Evaluation of the effect of changing the geometry of the abrasive grains of the grinding wheel on the characteristics of the roughness of the grinded surface

Vladimir Bogutsky1,*, Leonid Shron1, Elmar Yagyaev2
1Sevastopol State University, Universitetskaya st., 33, Sevastopol, 299053, Russian Federation
2Crimean Engineering and Pedagogical University, per.Uchebnyj, 8, Simferopol, 295015, Russian Federation

*bogutskivb@yandex.ru

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.

1. 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. Micrelief of grinded 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 dete1mined 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 modem 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 $R_{max}$ and profile peak-to-valley deviation by ten points $R_z$. In accordance with a certain preference of $R_a$ parameter to use for roughness estimate (GOST R 2789-73, etc.) its consideration is the main in the work performed.

2. Basic relations for $R_a$, $R_{max}$ and $R_z$ calculation.
Arithmetic mean deviation of the profile $R_a$ is calculated as [2, 16, 17]:

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

$$R_a = \frac{0.25 t_f ^{0.4} t_f ^{0.6}}{K_c (V_k \pm V_u)n_g \sqrt{D_e \rho_g} \sum_{i=0}^{n} (W_m - i \Delta r)^{3/2}} \text{ at } \Delta r \geq W_m.$$  

(1)

(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 $y_m = 0$, $P(M) = 0.5$, $G_k \sum_{i=0}^{n} (W_m - i \Delta r)^{3/2} - \ln 2 = 0$. At the value of radial metal removal $\Delta r \geq W_m$ $W_m = \left(\frac{\ln 2}{G_k}\right)^{1/3}$, where

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

(3)

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

$$G_k = \frac{0.598 \sqrt{\pi \rho_g D_e K_c (V_k \pm V_u)n_g}}{V_u H_u^{1.5}}$$

(4)

$$\Delta r = \frac{t_f ^2}{1.478 t_f + \frac{13.66 V_u}{K_c (V_k \pm V_u)n_g \sqrt{D_e \rho_g}}};$$

(5)

$$t_f = 0.739 \Delta r + \sqrt{0.546(\Delta r)^2 + \frac{13.66 V_u \Delta r}{K_c (V_k \pm V_u)n_g \sqrt{D_e \rho_g}}};$$

(6)

where in the dependencies (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; $\rho_g$ – radius of rounding for the top of abrasive grain; $V_k$ – speed of grinding wheel; $V_u$ – speed of workpiece; $D_e$ – equivalent diameter; $\Delta r$ – radial removal of material from the workpiece surface.
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.

Profile maximum peak-to-valley height $R_{max}$ 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 ($R_{max}$) 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 $R_{max}$ and $R_z$ parameters are defined as

$$M[R_{max}] = H - 2 \frac{2V_f t_f^{3/2}}{3n_g(V_k \pm V_u) L \sqrt{D_e}};$$

$$M[R_z] = H - 2.95 \frac{V_f t_f^{3/2}}{n_g(V_k \pm V_u) L \sqrt{D_e}}.$$  (8)

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

3. Materials and methods of research.

One of the main parameters of the tool working surface, which is 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. Waksner [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 $R_a$, $R_{max}$ and $R_z$ roughness parameters does not take into account the transformation process of the cutting part of the abrasive grain during grinding.

Considering these relationships as a base with reflecting the work of abrasive tools in some initial state, for example, after a pre-dressing, well 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.

3.1. To provide an improved relations for $R_a$, $R_z$ and $R_{max}$.

In the general case it can be write that calculating

$$\rho_g(\tau) = K_{\rho_g} \cdot \rho_g(0),$$

where $K_{\rho_g}$ – coefficient acceptant into account change of rounding radius of grain in the process of work of the abrasive tool; $\rho_g(0)$ – 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 3647-80 or in ISO 8486-1:2:1996 (E), such as the grain size or the main dimension of the abrasive grain $B_g$. 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 $\rho_g(0)$ on the basic size of the abrasive grain $B_g$.

For the implementation of practical calculations it would be preferable to use of 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 $B_g$. 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 $B_g$. 


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

$$\rho_{g0} = 0.0535 \cdot B_g^{0.955}$$  \hspace{1cm} (10)

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

Table 1. Initial radius of rounding tops of abrasive grains $\rho_{g0}$.

| The authors          | The granularity according to GOST R 3647-80 and ISO 8486-1,2:1996(E) |
|----------------------|------------------------------------------------------------------------|
|                      | 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  25  41  76  –  –  –  –                                     |
| A. Murdasov [6]      | –  19  –  30  68  97  115  130                                    |
| S. Malkin [10]       | –  26  45  –  –  –  –  –                                         |
| D. Wakser [3]        | 14  21  30  –  –  –  –  –                                         |
| S. Milton [11]       | 18  26  43  80  91  138                                           |
| A. Korolev [1]       | 12  –  –  48  –  93  119  149                                      |
| El-Hofy H [9]        | 13  19  27  38  60  –  –  –                                         |

The basic size of abrasive grains $B_g$, µm

|                      | 160  240  315  400  500  630  800  1000  1250  1600  2000 |
|----------------------|----------------------------------------------------------|
| The initial radius of rounding tops of the grains $\rho_{g0}$, µm. | |
| A. Baykalov [7]      | 13  19  28  45  68  97  114                               |
| E. Maslov [8]        | 11  17  25  41  76  97  115                                |
| A. Murdasov [6]      | –  19  30  68  97  115  130                               |
| S. Malkin [10]       | –  26  45  –  –  –  –                                      |
| D. Wakser [3]        | 14  21  30  –  –  –  –                                      |
| S. Milton [11]       | –  26  43  –  –  –  –                                      |
| A. Korolev [1]       | –  –  –  48  –  –  –                                      |
| El-Hofy H [9]        | 13  19  27  38  –  60  –  –                                |

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 figure 1. Check on the coefficient of correlation and the Fisher criterion showed the adequacy of the proposed dependence (10).

Table 2. Comparison of experimental and calculated values of the rounding radius $\rho_{g0}$ of the grain tops.

| Source                        | The granularity according to GOST R 3647-80 and ISO 8486-1,2:1996(E) |
|-------------------------------|------------------------------------------------------------------------|
|                               | 16  25  32  40  50  63  80  100  125  160  200                       |
|                               | F80  F60  F54  F46  F36  F30  F24  F20  F16  F12  F10                |
| The basic size $B_g$ of abrasive grains, µm |                                               |
|                               | 160  240  315  400  500  630  800  1000  1250  1600  2000           |
| The rounding radius $\rho_{g0}$ of the grain tops, µm. | |
| The average value of the experimental data in table 1 | 12,6  19  26  29  39,5  48  64  76  95  115,3  139,5 |
| The calculating by (10) | 12,8  19,4  24,5  30,7  38,1  47,6  59,6  74,3  92,4  115,4  143 |

With the account of (10) dependence (9) takes the form

$$\rho_g(\tau) = K_{\rho_g} \cdot \rho_{g0} = 0.0535 \cdot K_{\rho_g} \cdot B_g^{0.955},$$  \hspace{1cm} (11)

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

$$\rho_g(\tau) = \frac{1}{R_g(\varphi, \tau)} = \frac{\sqrt{R^g_2(\varphi, \tau) + 2R'_g(\varphi, \tau) - R_g(\varphi, \tau)R'_g(\varphi, \tau)}}{R_g^2(\varphi, \tau)}. $$  \hspace{1cm} (12)
Figure 1. Comparison of the calculated (1) and experimental (2) dependences between a radius $\rho_g$ at the top of the grain and the basic size $B_g$ of abrasive grains.

When combining of the pole of the polar coordinate with the center of curvature of the top of the grain, for angles in neighborhood of $\varphi_\rho=0$, the radius-vector of the initial profile is $\rho_{g0}$, and its current value is

$$\rho_g(\tau) = \frac{(\rho_{g0} + B - Be^{-A})^2}{\rho_{g0} - A\rho_{g0} - BA} e^{-A},$$

where $A = \frac{h_0(V_k \pm V_u)\tau}{H}$; $B = H - u_\rho$.

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

$$K_{\rho_g} = \frac{18.692H[0.0535B_e^{0.955} + (H - u_\rho)(1 - e^{-A})]}{[0.0535B_e^{0.955}(1 - h_0(V_k \pm V_u)\tau) - h_0(V_k \pm V_u)(H - u_\rho)e^{-A}]} B_e^{0.955},$$

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

In figure 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

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

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.

At [14] the initial quantities of abrasive grains on the surface of the grinding wheels $n_g$, 1/m², were determined with the account of the content $V_g$ % of abrasive grains in the wheels, the basic size $B_g$ of abrasive grains according to GOST R 3647-80, structure and hardness ($V_g = 45\%$ for grinding wheels with the structures of 5, 6 and hardness [4]), and implemented by the approximation of the method of least squares that allowed to obtain the dependence of:
\[ n_{g_0} = 0.62 \cdot B_g^{1.99} \div m^2. \]  \hspace{1cm} (16)

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 figure 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 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 |
|-----------------------------|-------------------------------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| F80 | F60 | F54 | F46 | F36 | F30 | F24 | F20 | F16 | F12 | F10 |      |
| The basic size \( B_g \) of abrasive grains, µm | 160 | 240 | 315 | 400 | 500 | 630 | 800 | 1000 | 1250 | 1600 | 2000 |

| 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 |

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

\[ n_g(\tau) = K_{n_g} \cdot n_{g_0} = 0.62 \cdot K_{n_g} \cdot B_g^{1.99} \div m^2. \]  \hspace{1cm} (17)

In work [2] it is obtained the dependency which allows to calculate the change in the number of grain for the period between dressing of the abrasive tools:

\[ n_g(\tau) = \frac{z_g}{P_p} + \left( n_{g_0} - \frac{z_g}{P_p} \right) (1 - P_p)^{v_k \tau}, \]  \hspace{1cm} (18)

where \( z_g \) – 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, \( z_g \) depends on the number \( n_{g_0} \) 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 of the bond does not exceed 0.01. With the increase of load probability \( P_p \) is growing: for \( P_z = 8N \) the probability \( P_p \approx 0.20, \) at \( P_z = 10N, P_p \approx 0.50. \) With the further \( P \) increase \( P_p \) probability is approaching to its maximum value of about 0.87 (\( P_z = 15N \)) [15].

The coefficient \( K_{n_g} \) 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

\[ K_{n_g} = \frac{n_g(\tau)}{n_{g_0}} \]  \hspace{1cm} or after the conversion with the account of the dependencies (16) and (18):

\[ K_{n_g} = 1.613 \left( \frac{z_g}{P_p} \left[ 1 - (1 - P_p)^{v_k \tau} \right] + \frac{0.62(1 - P_p)^{v_k \tau}}{B_g^{1.99}} \right) B_g^{1.99}. \]  \hspace{1cm} (19)

In figure 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 mm² 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):

\[
R_a = \frac{1,017V_u H_u^{1.5}}{K_c K_{n_g} (V_k \pm V_u) \sqrt{K_{p_g} B_{g}^{3.025} D_e} \sum_{n=0}^{u} (W_m - i \Delta r)^{1.5}} \quad \text{at } \Delta r < W_m; \quad (20)
\]

\[
R_a = \frac{0.544V_u^{0.4} \Delta f^{0.6} B_{g}^{0.605}}{K_c K_{n_g} (V_k \pm V_u) \sqrt{K_{p_g} D_e}^{0.2}} \quad \text{at } \Delta r \geq W_m. \quad (21)
\]

\[
\Delta r = \frac{\frac{t_f^2}{1,478f_f} + \frac{95,254V_u^{1.51}}{K_c K_{n_g} (V_k \pm V_u) \sqrt{K_{p_g} D_e}}}{1,478f_f}. \quad (22) \quad t_f = 0.739 \Delta r + \sqrt{0.546 \cdot \Delta r^2 + \frac{22,03 V_u \Delta r B_{g}^{1.51}}{K_c K_{n_g} (V_k \pm V_u) \sqrt{K_{p_g} D_e}}};
\]

\[
M[R_{max}] = H - 2,074 \sqrt{\frac{V_u^{1.5} B_{g}^{1.99}}{K_{p_g} (V_k \pm V_u) L \sqrt{D_e}}}; \quad \quad M[R_z] = H - 3,747 \sqrt{\frac{V_u^{1.5} B_{g}^{1.99}}{K_{n_g} (V_k \pm V_u) L \sqrt{D_e}}}. \quad (23) \]  

In figure 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 3.** Impact time \( \tau \) of the work of grinding wheel on the change the radius \( \rho_g(\tau) \) of rounding the top of the abrasive grain for different values of the basic size of abrasive grains \( B_g \).

**Figure 4.** Comparison of the dependences between the size \( B_g \) (grit) of abrasive grains and the number of grains per 1 mm² surface of grinding wheel \( n_{g0} \): 1 - the results of calculations by (16); 2 - according to [14].

**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 mm² of the surface of grinding wheel for different \( B_g \) values.

**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; \( B_g = 320 \mu m \).
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 parameters of the large number of passes of abrasive grains on the surface of the workpiece under a multistep grinding process.

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 with the instrument.

References
[1] Korolev A V, Novoselov Yu K 1987 Theoretical and Probabilistic Basis of Abrasive Treatment (Saratov: Saratovsk. un-t) p.160
[2] Novoselov Yu K 2012 The Dynamics of Formation of Surfaces in Abrasive Machining (Sevastopol: Publ. SevNTU) p 304
[3] Vakser D B 1960 The Influence of the Geometry of Abrasive Grains on the Properties of the Grinding Wheel (Moshgiz) p 165
[4] Ippolitov G M 1969 Abrasive-Diamond Treatment (Moscow: Mashinostroenie) p 334
[5] Kremen Z I 2007 Grinding Technology in Mechanical Engineering (Saint-Petersburg: Polytechnic) p 424
[6] Murdasov A V, Wolff A M 1967 Peculiarities of Working of Grinding Wheels from Abrasive Grains of Different Shapes (Abrasives and diamonds: scientific technical abstract collection vol 4) (Moscow: NIIMASH) pp 65–69
[7] Bajkalov A K 1978 Introduction to the Theory of Grinding Materials (Kiev: Naukova dumka) p 207
[8] Maslov E N 1974 Theory of Grinding Materials (Moscow: Mashinostroenie) p 400
[9] El-Hofy H 2006 Fundamentals of Machining Processes: Conventional and Nonconventional Processes. (CRC Press) p 562
[10] Malkin S, Guo C 2008 Grinding technology. Theory and Applications of Machining with Abrasives (New York: Industrial Press) p 369
[11] Shaw C M 1996 Principles of Abrasive Processing (Oxford Series on Advanced Manufacturing) (New York: Oxford University Press) p 592
[12] Jackson M, Davim P 2011 Machining with Abrasives (Springer Science+Business Media) p 432
[13] Marinescu I D, Hitchiner M, Uhlmann E, Rowe W B and Inasaki I 2007 Handbook of Machining with Grinding Wheels (CRC Press) p 629.
[14] Abrasive and diamond processing of materials. Reference book 1977 Ed. by Reznikov A N (Moscow: Mashinostroenie) p 391
[15] Bogutsky V 2018 Influence of Change of Geometric Characteristics of Abrasive Grain in the Process of Grinding on the Surface Roughness Parameters (Theoretical & Applied Science vol 7 (63)) pp 101-108 DOI: 10.15863/TAS
[16] Bogutsky V, Novoselov Yu, Bratan S 2016 Analysis of Relation between Grinding Wheel Wear and Abrasive Grains Wear (2nd International Conference on Industrial Engineering Procedia Engineering vol 150) pp. 809–814
[17] Bogutsky V, Novoselov Yu, Shron L 2017 Forecasting the Surface Roughness of the Work-Piece in the Round External Grinding / (International Conference on Modern Trends in Manufacturing Technologies and Equipment Web of Conferences vol. 129) DOI: 10.1051/matecconf/201712901080