 1):

$$\frac{V_M}{V_p} = 1 - K_b = 1 - \frac{S_1 + S_2}{f_{cp}} \quad (13)$$

where K_b—extrusion ratio.

Substituting the value V_P into Equation (13) from Equation (10), we determine the volume of metal removed by a single abrasive grain:

$$V_M = 2.1 \cdot 10^{-8} \cdot (1 - K_b) \cdot f_{cp} \cdot \left(1 \pm \frac{V_W}{60 \cdot V_K} \right) \cdot \sqrt{\frac{D \cdot d \cdot a_{cp}}{D + d}} \quad (14)$$

As a first approximation, it can be assumed that, when grinding, all the abrasive grains involved in the cutting process are located on the surface of the wheel at the same level. In this case, the number of sections of the processed metal with abrasive grains is determined by the equation:

$$N = \frac{6 \cdot 10^4 \cdot B \cdot V_K}{l_\varphi^2} \tag{15}$$

where l_φ^2 is the distance between the abrasive grains located on the surface of the wheel and involved in the cutting process, in mm.

According to the results of the work [12]:

$$l_\varphi \approx 3.5 \cdot 10^{-3} \cdot l_0 \tag{16}$$

where l_0 is the diameter of the average and most likely grain size, in µm.

The volume of metal removed per minute N by abrasive grains will be determined by:

$$Q_\Omega = \frac{103 \cdot (1 - K_b) \cdot f_{cp} \cdot B \cdot V_K \cdot \left(1 \pm \frac{V_W}{60 \cdot V_K}\right) \cdot \sqrt{\frac{D \cdot d \cdot a_{cp}}{D + d}}}{l_0^2} \tag{17}$$

In [8], it is shown that the surface roughness during grinding is determined by a set of single drawings. The correspondence of the surface roughness to the depth of individual drawings allows one to determine the average depth of penetration of single abrasive grains into the processed metal by roughness. The data in Figure 1 show that the surface roughness formed during cutting-scratching, $Ra = H$, is greater than the depth of embedding by the amount of bulk at the edges of the mark.

$$a_{cp} = K_R \cdot Ra_1 \tag{18}$$

where $K_R = a_{cp} / H$ is the coefficient of excess surface roughness.

Substituting the value of grinding performance by the volume of metal, Q_M, from Equation (17) into Equation (3) and taking into account the possibility of increasing productivity in the initial period of time by changing the mode by the coefficient K_Q, we obtain:

$$Q_\Omega = \frac{103 \cdot K_Q \cdot (1 - K_b) \cdot f_{cp} \cdot B \cdot V_K \cdot \left(1 \pm \frac{V_W}{60 \cdot V_K}\right) \cdot \sqrt{\frac{K_R \cdot Rz_1 \cdot D \cdot d}{D + d}}}{l_0^2 \cdot \Omega} \tag{19}$$

Formula (19) takes into account the impact of the size of the abrasive grain on the grinding performance, the grinding mode, the grinding allowance, the size of the workpiece, and the wheel. The formula can be divided into two functional parts:

$$Q_\Omega = G \cdot S \tag{20}$$

where

$$G = \frac{103 \cdot K_Q \cdot (1 - K_b) \cdot f_{cp} \cdot V_K \cdot \left(1 \pm \frac{V_W}{60 \cdot V_K}\right) \cdot \sqrt{K_R \cdot Rz_1}}{l_0^2 \cdot \Omega} \tag{21}$$

does not depend on the size of the part and the wheel;

$$S = B \cdot D_e \tag{22}$$

where $D_e = \sqrt{(D \cdot d)/(D + d)}$—equivalent diameter, a parameter that takes into account the dimensions of the workpiece and the wheel.

The functional part of the formula (19), which does not depend on the size of the workpiece and the size of the wheel, can be taken as an indicator of the performance of finishing grinding processes.

To analyze the influence of grinding conditions on the grinding performance indicator, it is necessary to experimentally determine the coefficients included in Equation (21), K_b and K_R.

3. Experimental Determination of Coefficients K_b and K_R

To experimentally determine the values of the coefficients K_b and K_R, a series of experiments on cutting and scratching polished steel samples L3 (USA standard) HRC = 55. . .60, with a diamond pyramid with an angle of 136° at the top, a radius of 60 microns at the top, and a series of experiments on cutting and scratching samples with grains of an abrasive bar of green silicon carbide GC 150 N7 V220 with a height of 10 mm and an angle of 45° at the top, was carried out.

To conduct these experiments, the diamond pyramid (1) was fixed in a metal disk (2) mounted on the faceplate of a circular grinding machine (3), Figure 2. To obtain drawings with different depths when cutting-scratching with a diamond pyramid, the axis of the part (4) was deflected by turning the table from its line of movement by 1–2 degrees. Cutting-scratching with a diamond pyramid was carried out at four speeds: 6, 10, 20 and 38 $m{\cdot}s^{-1}$. Cutting-scratching with abrasive bar grains was carried out at a bar speed of 35 $m{\cdot}s^{-1}$, a part speed of 40 $m{\cdot}min^{-1}$, $S = 1.0\ m{\cdot}min^{-1}$, and a cross feed $t = 0.05\ mm{\cdot}min^{-1}$. A 3% solution of $Na_2\,CO_3$ was used as a cutting fluid.

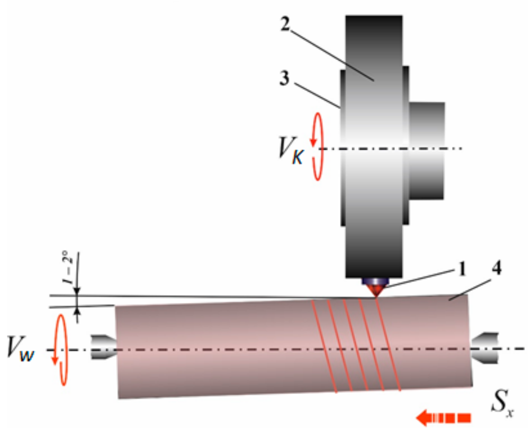


Figure 2. Scheme of cutting-scratching of a part with a diamond cone and an abrasive bar on a circular grinding machine.

The median profile of a single mark was recorded on a profiler model 33319-13. The measurement of the areas $S1$, $S2$, and fcp was carried out with a planimeter of the Planix 5 model.

The results of processing profilograms were calculated using the least squares method.

Figure 3 shows an example of the dependence of the change in the extrusion coefficient on the speed and depth of cutting-scratching. As the figure data show, the extrusion coefficient decreases with the increasing depth of cutting-scratching and the speed of the wheel, while the influence of the speed of the wheel on the extrusion coefficient is significantly less than the influence of the depth of cutting-scratching.

Mathematical processing of experimental data from 120 experiments established the following dependence of the extrusion coefficient on the depth and speed of cutting-scratching:

$$K_b = 1 - 0.34{\cdot}a_{cp}^{0.56}{\cdot}V^{0.06}, r_{ka} = 0.58,\ r_{kV} = 0.22, \quad (23)$$

where r_{ka} and r_{kV} are correlation coefficients of the coefficient K_b on the depth and speed of cutting-scratching.

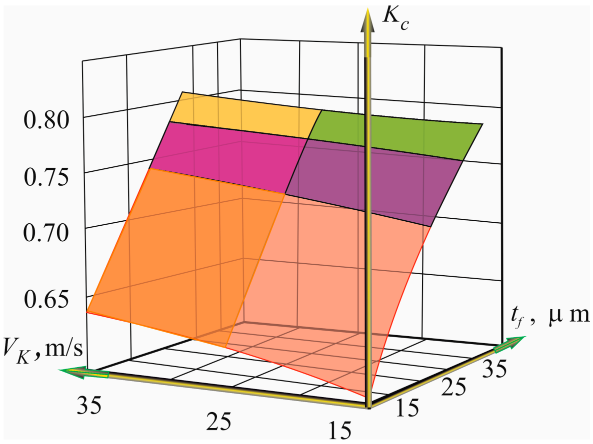


Figure 3. The effect of the speed and depth of cutting-scratching with a diamond cone on the extrusion coefficient.

Analysis of Equation (23) shows that the exponent at the cutting-scratching speed is seven times less than the exponent at the cutting-scratching depth, Figure 3. Figure 4 shows the dependence of the coefficients K_b and K_R on the depth of cutting-scratching by the grains of the abrasive bar. The coefficient of extrusion, as well as cutting-scratching with a diamond pyramid, decreases with increasing depth of cutting-scratching. So, by increasing a_{cp} from 0.2 to 1 μm, coefficient K_b decreases by 1.85 times. The coefficient of excess surface roughness increases with increasing cutting-scratching depth. So, by increasing a_{cp} from 0.2 to 1 μm, coefficient K_R increases from 0.42 to 0.8.

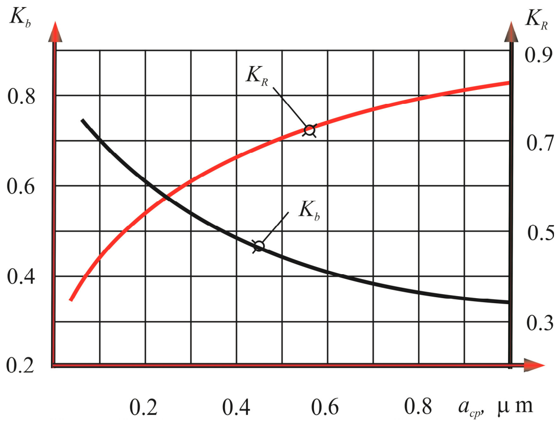


Figure 4. The effect of cutting depth: scratching by abrasive bar grains by 36 CM ВВП on the extrusion coefficient and the coefficient of excess surface roughness: $V_K = 35$ m·min^{-1}; $V_w = 20$ m·min^{-1}; $S = 1.0$ m·min^{-1}; $t_x = 0.05$ mm·unit^{-1}.

By processing the experimental data from 80 experiments, the following dependences of the extrusion coefficient and the coefficient of excess surface roughness on the depth of cutting-scratching were established:

$$K_b = 1 - 0.66 \cdot a_{cp}^{0.38},\ r_{kb \cdot a} = 0.44 \tag{24}$$

$$K_R = 0.8 \cdot a_{cp}^{0.27},\ r_{kR \cdot a} = 0.57 \tag{25}$$

where $r_{kb \cdot a}$ and $r_{kR \cdot a}$ are correlation coefficients.

During grinding in wheels GC 150 N7 V220, the surface roughness, depending on the mode, is within $Ra_0 = 0.32$–0.08 μm, with an average value: $Ra = 0.16$ μm. For the value of the depth of cutting-scratching, $a_{cp} = 1.0$ μm. The coefficients can be assumed to be equal: $K_b = 35$; $K_R = 0.8$. The considered dependences of the coefficients K_b and K_R on the cutting-scratching depth indicate an improvement in chip formation conditions with an increase in the depth of penetration of single grains and metal. With a decrease in the depth of cutting-scratching, the proportion of metal removed during the formation of a single mark decreases. This phenomenon is explained by Maslov [14] and Bogomolov [1] by the fact that the vertices of abrasive grains have radii of rounding. When the cutting-scratching depth decreases, the front cutting angle increases, and the folding resistance of the deformed layer increases. With a decrease in the depth of cutting-scratching, the volume of metal removed by a single grain becomes so insignificant that the metal of the treated surface will practically not be sanded, but instead deformed.

Thus, when analyzing the shaping process of a polished surface, the plastic deformation of the metal by single abrasive grains cannot be neglected. The extrusion coefficient varies depending on the depth of cutting-scratching in the range from 0.2 to 0.7, and the coefficient of excess surface roughness in the range from 0.4 to 0.8.

4. Performance Indicator Analysis

To analyze the impact of the number of finishing operations on the performance indicator G, it is necessary to express the components in the Equation (21).

To ensure that there are no traces of previous processing on the grinding surface, it is necessary to remove a layer of metal from the part Ω (Figure 5):

$$\Omega = 10^{-3} \cdot (C_0 \cdot Ra_0 - C_1 \cdot Ra_1) \quad (26)$$

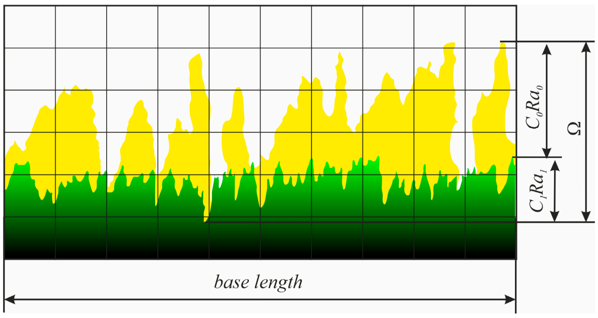


Figure 5. Scheme of surface roughness before and after grinding with a fine-grained wheel.

Abrasive grain size l_0 is not the only factor determining the roughness of the surface of the part after grinding, so the relationship between them cannot be presented in an unambiguous form.

Reducing the roughness of the surface of the part is possible:

(a) Through reduction of the depth of penetration of single grains into the metal at the same granularity as that of the wheel, $l_0 = const$;
(b) By changing the grain size of the wheel, the bundle, and/or the grinding mode, and changing the composition of the coolant. At the same time, the dependence l_0 from Ra can be expressed by the equation:

$$l_0 = a_0 \cdot R_a^{a_1} \quad (27)$$

where a_0 and a_1 are regression coefficients.

Consider the effect of surface roughness after grinding on the performance indicator when $l_0 = const$ and $l_0 = 25.5 \cdot R_a^{0.72}$ (Figure 6). In the calculations in accordance with the experimental data, the values of the coefficients were assumed to be equal: $K_Q = 2$; $K_b = 0.65$; $K_R = 0.8$; and $C_0 = C_1 = 2$. The radius of rounding of abrasive grains was assumed to be equal to: $\rho = 0.077 \cdot l_0$ µm [12].

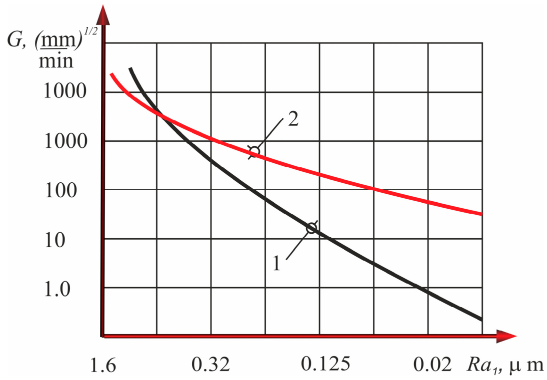


Figure 6. The dependence of the performance indicator on surface roughness after grinding: $V_K = 35\ \text{m}\cdot\text{s}^{-1}$; $1:\ l_0 = const$; $2:\ l_0 = 25.5\cdot R_a^{0.72}$.

The analysis of Figure 6 shows that the productivity indicator decreases with a decrease in surface roughness after grinding. Higher values of the performance indicator correspond to the case when the reduction of roughness is achieved by reducing the grain size of the wheel, the grinding mode, and the composition of the coolant. Therefore, the use of fine-grained wheels is a more effective method of reducing roughness than nursing. Considered dependencies Ω and l_0 on the preliminary and required roughness make it possible to calculate the performance indicator during grinding of parts, not only with one finishing operation, but also with two, three, or more operations. When grinding in several operations, the performance indicator can be determined by the equation:

$$G = \frac{1}{\frac{1}{G_1} + \frac{1}{G_2} + \ldots + \frac{1}{G_n}} \tag{28}$$

where n is number of finishing grinding operations; $G_1 \ldots G_n$ is the performance indicator of each individual operation.

Expressing the performance indicator of individual operations by the Formula (21) we obtain:

$$G = \frac{103}{\frac{\Omega_{01}\cdot l_{01}^2}{K_Q\cdot(1-K_b)\cdot f_{cp}\cdot V_K\cdot\left(1\pm\frac{V_W}{60\cdot V_K}\right)\cdot\sqrt{K_R\cdot Rz_1}} + \ldots + \frac{\Omega_{0n}\cdot l_{0n}^2}{K_Q\cdot(1-K_b)\cdot f_{cp}\cdot V_K\cdot\left(1\pm\frac{V_W}{60\cdot V_K}\right)\cdot\sqrt{K_R\cdot Rz_1}}} \tag{29}$$

When substituting the values into Equation (29)—f_{cp} from Equation (12), Ω from Equation (26), and l_0 from Equation (27)—we obtain:

$$G = \frac{187.5}{\frac{Ra_0 - Ra_{01}}{Ra_{01}^{0.87}} + \frac{Ra_{01} - Ra_{02}}{Ra_{02}^{0.87}} + \ldots + \frac{Ra_{0n-1} - Ra_1}{Ra_1^{0.87}}} \tag{30}$$

where Ra_{01}, Ra_{02}, … , Ra_{0n}—surface roughness after the first, second, etc. operations.

Consider the example of grinding a part to obtain surface roughness ($Ra_1 = 0.025$ μm; $Ra_0 = 0.50$ μm), the effect on the performance indicator of the number of operations and surface roughness after each operation.

During the grinding of the part in three operations, the dependence is obtained:

$$G = \frac{187.5}{\frac{0.50 - Ra_{01}}{Ra_{01}^{0.87}} + \frac{Ra_{01} - Ra_{02}}{Ra_{02}^{0.87}} + \ldots + \frac{Ra_{0n-1} - Ra_1}{0.04}} \tag{31}$$

Figure 7 shows a diagram of the levels of values of the productivity indicator from the surface roughness after the first and second finishing operations, constructed according to Equation (31).

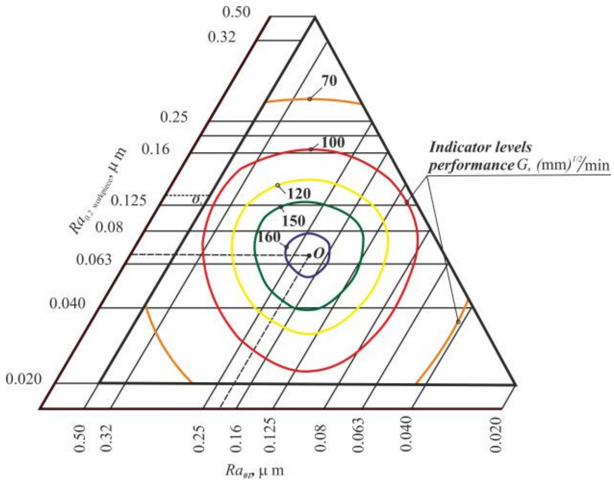


Figure 7. The dependence of the productivity indicator on the surface roughness after the first and second finishing operations when grinding parts in three operations to obtain: $Ra_0 = 0.50$ μm; $Ra_1 = 0.025$ μm; $V_K = 35$ m·s^{-1}.

The surface roughness after the first finishing operation is postponed along the axis X; the surface roughness after the second finishing operation is postponed along the axis Y. The vertices of the triangle ABC correspond to the efforts:

$$\begin{array}{c} A - Ra_{01} = Ra_0 \text{ and } Ra_{02} = Ra_1 \\ B - Rz_{01} = Rz_{02} = Rz_0 \\ C - Ra_{01} = Ra_{02} = Ra_1 \end{array} \tag{32}$$

The sides of the triangle ABC correspond to the efforts:

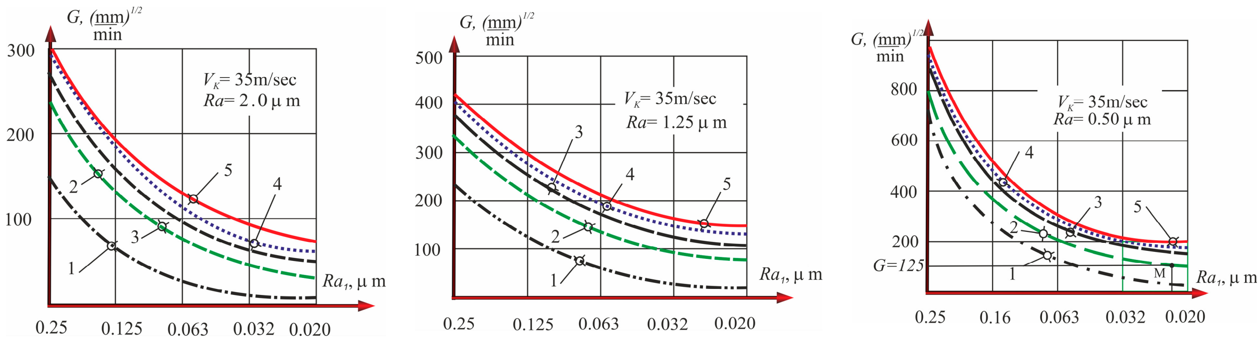
$$\begin{array}{c} AB - Ra_{01} = Ra_0 \\ BC - Ra_{01} = Ra_{02} \\ AC - Ra_{02} = Ra_1 \end{array} \tag{33}$$

For all sides, one of the finishing operations falls out, and grinding is carried out in two operations.

The analysis of Figure 7 shows that the performance indicator significantly depends on the surface roughness of each intermediate operation. The highest value of the performance indicator for grinding in three operations corresponds to the roughness after the first finishing operation. Any other combination of roughness values after the first and second finishing operations provides a lower value of the performance indicator. The roughness values determined by the point O, under the accepted conditions, should be considered optimal.

During grinding of a part in two operations, the maximum value of the performance indicator is determined by the point O_1, which corresponds to the roughness after the first finishing operation. Analytically optimal values of surface roughness after intermediate operations can be determined by studying the maximum of Equation (30).

Studies on the maximum of Equation (30) and the calculation of the process performance indicator were carried out by the approximation method. The dependence of the performance indicator on the number of grinding operations, and on the specified and preliminary surface roughness, are shown in Figure 8. The performance indicator increases with the introduction of additional grinding operations, and with a decrease in the preliminary surface roughness. With a decrease in surface roughness after grinding, the performance indicator decreases.



(**a**) (**b**) (**c**)

Figure 8. The dependence of the performance indicator on the surface roughness after grinding, and the number of finishing operations with preliminary roughness: (**a**) $Ra = 0.63$ µm, (**b**) $Ra = 0.32$ µm, (**c**) $Ra = 0.16$ µm: $1: n = 1$; $2: n = 2$; $3: n = 3$; $4: n = 5$; $5: n = 10$; $V_K = 35$ m/min).

The analysis of the influence of grinding conditions on the performance indicator shows that, to determine it when grinding a part in several operations, it is enough to know the values of the preliminary and required surface roughness.

At a certain indicator G, the productivity of the grinding process is determined by Equation (20), and the complexity of processing the part is determined according to Equation (1). Analysis of the complexity of grinding parts in one, two, or more operations, allows one to establish the optimal variant of the technological process.

Thus, the optimal number of finishing grinding operations, with the requirement of obtaining a surface roughness of $Ra = 0.02 - 0.04$, is determined in the following sequence:

(1) according to Equation (30), the productivity indicator is determined for different variants of the technological process (with one, two, or more finishing operations);
(2) according to Equation (20), the productivity of the grinding process is determined for each variant;
(3) according to Equation (1), the complexity of processing the part is calculated for all options and the option that provides the least complexity is selected.

As an example, let's use Figures 8–10. Using the dependencies shown in Figure 8, the value of performance indicator G is calculated. According to the graphs shown in Figure 9, the value of the equivalent diameter is determined $\sqrt{D{\cdot}d/D + d}$; according to the nomogram, Figure 10, the productivity of the grinding process is determined.

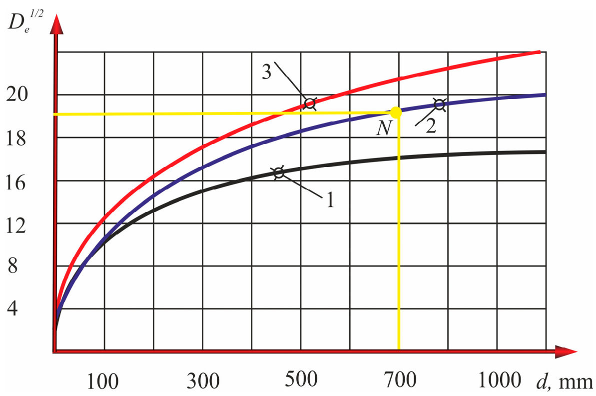


Figure 9. The effect of the diameter of the part and the diameter of the wheel on the value ${D_e}^{1/2} = \sqrt{D{\cdot}d/D + d}$; $1: D = 300$ mm; $2: D = 600$ mm; $3: n = 1000$ mm.

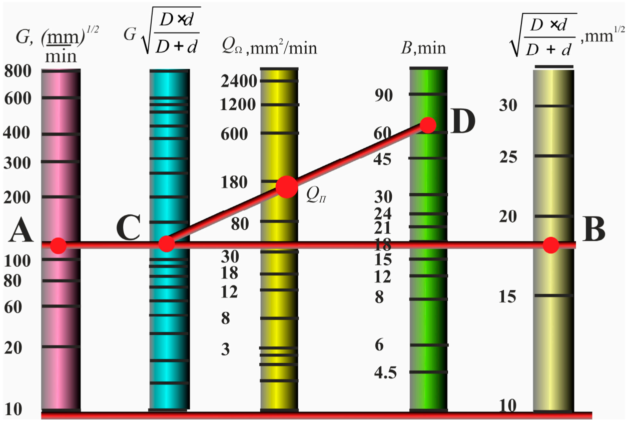


Figure 10. Nomogram for determining the performance of the grinding process with fine-grained wheels.

5. Experimental Verification of the Methodology

Consider the calculation of the optimal number of finishing operations of grinding cold rolling rolls to obtain roughness $Ra_0 = 0.50$ µm; $Ra_1 = 0.025$ µm. The dimensions of the grinding wheel are $1600 \times 75 \times 305$ mm, and the roll dimensions are $d \times l = 690 \times 1680$ mm. During grinding in two operations for the example in question, $G = 125$ mm$^{1/2}$·min^{-1} (Figure 9). According to Figure 10, we determine the values of the square root with a wheel diameter of 600 mm and a roll diameter of 690 mm, $\sqrt{D{\cdot}d/D+d} = 18$ (point N). On the nomogram (Figure 10), we draw from point A the scale of the performance indicator corresponding to the value $G = 125$, through the point B of the scale of the square root line to the intersection with the auxiliary line $G\sqrt{D{\cdot}d/D+d}$ in the point C. From point C of the auxiliary line through the point of the wheel height scale corresponding to the value $B = 75$ mm, draw the line to the intersection with the performance scale. The resulting point will determine the estimated productivity of the roll finishing process $Q_\Omega = 1.6 \times 10^5$ mm^2·min^{-1}.

According to Equation (1), we calculate the complexity of finishing the roll.

According to the timekeeping conducted at the Kamensk-Ural Metallurgical Plant, the sum of the auxiliary time and the time for organized maintenance of the working time for finishing the roll is: with one finishing operation, 48 min; with two finishing operations, 72 min; and with three finishing operations, 94 min. The time for rest and natural needs according to general technical standards with the accuracy of processing according to the fifth quality is 6% of the operational time, and the preparatory and final time for processing the roll is 8 min. With two finishing operations, the complexity of finishing the roll will be determined:

$$T_K = \frac{3.14{\cdot}690{\cdot}1680}{1.6{\cdot}10^5} + 72 + (22+72){\cdot}\frac{6}{100} + 8 = 108.3 \text{ min} \quad (34)$$

During the grinding of the roll in one operation, the estimated processing time will be 113 min; when grinding in three operations, it will be 124 min. The estimated processing time of the roll in two operations will be 103 min. Since 103 min < 113 min and 103 < 124 min, the optimal variant of the technological process will be the variant with two finishing operations.

Table 1 shows the calculated data on the machine time and labor intensity of finishing grinding of rolls of five standard sizes to obtain surface a roughness of $Ra = 0.04 - 0.02$ in one, two, three, and four operations. The preliminary roughness of the surface is assumed to be equal to $Ra = 0.63$ microns, the dimensions of the wheel are $B = 600$ mm and $B = 75$ mm. Calculations are given under the condition of grinding the roll on the same machine with the rearrangement of grinding wheels. The method of grinding cold rolling rolls with the rearrangement of grinding wheels, compared with the method of grinding with the rearrangement of rolls from machine to machine, provides greater roll accuracy, since the installation bases do not change during the roll processing period.

Table 1. Calculated data on the machine time and labor intensity of finishing grinding of rolls.

Rolls Size $d \times l$	Machine Grinding Time of the Roll T_M, Min during n Finishing Operations				Machine Grinding Time of the Roll T_K, Min during n Finishing Operations			
	$n = 1$	$n = 2$	$n = 3$	$n = 4$	$n = 1$	$n = 2$	$n = 3$	$n = 4$
500 × 740	18.6	7.6	5.8	5.1	73.2	87.5	111.9	137.6
500 × 1200	30.2	12.3	9.4	8.2	86.0	97.7	115.9	141
480 × 1680	40.2	16.4	12.5	11.0	97.0	97.2	119.3	144
690 × 1680	55	22.1	16.8	14.8	113	108.3	124.0	148.2
900 × 2800	113	45	34.5	30.5	177	129	143	165

For all the considered roll sizes (Table 1) with an increase in the number of finishing operations, the machine processing time of the roll decreases. The labor intensity of the roll processing is the lowest for rolls with dimensions $d \times l = 500 \times 740$ mm, $d \times l = 500 \times 1200$ mm and $d \times l = 480 \times 1680$ mm with one finishing operation; it is lowest for rolls with dimensions $d \times l = 690 \times 1680$ mm and $d \times l = 900 \times 2800$ mm with two finishing operations.

The method of grinding cold rolling rolls during the rotation of the grinding wheels, compared with the grinding method with the rearrangement of the rolls from machine to machine, provides greater accuracy of the roll, since the installation bases do not change during the processing of the roll.

The conducted research on the grinding of rolls has shown that, with an increase in the number of finishing operations, the machine processing time of the roll decreases. The labor intensity of the roll processing is the lowest for rolls of size $d \times l = 500 \times 740$ mm, $d \times l = 500 \times 1200$ mm, and $d \times l = 480 \times 1680$ mm with one finishing operation, and for rolls of sizes $d \times l = 690 \times 1680$ mm and $d \times l = 900 \times 2800$ mm, with two finishing operations.

Based on the above, it can be concluded that the complexity of processing rolls and the optimal number of finishing grinding operations largely depends on the size of the roll.

Figure 11 shows the data for calculating the optimal number of operations when grinding rolls to obtain a surface roughness of $Ra_0 = 0.50$ µm; $Ra_1 = 0.025$ µm, depending on the diameter and length of the roll barrel.

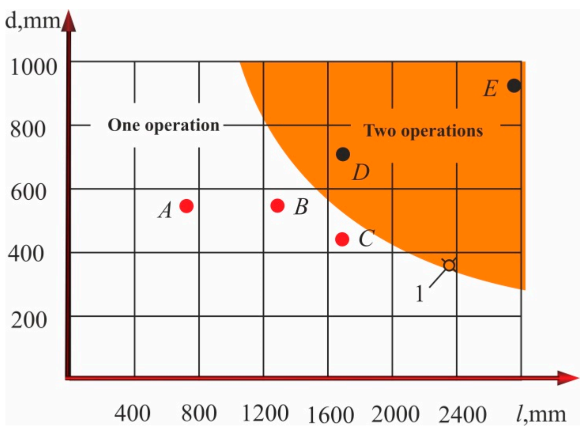


Figure 11. Dependence of the optimal number of finishing operations of grinding rolls to obtain a surface roughness of $Ra = 0.04$–0.02 µm.

With an increase in the allowance for processing, the surface roughness after pre-grinding increases for all cases.

It is advisable to process all rolls whose dimensions correspond to points lying below line 1 in one operation, and rolls whose dimensions correspond to points lying above line 1 in two operations. The points *A*, *B*, *C*, *D*, and *E* are marked by the standard sizes of the rolls, according to which the calculations were summarized. Most of the rolls obtaining a surface roughness of $Ra_0 = 0.04$–0.02 µm can be processed with a single finishing operation. However, rolls of sizes $d \times l = 690 \times 1680$ mm and $d \times l = 90 \times 2800$ mm should be processed with two finishing operations.

Figure 12 shows the dependence of the optimal values of the surface roughness after pre-grinding on the processing allowance when grinding cold rolling rolls $d \times l = 500 \times 1200$ mm to obtain a surface roughness of $Ra = 0.02 - 0.01$ µm when conducting the process in one, two, and three operations.

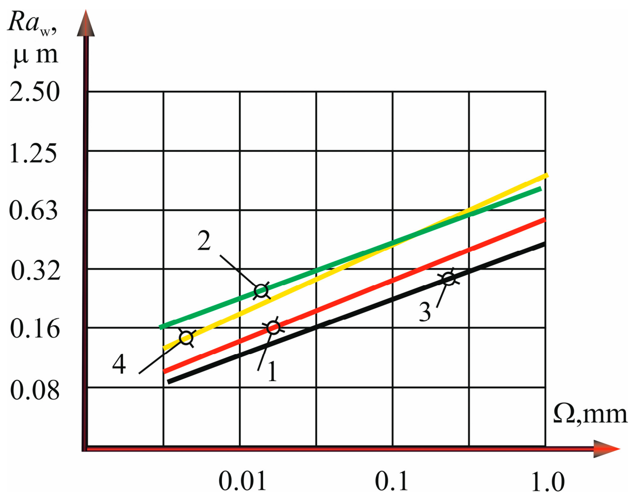


Figure 12. The dependence of the optimal values of the preliminary roughness of the surface on the allowance for processing when grinding rolls with dimensions $d \times l = 500 \times 1200$ mm to obtain surface roughness: 1 : $Ra = 0.04$–0.02 µm (in a single operation); 2 : $Ra = 0.04$–0.02 µm (in two operations); 3 : $Ra = 0.02$–0.01 µm (in two operations); 4 : $Ra = 0.02$–0.01 µm (in three operations).

6. Conclusions

The proposed method makes it possible to calculate not only the optimal number of finishing grinding operations, but also the optimal value of the preliminary surface roughness.

Provided that the characteristics of the abrasive tool for the preliminary grinding operation are not set, and the surface roughness after it is not predetermined, the optimal value of the latter can also be calculated from the condition of the lowest labor intensity of the technological process. To determine the optimal surface roughness after preliminary grinding, it is sufficient to supplement the denominator of Equation (28) with the summand $1/G_0$, where G_0 is the performance indicator of the preliminary operation as determined by Equation (21).

According to the results of production tests, technological processes for grinding rolls with the number of finishing operations corresponding to the calculated ones are proposed (Table 1). Grinding of cold rolling rolls with dimensions $d \times l = 500 \times 740$ mm, $d \times l = 500 \times 1200$ mm, and $d \times l = 480 \times 1680$ mm, obtaining a surface roughness of $Ra = 0.02 - 0.01$ µm is recommended conduct with one finishing operation, while grinding of rolls with dimensions $d \times l = 690 \times 1680$ mm should be processed with two finishing operations.

In the future, it is possible to consider automating the whole process of decision-making about and optimization of the number of operations (one, two, three, etc.) via CA systems. The production process can also be controlled and diagnosed in an automated or automatic mode [19]. It is possible to use CNC (Computer Numerical Control) systems, artificial intelligence, fuzzy logic, mechatronic nodes, or neural networks. In the future, the authors plan to support the methodology presented in this paper with automated computer modeling and simulation systems.

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