INFLUENCE OF CHANGE OF GEOMETRIC CHARACTERISTICS OF ABRASIVE GRAIN IN THE PROCESS OF GRINDING ON THE SURFACE ROUGHNESS PARAMETERS

Abstract: In the article, based on the analysis of literature sources, the effect of changing the geometric characteristics of abrasive grains during circular grinding on the roughness parameters of the treated surface was evaluated. The proposed dependencies take into account the parameters of processing modes, the size of the abrasive grain and the radius of its rounding, their change during operation, as well as the change in the state of the working surface of the tool, taking into account the processing time. The obtained dependences make it possible to predict the kinetics of changes in the surface roughness in multi-pass grinding.

Key words: abrasive grain, cylindrical grinding, machining surface, roughness calculation.

Language: English

Introduction

The main parameters of quality of the processed surface is its roughness and depth of the defective layer. Usually the determination of roughness parameters is added up to tabulation of the profilogram and further calculations in the tables, for example, with the help of computer. The processes of grinding have a complex stochastic nature, which leads to disorder of indicators of quality of products and does not allow to use all possibilities of finishing methods. Microrelief of ground surface in the workpiece material is a combination of mappings of the transient surfaces which are formed by the movement of cutting edges in the space of the workpiece. Forms of unit scratches are determined by the forms of cutting edges and the peculiarities of their contact with the material surface. Analytical relations for definition of the most important parameters of a surface roughness, under the condition that the describing the ordinate random process is stationary and normal, are obtained in works of Yu. Vitenberg, A. Husu, Yu. Linnik and a number of other researchers. Roughness parameters were calculated using the correlation functions. The form of the function was considered well-known, and its coefficients are determined on the basis of experimental studies of grinding process.

Principles of forecasting the most important parameters of a surface roughness depending on technological factors are considered in papers [1, 2]. In [2], where the calculation of roughness parameters is made on the basis of functional obtained in the theoretical analysis of the processes of fanning surfaces, known relations are considerably refined taking into account influence of the processes occurring in a dynamical system.

The developed approach is presented first of all applied to a one-dimensional evaluation of average roughness (arithmetic mean deviation of the profile) \( R_a \) which is the main in the nomenclature of amplitude roughness parameters in standards of the International Organization for Standardization (ISO 4287:1997, the Russian Federal Agency on Technical Regulating and Metrology (GOST R 25142-82), the American Society of the Mechanical Engineers (ANSI/ASME B46. 1-1995), in Ukraine it is also DSSU ISO 4287:2012),and other leading national and international subjects of development a supranational technological structure for economic progress of modern civilization. Objects of attention of the fulfilled elaboration are also widely used in the international and national practice such one-
dimensional roughness amplitude estimates as profile maximum peak-to-valley height $R_{\text{max}}$ and profile peak-to-valley deviation by ten points $R_z$. In accordance with a certain preference of $R_z$ parameter to use for roughness estimate (GOST R 2789-73),

$$R_a = \frac{\sqrt{2V_u H_u^{3/2}}}{\pi^2 K_c(V_k \pm V_u)n_g \sqrt{D_c \rho_g}} \sum_{i=0}^{n} (W_m - i \Delta r)^{3/2}$$

$$R_a = \frac{0.25V_u^{1/4}Z_f}{K_c^{0.4}(V_k \pm V_u)^{0.4}n_g^{0.4}D_c^{0.2} \rho_g^{0.2}}$$

where $W_m$ is the distance from the deepest profile point to the middle line of the profile which is calculated from the condition of the $y_m = 0$,

$$P(M) = 0.5, \quad G_k \sum_{i=0}^{n} (W_m - i \Delta r)^{1/2} - \ln 2 = 0.$$  

At the value of radial metal removal $W_m$,

$$W_m = \left(\frac{\ln 2}{G_k}\right)^{1/2}$$

where

$$G_k = \frac{\sqrt{\pi D_c \Gamma(m+1) \Gamma(\chi) \chi K_c C_p(V_k \pm V_u)n_g}}{\Gamma(m + \chi + 3/2)W_m H_u^\chi}$$

With private values $m = 0.5$, $\chi = 1.5$ the relation of the (3) takes the form:

$$G_k = \frac{0.598 \sqrt{2V_u H_u^{1.5}}}{V_k C_p(V_k \pm V_u)n_g}$$

$$\Delta r = \frac{1.47t_f + \frac{13.66V_u}{K_c(V_k \pm V_u)n_g \sqrt{D_c \rho_g}}}{1.739 \Delta r + \sqrt{0.546(\Delta r)^2 + \frac{13.66V_u \Delta r}{K_c(V_k \pm V_u)n_g \sqrt{D_c \rho_g}}}}$$

where in the formulas of the (1)-(6): $K_c$ – coefficient of chip formation (it shows that not the whole material is removed from the scratch, and part of it is displaced and forms the overstating along the scratch edges); $n_g$ – the number of grain vertices on the unit of the surface of wheel working layer; $H_u$ - the value of the layer of the wheel working surface in depth for calculation of the $n_g$ number of abrasive grains; $P(M)$ – the probability of material removal; $m$ and $\chi$ – indices of the power characteristic; $p_x$ – radius of rounding for the top of abrasive grain; $V_k$ – speed of grinding wheel; $V_u$ – speed of workpiece; $D_c$ – equivalent diameter; $\Delta r$ – radial removal of material from the workpiece surface.

eetc.) its consideration is the main in the work performed.

**Basic relations for $R_z$ calculation.**

Arithmetic mean deviation of the profile $R_z$ is calculated [2] as [2, 16, 17]:

$$\Delta r < W_m; \quad (1)$$

$$\Delta r \geq W_m. \quad (2)$$

The structure of equations (1) and (2) and the value of indicator of the degree are similar to exponential function existing in the literature, but unlike them, they reflect the physical nature of the process of forming and correspond to the dimensional theory.

**Basic relations for $R_{\text{max}}$ and $R_z$ calculation.**

Profile maximum peak-to-valley height $R_{\text{max}}$ and profile peak-to-valley deviation by ten points $R_z$ are calculated on the depth of the layer in which the surface roughness is distributed ($R_{\text{max}}$) and mathematical expectations of the distances from the upper boundary of layer up to five highest points of the profile and the distances from the lower boundary of layer up to the five lowest points of the profile ($R_z$). For a stationary process, which is close to normal, we can be considered that the distances from the upper boundary of roughness layer to the most protruding tops of the profile are distributed according to the laws similar to the distribution of the distances from the hollows to the lower boundary of roughness layer. In this case the mathematical expectation values of $R_{\text{max}}$ and $R_z$ parameters are defined (2) as

$$M[R_{\text{max}}] = H - 2 \frac{2V_u \Delta r^{3/2}}{3n_g (V_k \pm V_u) L \sqrt{D_c}}$$

$$M[R_z] = H - 2.95 \frac{V_u^{3/2}}{\sqrt{3n_g (V_k \pm V_u) L \sqrt{D_c}}}$$

where $H = t_f - \Delta r$ – value layer of surface roughness (the size of the transition area between the material and the environment).

**Materials and methods of research**

One of the main parameters of the tool working surface, which is a large extent influence the characteristics of roughness of the workpiece processed surface, is the rounding radius of the grain top $\rho_G$. According to D. Wakser [3], G. Ippolitov [4] and other researchers [5, 6, 12, 13], radius at the top of the grain depends on the material of abrasive
grain, method of production, grain size, mode of tool dressing.

The current rounding radius depends on its initial state, conditions of contact of the abrasive grain with the processed material, cutting mode and time of a tool work. With the $\tau$ increase $\rho_g(\tau)$ increases regularly, and rounded wear area appears at the top of the grain in a plane which is perpendicular to the vector of the cutting speed, and there is a blunting of the abrasive grain.

However, according to the above exhibited (1), (2), (5)-(8) relations for the calculation of $R_a$, $R_{\text{max}}$ and $R_z$ roughness parameters does not take into account the transformation process of the cutting part of the abrasive grain during dressing.

Considering these relationships as a base with reflecting the work of abrasive tools in some initial state, for example, after a pre-dressing, we'll enhance their taking into account changes of the radius of the grain rounding and state of the working surface of the tool during its operation.

To provide an improved relations for $R_a$, $R_z$ and $R_{\text{mat}}$.

In the general case it can be write that calculating

$$\rho_g(\tau) = K_{\rho_g} \cdot \rho_{g0},$$

(9)

where $K_{\rho_g}$ – coefficient acceptant into account change of rounding radius of grain in the process of work of the abrasive tool, $\rho_{g0}$ – the initial rounding radius of the grain top.

To perform practical calculations, it would be more expedient to use the characteristics of the abrasive material given in GOST 3646-80 or in ISO 8486-1:2:1996 (E), such as the grain size or the main dimension of the abrasive grain $B_z$. Based on the analysis of the experimental data presented in the works of a number of authors compiled table 1, reflecting the dependence of the initial radius of rounding of the peaks of grains $\rho_{g0}$ on the basic size of the abrasive grain $B_z$.

### Table 1.

| The authors | The granularity according to GOST R 3647-80 and ISO 8486-1:2:1996(E) | The basic size of abrasive grains $B_z$, lm | The initial radius of rounding tops of the grains $\rho_{g0}$, lm |
|-------------|-------------------------------------------------|----------------------------------------|----------------------------------------|
|             | 16 | 25 | 32 | 40 | 50 | 63 | 80 | 100 | 125 | 160 | 200 | A. Baykalov [7] | 13 | 19 | 28 | – | – | – | – | – | – | – | 114 |
| E. Maslov [8] | 11 | 17 | 26 | – | 41 | – | – | – | – | – | 76 |
| A. Murdasov [6] | – | – | 30 | – | – | – | – | – | – | – | 97 | 115 | 130 |
| S. Malkin [10] | – | – | 26 | – | – | 45 | – | – | – | – | 117 |
| D. Wakser [3] | 14 | 21 | 30 | – | – | – | 80 | 91 | – | – | 138 |
| S. Miloš [11] | – | 18 | 26 | – | 43 | – | – | 80 | 91 | – | 119 | 149 |
| A. Korolev [1] | 12 | – | – | – | 48 | – | – | 93 | 119 | – | – |
| T. Bozhko [9] | 13 | 19 | 27 | 28 | 38 | – | 60 | – | – | – | – |

For the implementation of practical calculations it would be preferable to use the characteristics of abrasive material given in GOST R 3647-80 or in ISO 8486-1:2:1996(E), such as granularity or the base size of the abrasive grain $B_z$. On the basis of analysis of experimental data that is presented in the works of several authors was compiled table 1 with reflect in it the dependence of the initial radius of rounding tops of the grains from the size of the abrasive grain $B_z$.

The experimental dependence obtained on the basis of data given in table 1 has the form:

$$\rho_{g0} = 0.0535 \cdot B_z^{0.955}$$

(10)

where $B_z$ – the basic size of abrasive grains to GOST R 3647-80 and ISO 8486-1:2:1996(E), m.

Approximation of a power-law dependence was carried out by the least squares method.

In the table 2 it is shown the comparison of the mean values of the experimental data in table 1 and the values calculated by the formula (10). Graphically this comparison is shown in Fig. 1. Check on the coefficient of correlation and the Fisher criterion showed the adequacy of the proposed dependence (10).

### Table 2.

| The granularity according to GOST R 3647-80 and ISO 8486-1:2:1996(E) | The basic size $B_z$ of abrasive grains, lm |
|-------------------------------------------------|----------------------------------------|
| 16 | 25 | 32 | 40 | 50 | 63 | 80 | 100 | 125 | 160 | 200 | F80 | F60 | F54 | F46 | F36 | F30 | F24 | F20 | F16 | F12 | F10 |
| A. Baykalov [7] | 13 | 19 | 28 | – | – | – | – | – | – | – | – | 114 |
| E. Maslov [8] | 11 | 17 | 26 | – | 41 | – | – | – | – | – | 76 |
| A. Murdasov [6] | – | – | 30 | – | – | – | – | – | – | – | 97 | 115 | 130 |
| S. Malkin [10] | – | – | 26 | – | – | 45 | – | – | – | – | 117 |
| D. Wakser [3] | 14 | 21 | 30 | – | – | – | 80 | 91 | – | – | 138 |
| S. Miloš [11] | – | 18 | 26 | – | 43 | – | – | 80 | 91 | – | 119 | 149 |
| A. Korolev [1] | 12 | – | – | – | 48 | – | – | 93 | 119 | – | – |
| T. Bozhko [9] | 13 | 19 | 27 | 28 | 38 | – | 60 | – | – | – | – |
With the account of (10) dependence (9) takes the form

$$\rho_g(\tau) = K\rho_g \cdot \rho_{g0} = 0.0535 \cdot K\rho_g \cdot B_g^{0.955}, \quad (11)$$

$$\rho_g(\tau) = \frac{\left[R_g^2(\varphi, \tau) + R_g^2(\varphi, \tau) - R_g(\varphi, \tau)R_g(\varphi, \tau)\right]^{1/2}}{R_g^2(\varphi, \tau) + 2R_g^2(\varphi, \tau) - R_g(\varphi, \tau)R_g(\varphi, \tau)}.$$  \quad (12)

As shown in [2], for any point of the profile of the abrasive grain (Fig. 2) the radius of curvature in the polar coordinate is calculated by the equation:

$$A = \frac{h_0(V_k \pm V_u)\tau}{H}; \quad B = H - u_p.$$  \quad (13)

The coefficient $K_{\rho_g}$ acceptant into account change of rounding radius of grain in the process of work of the abrasive tool can be represented as

$$K_{\rho_g} = \frac{\rho_g(\tau)}{\rho_{g0}}, \quad \text{or after the conversion:}$$

$$K_{\rho_g} = \frac{18.692H(0.0535B_g^{0.955} + (H - u_p)(1 - e^{-A}))}{(0.0535B_g^{0.955}(1 - h_0(V_k \pm V_u)\tau) - h_0(V_k \pm V_u)(H - u_p)\tau)B_g^{0.955}}, \quad (14)$$

where $h_0$ is the relative depreciation of the abrasive material; $\tau$ – time of work of the abrasive tool.

In Fig. 3 it is shown the graphics allowing to evaluate the impact time of the work of grinding wheel on the change the radius of rounding the top of the abrasive grain.

Depending on the number $n_g$ of grains per the unit of the grinding wheel included in (1), (2), (4)-(8), also in many respects is defined by the basic size $B_g$ of abrasive grains. At the same time, the existing experimental data show about a substantial change of the number of cutting edges for the period of the durability of the tool. Some portion of the abrasive grains will be destroyed or to removed from the grinding wheel for each contact with the processed material due to the limited strength of abrasive grains and their fastening in the tool. At the same time new cutting edges lying in the deeper layers of the tool will come into operation.

Therefore, in general case, it can be wrote

$$n_{g}(\tau) = K_{n_g} \cdot n_{g0}$$  \quad (15)

where $K_{n_g}$ – is the coefficient acceptant into account the change in the number of abrasive grains on the surface of the wheel in the period between dressings; $n_{g0}$ – the initial amount of abrasive grains on the working surface of the wheel.
Table 3 gives a comparison of the number of grains per mm² calculated from [14] and the calculated values from formula (16), graphically this comparison is shown in fig. 4. A check on the correlation coefficient and Fisher's criterion showed the significance of equation (16).

Table 3.

Comparison of the calculating values of the initial amount \( n_{g0} \) of abrasive grains.

| Source of calculated values | The granularity according to GOST R 3647-80 and ISO 8486-1:1996(E) | 16 | 25 | 32 | 40 | 50 | 63 | 80 | 100 | 125 | 160 | 200 |
|----------------------------|-------------------------------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|                            | The basic size \( B_g \) of abrasive grains, \( \mu m \) | 160 | 240 | 315 | 400 | 500 | 630 | 800 | 1000 | 1250 | 1600 | 2000 |
|                            | The amount \( n_{g0} \) of abrasive grains, \( \sqrt{\frac{1}{m^2}} \) | Value by [11] | 23.2 | 9.2 | 5.7 | 3.56 | 2.28 | 1.44 | 0.89 | 0.57 | 0.366 | 0.224 | 0.144 |
|                            | The calculated value by the formula (16) | 22.4 | 9.4 | 5.6 | 3.57 | 2.29 | 1.44 | 0.89 | 0.57 | 0.369 | 0.226 | 0.145 |

In the Tab. 3 it is given a comparison of the number of grains per 1 mm² calculated according to [14] and the calculating values by formula (16). Graphically this comparison is shown in Fig. 4.

Check on the coefficient of correlation and the Fisher criterion showed the adequacy of the proposed dependence (16).
Impact Factor:

| Journal   | Impact Factor |
|-----------|---------------|
| ISRA (India) | 1.344         |
| ISI (Dubai, UAE) | 0.829        |
| GIF (Australia)  | 0.564         |
| JIF        | 1.500         |
| SIS (USA)  | 0.912         |
| GIF (Russia) | 0.156        |
| ESJI (KZ)  | 4.102         |
| IBI (India) | 4.260         |
| PIF (India) | 1.940         |
| SJIF (Morocco) | 2.031      |
| ICV (Poland)| 6.630         |
| Philadelphia, USA | 106      |

**Figure 4** – Comparison of the dependences between the size $B_g$ (grit) of abrasive grains and the number of grains per 1 mm$^2$ surface of grinding wheel $n_{g0}$: 1 - the results of calculations by (16); 2 - according to [14].

With the account of (16) the formula (15) takes the form:

$$n_g(\tau) = K_{ng} \cdot n_{g0} = 0.62 \cdot K_{ng} \cdot B_g^{1.99} \cdot \frac{1}{m^2},$$

(17)

where $z_{g_x}$ – is the number of abrasive grains that are entering in the work at the contact $i$ of the tool with the surface; $P_p$ – probability the destruction of grain; $v_k$ – frequency of rotation of the grinding wheel; $\tau$ – work time work after dressing.

In the general case, $z_{g_x}$ depends on the number $n_{g0}$ of grains on the surface of the instrument after dressing, law the distribution of the grain in depth of grinding wheel, radial wear of grinding wheel, durability of fastening of grains and cutting forces arising in the zone of contact, which are random variables. So, if the load on the top of the grains during grinding does not exceed 4N, then the probability $P_p$ of extraction of grain out off the bond does not exceed 0.01. With the increase of load probability $P_p$ is growing: for $P_p=8N$ the probability $P_p \approx 0.20$, at $P_p=10N$, $P_p=0.50$. With the further $P$ increase $P_p$ probability is approaching to its maximum value of about 0.87 ($P_p=15N$) [15].

The coefficient $K_{ng}$ acceptant into account the change in the number of grains on the surface of the instrument in the process of its work can be represented as

$$K_{ng} = \frac{n_g(\tau)}{n_{g0}}$$

or after the conversion with the account of the dependencies (16) and (18):

$$K_{ng} = \frac{z_g}{P_p} + \left( n_{g0} - \frac{z_g}{P_p} \right) (1 - P_p)^{v_k \tau} + \left( \frac{1}{m^2} \right) B_g^{1.99}$$

(19)

In Fig. 5 it is shown the curves of the influence the time of work on the change in the number of abrasive grains $n_g$ per 1 mm$^2$ of the working surface of the grinding wheel under its work in the mode of blunting.

Equations (1), (2), (5)-(8) for the calculation of the characteristics of surface roughness will take the following form considering the obtained dependences (11) and (17):
Impact Factor:

| Journal    | Impact Factor |
|------------|---------------|
| ISRA (India) | 1.344         |
| ISI (Dubai, UAE) | 0.829     |
| GIF (Australia) | 0.564       |
| JIF         | 1.500         |
| PHHII (Russia) | 0.156       |
| ESJI (KZ)   | 4.102         |
| SIS (USA)   | 0.912         |
| ICV (Poland) | 6.630        |
| PIF (India) | 1.940         |
| IBI (India) | 4.260         |
| GIF (Australia) | 0.564       |
| JIF         | 1.500         |

Figure 5 – The influence of the work time $\tau$ of the grinding wheel on the change in the number $n_g(\tau)$ of grains per 1 mm$^2$ of the surface of grinding wheel for different $B_g$ values.

$$R_u = \frac{1.017V_uH_u^{1.5}}{K_cK_n_k(V_k \pm V_u)\sqrt{K_{\rho_k}B_g^{3.025}D_c\sum_{i=0}^n(W_m - i\Delta r)^{1.5}}}$$

at $\Delta r < W_m$; \hspace{1cm} (20)

$$R_u = \frac{0.544V_u^{0.4}t_f^{0.6}B_g^{0.605}}{K_c^{0.4}K_{\rho_k}^{0.2}(V_k \pm V_u)^{0.4}D_c^{0.2}}$$

at $\Delta r \geq W_m$. \hspace{1cm} (21)

$$\Delta r = \frac{t_f^2}{1.478t_f + 95.254V_uB_g^{1.51}}.$$ \hspace{1cm} (22)

$$t_f = 0.739\Delta r + \sqrt{0.546 \cdot \Delta r^2 + \frac{22.03V_u^2\Delta rB_g^{1.51}}{K_cK_n_k(V_k \pm V_u)\sqrt{K_{\rho_k}D_c}}}$$

$$M(R_{\text{max}}) = H - 2.074\sqrt{\frac{V_u^{1.5}B_g^{1.99}}{K_n_k(V_k \pm V_u)L\sqrt{D_c}}}$$ \hspace{1cm} (23)

$$M(R_z) = H - 3.747\sqrt{\frac{V_u^{1.5}B_g^{1.99}}{K_n_k(V_k \pm V_u)L\sqrt{D_c}}}$$ \hspace{1cm} (24)

In Fig. 6 it is shown curves illustrating the influence of time of work of grinding wheel on the parameters of a roughness of the processed surface.

Figure 6 – The influence of the time $\tau$ the work of the grinding wheel on the $R_a$ (a) and $R_z$ (b) parameters of roughness; $B_g$ = 320 $\mu$m.
The proposed relations allow to predict the kinetics of changes of roughness parameters. In equations (24) and (25) implicitly includes the likelihood of removal of material, which is calculated with taking into account the roughness of the workpiece and it changes with every contact the surface of the workpiece with the instrument of the workpiece under a multistep grinding process.

Conclusion

Feature of the obtained equations (20)-(25) is that the calculations take into account the parameters cutting mode, the grain size of the grinding wheel, as well as operational change of the working surface of the instrument. It allows to estimate influence on the roughness of the large number of passes of abrasive grains on the surface of the workpiece under a multistep grinding process.

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