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Vladimir Bogutsky
Associate Professor, Ph.D.,
Sevastopol State University,
Russian Federation
bogutskivb@yandex.ru

SECTION 7. Mechanics and machine construction.

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*

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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 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. l-l995), 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 ce1tain preference of R_a parameter to use for roughness estimate (GOST R 2789-73, etc.) its consideration is the main in the work performed.

Basic relations for R_a calculation.

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

$$R_a = \frac{\sqrt{2} V_u H_u^{3/2}}{\pi^2 K_c (V_k \pm V_u) n_g \sqrt{D_e \rho_g} \sum_{i=0}^{n} (W_m - i\Delta r)^{3/2}} \quad \text{at } \Delta r < W_m; \tag{1}$$

$$R_a = \frac{0{,}25 V_u^{0{,}4} t_f^{0{,}6}}{K_c^{0{,}4} (V_к \pm V_u)^{0{,}4} n_g^{0{,}4} D_e^{0{,}2} \rho_g^{0{,}2}} \quad \text{at } \Delta r \geq W_m. \tag{2}$$

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 $y_m = 0$, $P(M) = 0{,}5$, $G_k \sum_{i=0}^{n} (W_m - i\Delta r)^{\nu} - \ln 2 = 0$. At the value of radial metal removal $\Delta r \geq W_m$ $W_m = \left(\frac{\ln 2}{G_k}\right)^{1/\nu}$, where

$$G_k = \frac{\sqrt{\pi D_e}\, \Gamma(m+1) \Gamma(\chi) \chi K_c C_b (V_к \pm V_u) n_g}{\Gamma(m + \chi + 3/2) V_u H_u^{\chi}} \tag{3}$$

With private values $m = 0{,}5$, $\chi = 1{,}5$ the relation of the (3) takes the form:

$$G_k = \frac{0{,}598 \sqrt{\pi \rho_g D_e}\, K_c (V_к \pm V_u) n_g}{V_u H_u^{1{,}5}} \tag{4}$$

$$\Delta r = \frac{t_f^2}{1{,}478 t_f + \dfrac{13{,}66 V_u}{K_c (V_k \pm V_u) n_g \sqrt{D_e \rho_g}}}; \tag{5}$$

$$t_f = 0{,}739 \Delta r + \sqrt{0{,}546 (\Delta r)^2 + \frac{13{,}66 V_u \Delta r}{K_c (V_k \pm V_u) n_g \sqrt{D_e \rho_g}}}; \tag{6}$$

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 χ – indices of the power characteristic; p_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; Δr – 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.

Basic relations for R_{max} and R_z calculation.

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 sin1ilar 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 (2) as

$$M[R_{\max}] = H - 2\sqrt{\frac{2 V_u t_f^{3/2}}{3 n_g (V_k \pm V_u) L \sqrt{D_e}}}; \tag{7}$$

$$M[R_z] = H - 2{,}95\sqrt{\frac{V_u t_f^{3/2}}{n_g (V_k \pm V_u) L \sqrt{D_e}}}. \tag{8}$$

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 large extent influence the characteristics of roughness of the workpiece processed surface, is the rounding radius of the grain top ρ_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 τ 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, 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_{max}.

In the general case it can be write that calculating

$$\rho_g(\tau) = K_{\rho_g} \cdot \rho_{g_0}, \qquad (9)$$

where $K_{\rho g}$ – coefficient acceptant into account change of rounding radius of grain in the process of work of the abrasive tool; ρ_{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 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 ρ_{g0} on the basic size of the abrasive grain B_g.

Table 1.

Initial radius of rounding tops of abrasive grains ρ_{g0}

The authors	The granularity according to GOST R 3647-80 and ISO 8486-1,2:l996(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 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 ρ_{g0}, μm.										
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	–	–	–	117	–
D. Wakser [3]	14	21		30	–	–	–	–	–	–	–
S. Milton [11]	–	18	26	–	43	–	–	80	91	–	138
A. Korolev [1]	12	–	–	–	–	48	–	–	93	119	149
T. Bozhko [9]	13	19	27	28	38	–	60	–	–	–	–

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-l ,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:

$$\rho_{g_0} = 0.0535 \cdot B_g^{0.955} \qquad (10)$$

where B_g – 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.

Comparison of experimental and calculated values of the rounding radius ρ_{g0} of the grain tops.

Source	The granularity according to GOST R 3647-80 and ISO 8486- l ,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 ρ_{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

$$\rho_g(\tau) = K_{\rho_g} \cdot \rho_{g_0} = 0{,}0535 \cdot K_{\rho_g} \cdot B_g^{0{,}955}, \quad (11)$$

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:

$$\rho_g(\tau) = \frac{\left[R_g{}^2(\varphi,\tau) + R_g'{}^2(\varphi,\tau)\right]^{3/2}}{R_g{}^2(\varphi,\tau) + 2R_g'{}^2(\varphi,\tau) - R_g(\varphi,\tau)R_g''(\varphi,\tau)}. \quad (12)$$

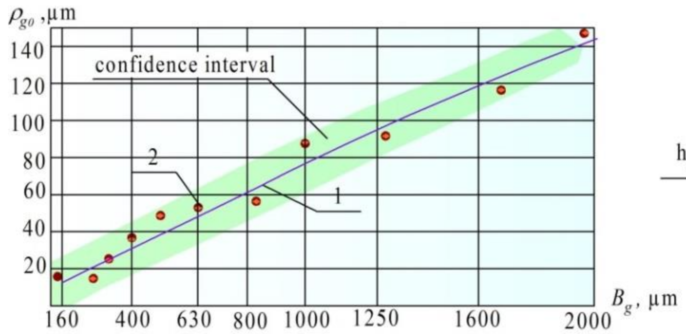

Figure 1 – Comparison of the calculated (1) and experimental (2) dependences between a radius ρ_g at the top of the grain and the basic size B_g of abrasive grains.

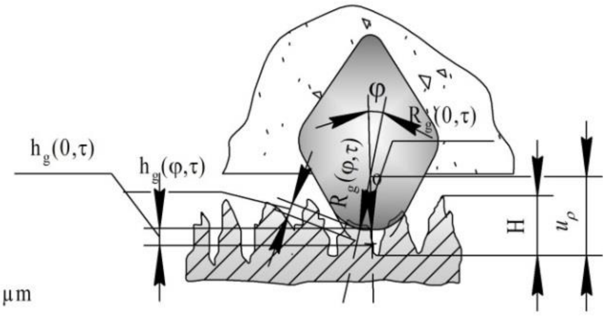

Figure 2 – Scheme for the calculation of change of the contour of the abrasive grain.

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 φ_ρ=0, the radius-vector of the initial profile is ρ_{g0}, and its current value is

$$\rho_g(\tau) = \frac{(\rho_{g_0} + B - Be^A)^2}{\rho_{g_0} - A\rho_{g_0} - BA} e^{-A}, \quad (13)$$

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 $K_{\rho_g} = \frac{\rho_g(\tau)}{\rho_{g_0}}$, or after the conversion:

$$K_{\rho_g} = \frac{18{,}692H(0{,}0535B_g^{0.955} + (H - u_\rho)(1 - e^{\left(\frac{h_0(V_k \pm V_u)\tau}{H}\right)}))^2 e^{-\left(\frac{h_0(V_k \pm V_u)\tau}{H}\right)}}{(0.0535B_g^{0{,}955}(1 - h_0(V_k \pm V_u)\tau) - h_0(V_k \pm V_u)(H - u_\rho)\tau)B_g^{0.955}}, \quad (14)$$

where h_0 is the relative depreciation of the abrasive material; τ – 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 (I), (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 lin1ited 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

$$n_g(\tau) = K_{n_g} \cdot n_{g_0} \quad (15)$$

where K_{ng} – 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.

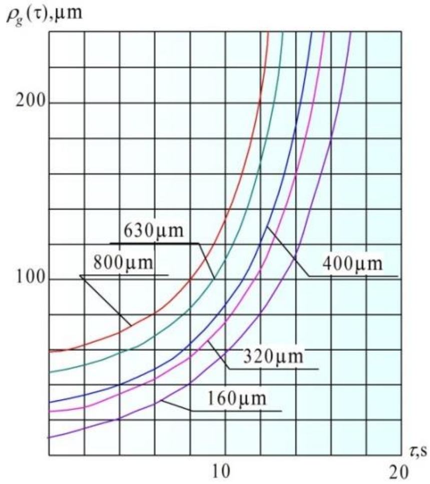

Figure 3 – Impact time τ of the work of grinding wheel on the change the radius $\rho_g(\tau)$ of rounding the top of the abrasive grain for different values of the basic size of abrasive grains B_g.

At [14] the initial quantities of abrasive grains on the surface of the grinding wheels n_g, 1/m^2, 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:

$$n_{g0} = 0{,}62 \cdot B_g^{-1{,}99}, \frac{1}{m^2}. \qquad (16)$$

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 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 8486-1,2:l996(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 amount n_{g0} of abrasive grains, n_{g0}, $1/\text{mm}^2$										
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 mm^2 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).

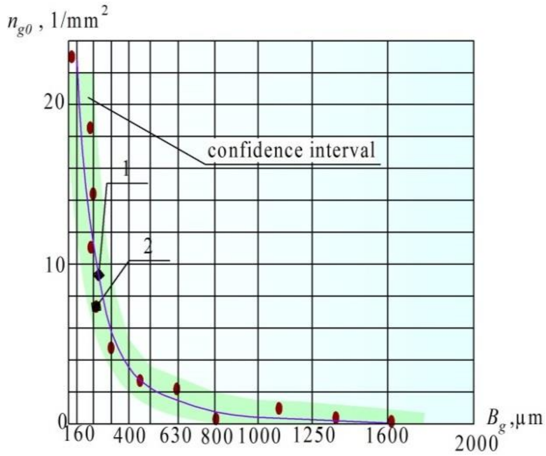

Figure 4 – Comparison of the dependences between the size B_g (grit) of abrasive grains and the number of grains per 1 mm² surface of grinding wheel n_{g0}: 1 - the results of calculations by (16); 2 - according to [14].

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

$$n_g(\tau) = K_{n_g} \cdot n_{g_0} = 0{,}62 \cdot K_{n_g} \cdot B_g^{-1{,}99}, \frac{1}{m^2} \quad (17)$$

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:

$$n_g(\tau) = \frac{z_g}{P_p} + \left(n_{g_0} - \frac{z_g}{P_p}\right)(1-P_p)^{v_k \tau}, \quad (18)$$

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; τ – work time work after dressing.

In the general case, z_g 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_z=8N the probability $P_p \Rightarrow 0.20$, 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_{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

$$K_{n_g} = \frac{n_g(\tau)}{n_{g_0}}$$

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

$$K_{n_g} = 1{,}613 \left(\frac{z_g\left[1-(1-P_p)^{v_k \tau}\right]}{P_p} + \frac{0{,}62(1-P_p)^{v_k \tau}}{B_g^{1{,}99}} \right) B_g^{1{,}99} \quad (19)$$

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 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):

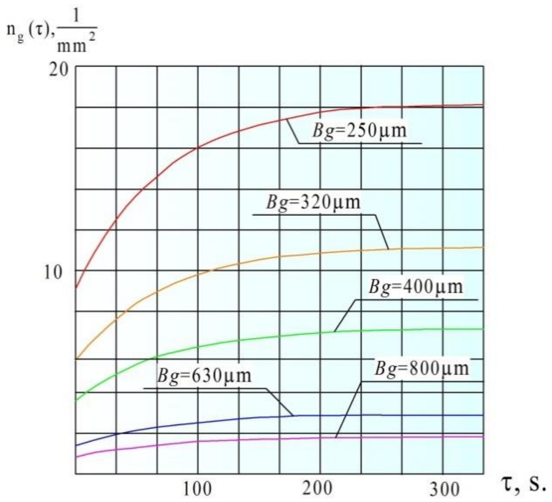

Figure 5 – The influence of the work time *τ* of the grinding wheel on the change in the number $n_g(\tau)$ of grains per 1 mm^2 of the surface of grinding wheel for different B_g values.

$$R_a = \frac{1{,}017 V_u H_u^{1{,}5}}{K_c K_{n_g}(V_k \pm V_u)\sqrt{K_{\rho_g} B_g^{-3.025} D_e} \sum_{i=0}^{n} (W_m - i\Delta r)^{1{,}5}}$$

at $\Delta r < W_m$; (20)

$$R_a = \frac{0{,}544 V_u^{0{,}4} t_f^{0{,}6} B_g^{\,0{,}605}}{K_c^{0{,}4} K_{n_g}^{0{,}4} K_{\rho_g}^{0{,}2} (V_\kappa \pm V_u)^{0{,}4} D_e^{\,0{,}2}}$$

at $\Delta r \geq W_m$. (21)

$$\Delta r = \frac{t_f^2}{1{,}478 t_f + \dfrac{95{,}254 V_u B_g^{1{,}51}}{K_c K_{n_g}(V_k \pm V_u)\sqrt{K_{\rho_g} D_e}}}. \quad (22)$$

$$t_f = 0{,}739\Delta r + \sqrt{0{,}546 \cdot \Delta r^2 + \frac{22.03 V_u \Delta r B_g^{1.51}}{K_c K_{n_g}(V_k \pm V_u)\sqrt{K_{\rho_g} D_e}}}; \quad (23)$$

$$M[R_{\max}] = H - 2{,}074\sqrt{\frac{V_u t_f^{1{,}5} B_g^{1.99}}{K_{n_g}(V_k \pm V_u) L \sqrt{D_e}}}; \quad (24)$$

$$M[R_z] = H - 3{,}747\sqrt{\frac{V_u t_f^{1{,}5} B_g^{1{,}99}}{K_{n_g}(V_k \pm V_u) L \sqrt{D_e}}} \quad (25)$$

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.

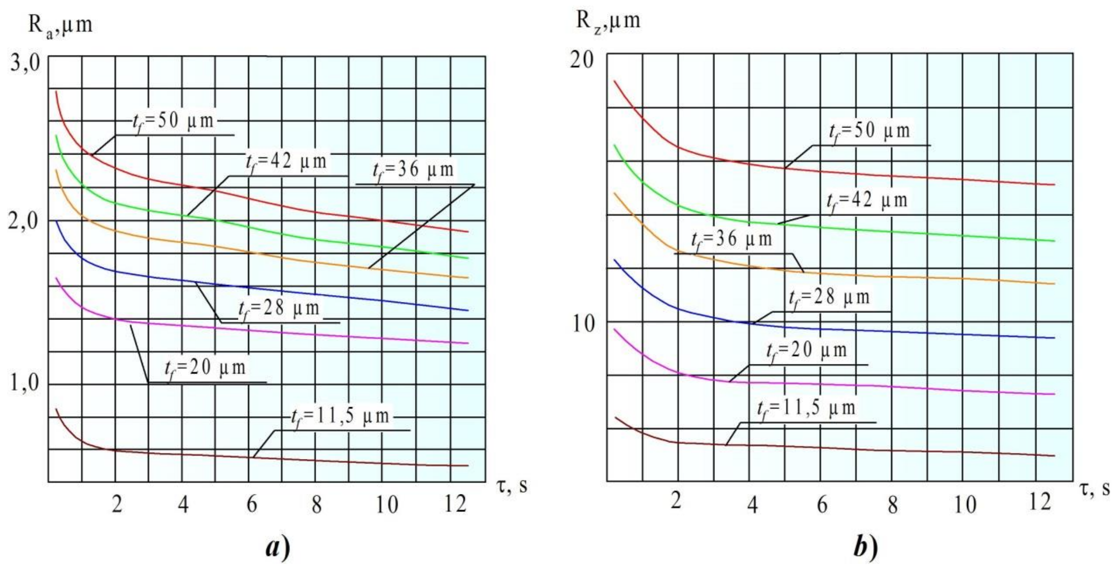

Figure 6 – The influence of the time *τ* the work of the grinding wheel on the R_a (a) and R_z (b) parameters of roughness; B_g =320 µm.

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.

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