Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science. 2021 vol. 23 no. 3 pp. 31–44
ISSN: 1994-6309 (print) / 2541-819X (online)
DOI: 10.17212/1994-6309-2021-23.3-31-44

NSTU NETI

Obrabotka metallov - Metal Working and Material Science

Journal homepage: http://journals.nstu.ru/obrabotka_metallov

Calculation of radial material removal and the thickness of the layer with the current roughness when grinding brittle non-metallic materials

Sergey Bratan [a, *], ***Stanislav Roshchupkin*** [b], ***Alexander Kharchenko*** [c], ***Anastasia Chasovitina*** [d]

Sevastopol State University, 33 Universitetskaya str., Sevastopol, 299053, Russian Federation

[a] https://orcid.org/0000-0002-9033-1174, bratan@gmail.com, [b] https://orcid.org/0000-0003-2040-2560, st.roshchupkin@yandex.ru,
[c] https://orcid.org/0000-0003-1704-9380, khao@list.ru, [d] https://orcid.org/0000-0001-6800-9392, nastya.chasovitina@mail.ru

ARTICLE INFO

Article history:
Received: 27 June 2021
Revised: 23 July 2021
Accepted: 14 August 2021
Available online: 15 September 2021

Keywords:
Grinding of brittle materials
Sanding of holes in silicon workpieces
Radial material removal
Layer thickness with current surface roughness
Probability of material removal, micro-cutting depth

Acknowledgements
Research were conducted at core facility "Structure, mechanical and physical properties of materials".

ABSTRACT

Introduction. The quality parameters of products, which determine its performance and functionality, are finally formed in the finishing operations, which include the internal grinding process. In this case, the removal of material from the rough surface of the workpiece occurs due to the presence of several simultaneously running random processes of shaping, occurring during the contact of the grinding wheel and the workpiece. A probabilistic theoretical approach is used to simulate grinding operations. However, for determination of radial material removal and thickness of layer with current roughness, the known models cannot be used, as it does not allow taking into account specific features of machining products made of brittle non-metallic materials. **Purpose of the work.** Creation of a new theoretical and probabilistic model allowing to calculate radial material removal and layer thickness, in which current roughness is distributed during grinding of brittle non-metallic materials. The aim is to investigate the regularities of brittle non-metallic material particles removal by radial removal and study the current (for the moment) roughness formed after every radial removal in the contact area. In the work, radial material removal and the layer with current roughness are determined by grinding modes, tool surface condition, workpiece and wheel dimensions, and the initial condition of the machined surface after the previous contact. **The research methods** are mathematical and physical simulation using basic probability theory, distribution laws of random variables, as well as the theory of cutting and the theory of deformable solids. **Results and discussion**. The developed mathematical models make it possible to trace the dimensions and shape of the contact zone when grinding holes in billets made of silicon, which are somewhat different from those known when machining billets made of metal. The proposed dependencies show that with an increase in the depth of micro-cutting, the radial material removal and the thickness of the layer with the current surface roughness increase for all values of wheel speed and workpiece speed. From the experimental values obtained, the maximum micro-cutting depth and the thickness of the layer with current surface roughness are calculated. The thickness of the said layer is compared with the experimental values obtained from the ground surface profilographs. A comparison of the calculated and experimental data indicates its compliance with almost all feed values, which confirms the adequacy of the obtained equations, which model the real process of grinding holes made of brittle non-metallic materials quite well.

For citation: Bratan S.M., Roshchupkin S.I., Kharchenko A.O., Chasovitina A.S. Calculation of radial material removal and the thickness of the layer with the current roughness when grinding brittle non-metallic materials. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2021, vol. 23, no. 3, pp. 31–44. DOI: 10.17212/1994-6309-2021-23.3-31-44. (In Russian).

Introduction

Modern machines are designed to perform numerous functions in various fields of human activity and are characterized by continuously increasing indicators of versatility and productivity, speed and continuity of the working cycle, a high degree of automation and reliability. These features led to the corresponding requirements for the properties of individual parts, as well as problems associated with its processing. Well-known general processing problems are significantly aggravated in the process of obtaining precise holes

*** Corresponding author**
Bratan Sergey M., D. Sc. (Engineering), Professor
Sevastopol State University,
33 Universitetskaya str,
299053, Sevastopol, Russian Federation
Tel.: +7 (978)7155019, **e-mail:** serg.bratan@gmail.com

in parts made of brittle non-metallic materials. Such a technological operation is one of the most common and in terms of volume is not inferior to the processing of external surfaces. In addition, the processing of precise holes is among the most labor-intensive and is more complex than the processing of external surfaces, which is due to more severe process conditions and less rigidity of processing tools. The quality parameters of the products that determine its operational properties and functional features are finally formed at the finishing operations, which include the internal grinding process. In this case, the removal of material from the rough surface of the workpiece is carried out due to the presence of several simultaneously running random processes of shaping that occur when the grinding wheel and the workpiece are in contact. To simulate grinding operations, a probabilistic-theoretical approach is used. [1]. The idea of using such an approach in the study of surface roughness was first expressed by the American mathematician *J. Rice* (1937) and the famous Russian scientist-academician *Yu. V. Linnik* (1954). Later there were studies by *A. P. Husu*, *Yu. R. Witenberg*, *I. V. Dunin-Barkovsky*, which were paid attention to by domestic and foreign scientists. However, these studies were aimed only at studying the characteristics of rough surfaces, without taking into account the conditions of its formation [2]. The probabilistic-theoretical approach was further developed in the works of *A. N. Reznikov*, *O. B. Fedoseev*, *N. I. Bogomolov*, *L. A. Glazer*, *P. I. Lizarditsyn*, *Yu. D. Avrutin*, *D. G. Evseev*, *A.V. Korolev*, *Yu.K. Novoselov* and other authors who use various statistical-probabilistic methods to obtain calculated dependencies for specific schemes and grinding conditions. The authors show that any conclusions about the number of working grains, its percentage ratio with grains on the surface of the grinding wheel can have real meaning only in relation to specific conditions inherent in this process, which is associated with the non-stationary grinding operations. These works of domestic and foreign authors make a significant contribution to the development of the theory of polished surfaces shaping, but it does not allow taking into account the specifics of processing products made of brittle non-metallic materials, and therefore the scope of its application is limited [3-17].

Taking into account the above, the **purpose of this work** is to create a new probabilistic-theoretical model that allows calculating the radial removal of the material and the thickness of the layer in which the current roughness is distributed when grinding brittle non-metallic materials. The task is to study the regularities of removing particles of brittle non-metallic material by radial removal and to study the current (at this point in time) roughness formed after each radial removal in the contact zone.

Simulation of the process

The probability of removing the material for processing workpieces made of brittle non-metallic materials by abrasive tools is calculated according to the dependence [1]:

$$P(M) = 1 - \exp\left(-b_0 - b_1(y,\tau) - b_2(y,\tau) - \ldots - b_n(y,\tau)\right), \quad (1)$$

where b_n – a parameter that characterizes the change in the area of depressions due to the processes of mechanical cutting and brittle chipping, respectively; $b_n = a_n + a_{n+1}$.

In works [18, 19], dependencies were obtained that simulate indicators:

$$a_1(y,z) = \frac{3\pi n_3 K_c \sqrt{2\rho_3}(V_k \pm V_u)(1-P_0)(t_f - y)^2}{8 H_u^{3/2} V_u}\left(z - \frac{2z^3}{3\sqrt{L_y}} + \frac{z^5}{5L_y} + \frac{8}{15}L_y\right) +$$

$$+\frac{3\pi n_3 K_c \sqrt{2\cdot\rho_3}(V_k \pm V_u)(t_f - y)^4}{16 H_u^{3/2} V_u t_f^2}\left(z + \frac{z^9}{9L_y^2} - \frac{4z^7}{7L_y^{3/2}} + \frac{6z^5}{5L_y} - \frac{4z^3}{3\sqrt{L_y}} + \frac{8}{20}L_y\right) \quad (2)$$

$$a_2(y,z) = \frac{3\pi n_3 K_c \sqrt{2\rho_3}(V_k \pm V_u)(1-P_0)(t_f - y)^2}{8 H_u^{3/2} V_u}\left(z - \frac{2z^3}{3\sqrt{L_y}} + \frac{z^5}{5L_y} + \frac{8}{15}L_y\right) +$$
$$+ \frac{0,05 n_3 K_c \sqrt{2\rho_3}(V_k \pm V_u)(t_f - y + \Delta r_x)^4}{H_u^{1,3} V_u (t_f + \Delta r_x)^2}\left(z + \frac{z^9}{9L_y^2} - \frac{4z^7}{7L_y^{3/2}} + \frac{6z^5}{5L_y} - \frac{4z^3}{3\sqrt{L_y}} + \frac{8}{20}L_y\right), \quad (3)$$

where $a_1(y,z)$ – an indicator that characterizes the change in the area of depressions formed due to the process of mechanical cutting; $a_2(y,z)$ – an indicator that characterizes the change in the area of depressions formed due to the brittle chipping process; Δr_x – the value of the increment of material removal in the process of brittle chipping of brittle non-metallic material; n_3 – the number of grains per unit area of the working layer of the tool; V_k – peripheral speed of the tool (wheel); V_u – peripheral speed of the bar; H_u – the thickness of the working surface layer of the tool in contact with the workpiece; t_f – actual cutting depth; L_y – the length of the contact zone from the nominal external surface of the tool to the main plane; P_0 – probabilistic characteristic of a brittle non-metallic material chipping; K_c – chip formation coefficient; z – the coordinate directed along the contact zone; ρ_3 – the radius of rounding the grain top.

Dependencies (1), (2), (3) allow considering the method of analytical calculation of the radial material removal and surface roughness according to the input technological variables of the grinding process. As noted in [18], the “material – medium” boundary region can be specified by levels of equal probability of material removal.

Figures 1 and 2 shows illustrations of material removal during grinding holes in sitall blanks (AS-370) by a tool AW 60×25×13 63C F90 M 7 B A 50 m/s (at the speeds of the grinding head – 35 and 50 m/s, the workpiece speed – 0.25 m/s, longitudinal feed – 33 mm/s, transverse feed – 0.008 mm/stroke). When passing the surface of the contact zone, the levels are shifted to the center of the workpiece (Fig. 1).

By observing the change in the position of the level $P(M) = \beta_m$ limiting the transition area “material-medium” from the medium side, it is possible to follow the dynamics of the removal of the allowance in the contact zone of the workpiece with the tool. The distance between the radius vectors of the initial surface and the surface after contact will determine the radial removal of the material Δr per touch, and the position

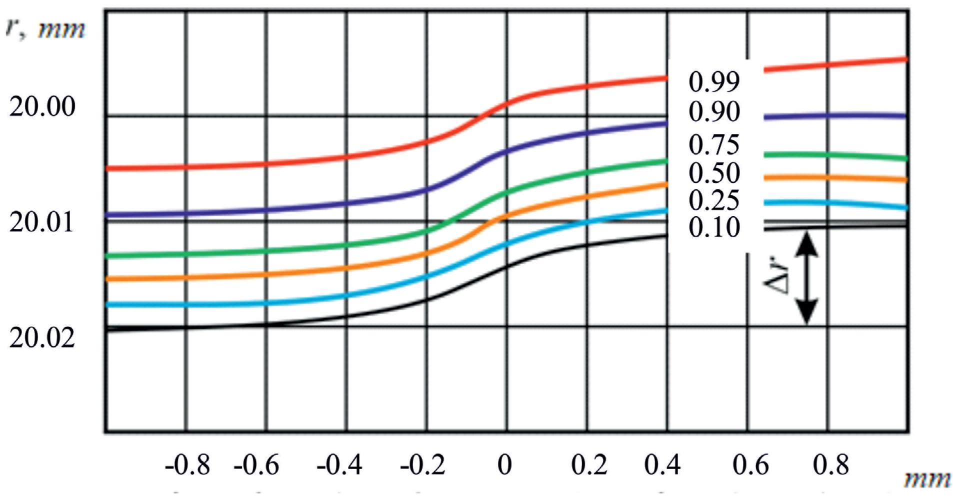

Fig. 1. Changing the radius vectors of equal probability levels

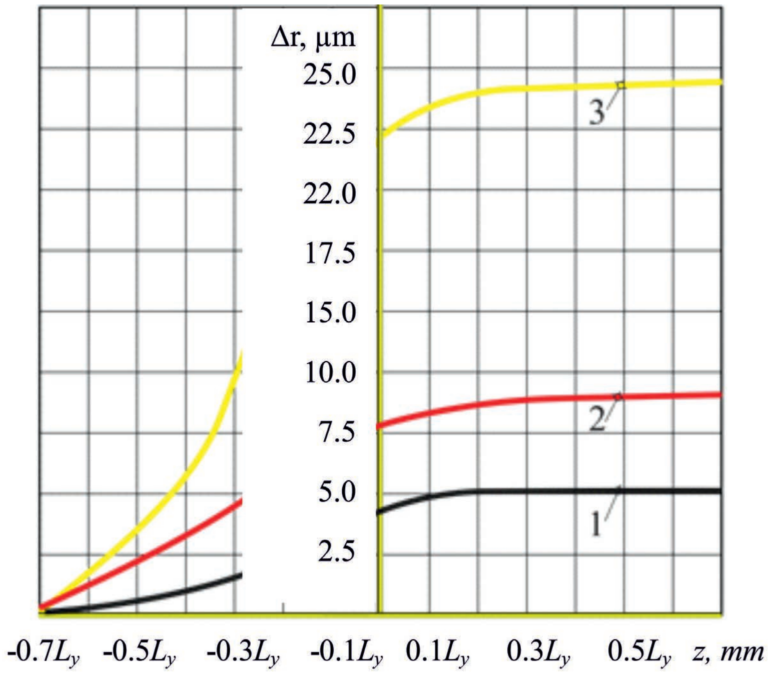

Fig. 2. Influence of the micro-cutting depth on the radial material removal when grinding holes in silicon workpieces (hole diameter – 150 mm, tool AW 60×25×13 63C F90 M 7 B A 50 m/s 1 – $t_f = 0,010$ mm; 2 – $t_f = 0,020$ mm; 3 – $t_f = 0,050$ mm)

of the line with probability $P(M) = \beta_m$ during the contact is the current value of the radial removal and the shape of the curve that limits the contact zone from the tool side (Fig. 2).

The most intense decrease in the radius vector of the workpiece is observed near the plane passing through the center of the wheel and the center of the workpiece when the depth of micro-cutting $t(z)$ is maximum and the largest number of cutting edges of the tool passes through the section. The equation of the line bounding the contact zone of the workpiece with the grinding head on the tool side (Fig. 3) is written as follows, if in equation (1) the probability of material removal is given the value β_m:

$$P(M) = \beta_m = 1 - \exp\left(-b_0 - b_1(y,\tau) - b_2(y,\tau) - \ldots - b_n(y,\tau)\right). \tag{4}$$

Let us denote:

$$G_1 = \frac{3\pi n_3 K_c \sqrt{2\rho_3}(V_k \pm V_u)(1 - P_0)}{8 H_u^{3/2} V_u} \quad G_2 = \frac{3\pi n_3 K_c \sqrt{2\rho_3}(V_k \pm V_u)}{16 H_u^{3/2} V_u}$$

$$G_3 = \frac{0,05 n_3 K_c \sqrt{2\rho_3}(V_k \pm V_u)}{H_u^{1,3} V_u}.$$

The amount of material removed for the j-th contact of the surface with the wheel is numerically equal to the displacement to the center of the workpiece with the accepted probability of material removal and is calculated from equation (4), which at can be written as:

$$-\ln(1 - \beta_m) = G_1 (t_f - y)^{m+\chi} + G_2 \frac{(t_f - y)^{m+\chi+\beta}}{t_f^{\beta}} + G_1 (t_f - y)^{m+\chi} + G_3 \frac{(t_f - y + \Delta r_x)^{m_x+\chi+\beta}}{(t_f + \Delta r_x)^{\beta}}. \tag{5}$$

Let's replace the variables:

$$y = y_{j-1} + H_j; \qquad t_f = H_j + \Delta r; \qquad \Delta r_x = \zeta \cdot t_f,$$

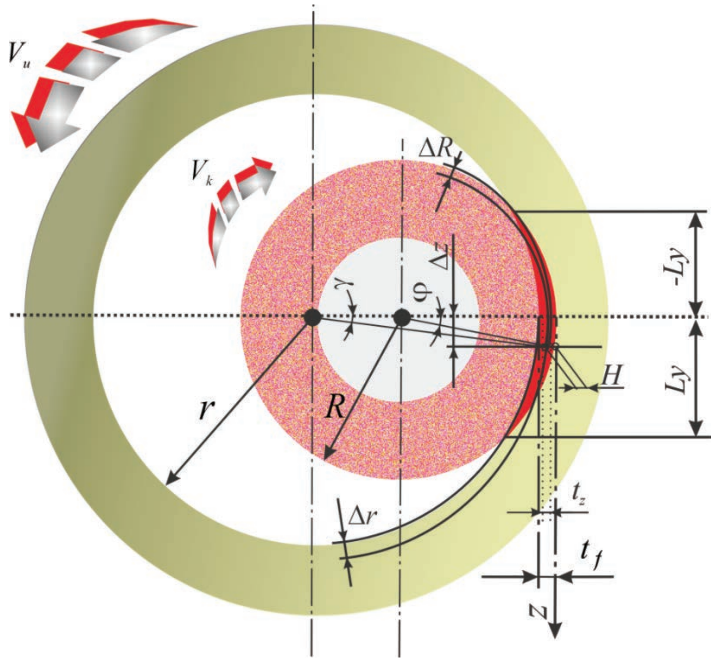

Fig. 3. Hole grinding diagram

where Δr_x – increment of the amount of material removal due to brittle fracture; ζ – the parameter depending on the shape of the abrasive grains, the properties of the processed material and the law of grain distribution over the depth of the working layer of the tool is calculated according to formula [19]:

$$\zeta = \frac{1}{\theta^{(m_x+\chi+\beta)^2}}.$$

Then the dependency (5) will take the form:

$$-\ln(1-\beta_m) = G_1\left(H_j + \Delta r_p - (y_{j-1} + H_j)\right)^{m+\chi} + G_2\frac{\left(H_j + \Delta r_p - (y_{j-1} + H_j)\right)^{m+\chi+\beta}}{(H_j + \Delta r_p)^{\beta}} +$$

$$+G_1\left(H_j + \Delta r_p - (y_{j-1} + H_j)\right)^{m+\chi} +$$

$$+\;G_3\frac{\left(H_j + \Delta r_p - (y_{j-1} + H_j) + \dfrac{1}{\theta^{(m_x+\chi+\beta)^2}}(H_j + \Delta r_p)\right)^{m_x+\chi+\beta}}{\left(H_j + \Delta r_p + \dfrac{1}{\theta^{(m_x+\chi+\beta)^2}}(H_j + \Delta r_p)\right)^{\beta}}.$$

After arithmetic operations:

$$-\ln(1-\beta_m) = G_1(\Delta r_p - y_{j-1})^{m+\chi} + G_2\frac{(\Delta r_p - y_{j-1})^{m+\chi+\beta}}{(H_j + \Delta r_p)^{\beta}} + +G_1(\Delta r_p - y_{j-1})^{m+\chi} +$$

$$+\;G_3\frac{\left(\Delta r_p - y_{j-1} + \dfrac{1}{\theta^{(m_x+\chi+\beta)^2}}(H_j + \Delta r_p)\right)^{m_x+\chi+\beta}}{\left(H_j + \Delta r_p + \dfrac{1}{\theta^{(m_x+\chi+\beta)^2}}(H_j + \Delta r_p)\right)^{\beta}}. \qquad (6)$$

The numerical solution of equation (6) is performed for the conditions of grinding holes in bars made of sitall (AS-370) with a tool AW 60×25×13 63C F90 M 7 B A 50 m/s (the speed of the grinding head – 35 and 50 m/s, the speed of the bar – 0.25 m/s, the axial feed – 33 mm/s, the cross feed – 0.008 mm/stroke). The results are presented in graphs in figures 4 and 5.

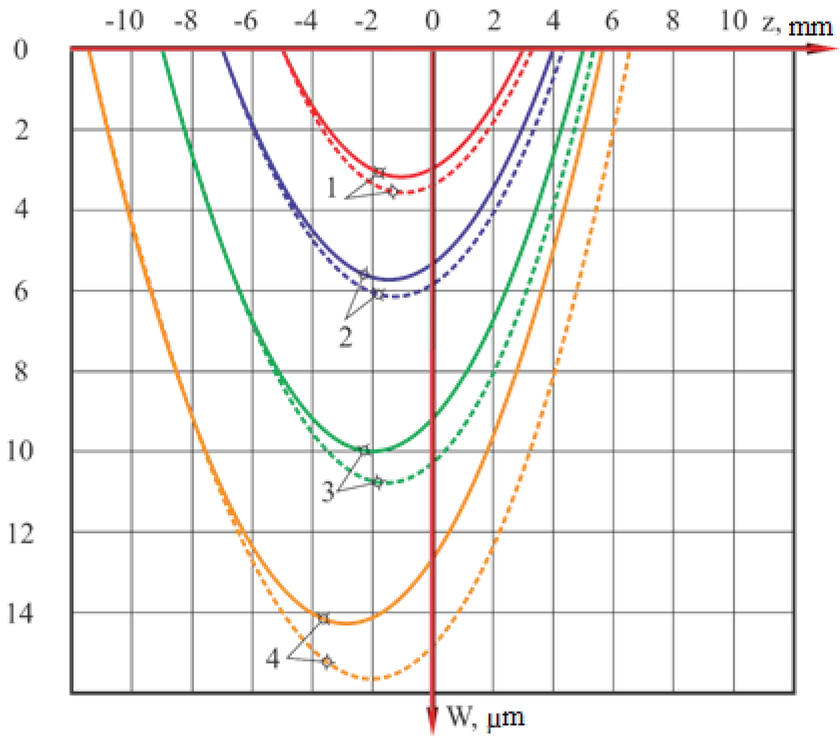

Fig. 4. Width of the contact area of the workpiece with the grinding wheel without (____) and with (– – –) radial material removal:
1– $t_f = 9,22$ µm, 2 – $t_f = 14,65$ µm; 3 – $t_f = 23,76$ µm,
4 – $t_f = 30,58$ µm

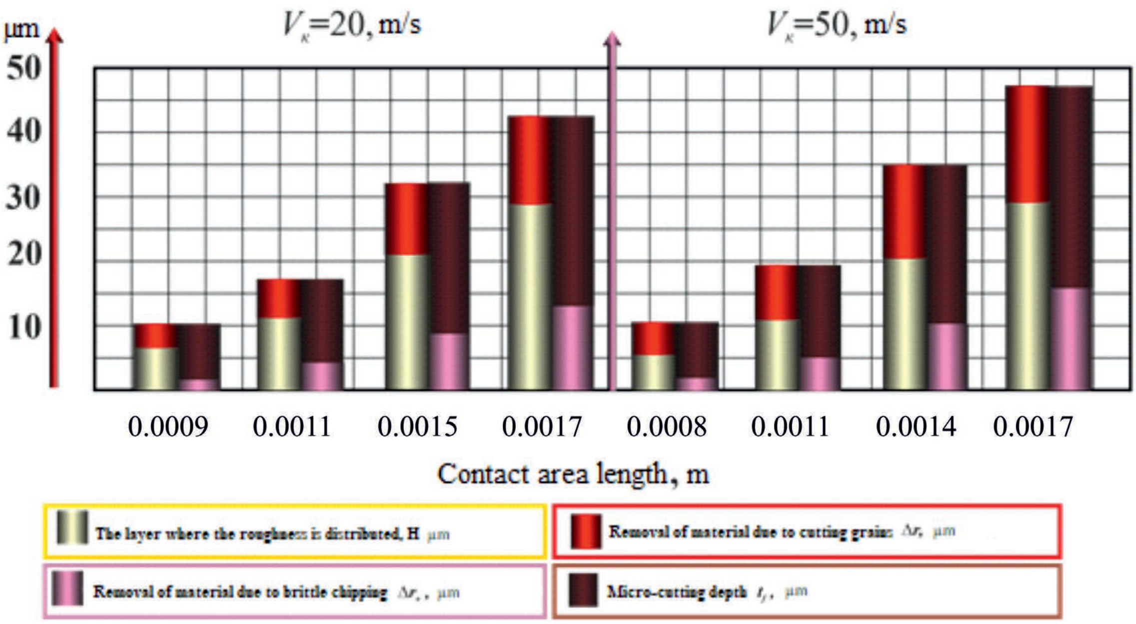

Fig. 5. Influence of wheel speed on radial metal removal and thickness of layer with current roughness when grinding sitall workpieces (AS-370)

In comparison with the process of metals grinding, the size and shape of the contact zone when grinding holes of bars made of sitall (Fig. 4) vary from those known from literary sources [17–19]. The actual size of the zone by coordinate z 75...80 % larger than the one accepted for comma-shaped slices and 10...15 % smaller than the one accepted for segment-shaped slices. The width of the zone differs from the maximum possible by the amount of the current radial removal of the material (Fig. 4).

The radial removal of the material and the layer with the current roughness are determined by the grinding modes, the state of the tool surface, the dimensions of the workpiece and the wheel, the initial state of the processed surface after the previous contact.

With a steady grinding process, to deduce the dependence of the radial removal on the elements of the grinding mode in an explicit form, taking into account the multi-pass process, we combine the origin of the coordinates with the level of the maximum vertices of the profile on $(j-n)$-th touch, where n – the number of touches of the surface with the wheel required for a complete update. Then at $0 \le y_{j-1} \le \Delta r_p$ we will receive:

$$t_f = (n+1)\Delta r_p - y_{j-1}. \tag{7}$$

It is known that with a sufficiently wide change in the elements of the cutting mode, the number of touches n, that are necessary to completely remove the initial surface roughness varies from 2 to 12 [18].

Taking into account the above, under the assumption, that n is a continuous value, based on the dependencies (6) and (7) after expansion into a series and convolution of the first 12 terms at the selected probability value β_m, we obtain an approximate solution for calculating the radial removal of the material obtained by mechanical cutting for the conditions of grinding workpieces made of brittle non-metallic materials (Fig. 7):

$$\Delta r_p = \frac{\left(0.677 t_f V_u + 0.073 t_f^2 K_c (V_k \pm V_u) n_3 \sqrt{D_e \rho_3}\right)}{V_u}, \tag{8}$$

where D_e – equivalent diameter.

The thickness of the layer with the current roughness (Fig. 6), based on geometric considerations, can be calculated according to the dependence:

$$H = t_f - \Delta r_p + \Delta r_x. \tag{9}$$

After substituting the parameter values in expression (9), a mathematical model of the formation of a layer with the current roughness after grinding workpieces made of brittle non-metallic materials is obtained:

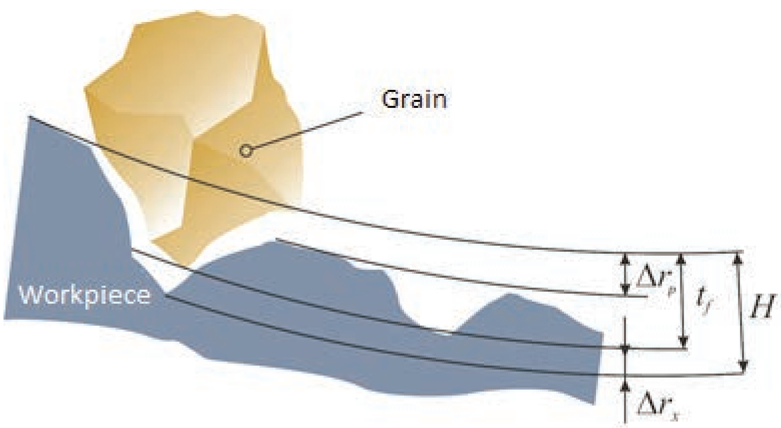

Fig. 6. Pattern of abrasive grain contact with brittle workpiece material

$$H = t_f - \frac{\left(0.677 t_f V_u + 0.073 t_f^2 K_c (V_k \pm V_u) n_3 \sqrt{D_e \rho_3}\right)}{V_u} \times$$

$$\times \left(1 + \left(1 - \exp\left[-\frac{\left(0.677 t_f V_u + 0.073 t_f^2 K_c (V_k \pm V_u) n_3 \sqrt{D_e \rho_3}\right)}{V_u \theta^{(m_x + \chi + \beta)^2}}\right]\right)\right). \quad (10)$$

Example. Calculate the thickness of the layer with the current surface roughness during internal grinding of the hole $d = 150 \cdot 10^{-3}$ m the workpiece AS-370. At the same time, the grinding head is selected as the tool AW 60×25×13 63C F90 M 7 B A 35 m/s with the value of the transverse feed $\Delta A_{si} = 5$ μm per revolution of the workpiece and the speed of rotation of the workpiece V_u = 0.25 m/s. Increments of elastic deformation of the tool and the workpiece, as well as temperature deformations of the system elements, are not taken into account. Current system status is t_f = 14.65 μm. For the specified conditions $K_c = 1$, n_3 = 15.866·10^6 m, ρ_3 = 7.31 ·10^{-6} m, θ = 0.5, β = 2 , m_x = 0.7 and χ = 1.3.

We determine the value of the radial removal of the material obtained by mechanical cutting, m:

$$\Delta r_p = \frac{1}{0.25}\Big((0.677 \cdot 14.65 \cdot 10^{-6} \cdot 0.25 + 0.073 \cdot (14.65 \cdot 10^{-6})^2 1(35 \pm 0.25) \times$$

$$\times 15.866 \cdot 10^6 \sqrt{0.1 \cdot 7.31 \cdot 10^{-6}})\Big) = 7.458 \cdot 10^{-6}.$$

Then calculate the amount of removal due to the brittle destruction of grains, m:

$$\Delta r_x = \frac{1}{0.25}\Big((0.677 \cdot 14.65 \cdot 10^{-6} \cdot 0.25 + 0.073(14.65 \cdot 10^{-6})^2 1(35 \pm 0.25) \times$$

$$\times 15.866 \cdot 10^6 \sqrt{0.1 \cdot 7.31 \cdot 10^{-6}})\Big)\Bigg[1 - \exp\Bigg(-\frac{1}{0.25 \cdot 0.5^{(0.7+1.3+2)^2}}\Big(00.677 \cdot 14.65 \cdot 10^{-6} \cdot 0.25 +$$

$$+ 0.073(14.65 \cdot 10^{-6})^2 1(35 \pm 0.25) \cdot 15,866 \cdot 10^6 \sqrt{0.1 \cdot 7.31 \cdot 10^{-6}}\Big)\Bigg)\Bigg] = 4.603 \cdot 10^{-6}.$$

So the thickness of the layer with the current roughness will be equal to, m:

$$H = t_f - \Delta r_p + \Delta r_x = 14.65 \cdot 10^{-6} - 7.458 \cdot 10^{-6} + 4.603 \cdot 10^{-6} = 11.795 \cdot 10^{-6}.$$

A comparison of the values of the radial removal of the material and the layer with the current roughness, calculated from the dependencies (8) and (9) for the case of internal grinding of the hole d = 150·10^{-3}m of the workpiece made of AC-370 is given in Table 1. At the same time, the conditions of the above example with the initial state of the system are preserved; t_{f0} = 0; V_k = 35 m/s; V_u = 0.25 m/s.

For most grinding modes, the deviation of the values of the radial removal and the layer with the current roughness of the material, calculated according to simplified models, does not exceed 1 %. Only for modes 4 and 6, these deviations are 1.17 and 1.19 % respectively. Thus, the accepted approximations provide a sufficiently high accuracy of calculations and allow to evaluate analytically the impact on the radial removal of the material and the layer with the current surface roughness of the elements of the grinding mode and the characteristics of the abrasive tool. The radial removal and the layer with the current surface roughness depend on the actual depth of micro-cutting, the speed of the workpiece, the dimensions of the workpiece and the wheel, the geometry of the abrasive grain, the number of cutting edges on the surface of the wheel.

With an increase in the depth of micro-cutting, the radial removal of the material and the thickness of the layer with the current surface roughness increase for all values of the wheel speed and the workpiece speed (Fig. 5 and 7).

Table 1

Comparison of numerical results with those based on simplified dependencies

№	Actual depth t_f, μm	Number of contacts, n	Radial material removal, μm		Layer thickness with current roughness H, μm			Contact area length, mm
			Δr_p	Δr_x	dependency (6)	simplified model (10)	deviation, %	
1	9.22	5	4.096	1.857	6.998	6.982	0.23	0.0008
2	14.65	2	7.458	4.603	11.849	11.795	0.46	0.0011
3	16.04	3	8.345	5.428	13.161	13.12	0.31	0.0011
4	23.76	7	13.37	10.55	21.19	20.94	1.17	0.0014
5	27.92	6	16.11	13.53	25.49	25.33	0.63	0.0016
6	29.77	12	17.34	14.89	27.64	27.31	1.19	0.0017
7	30.58	9	17.88	15.47	28.369	28.17	0.71	0.0017

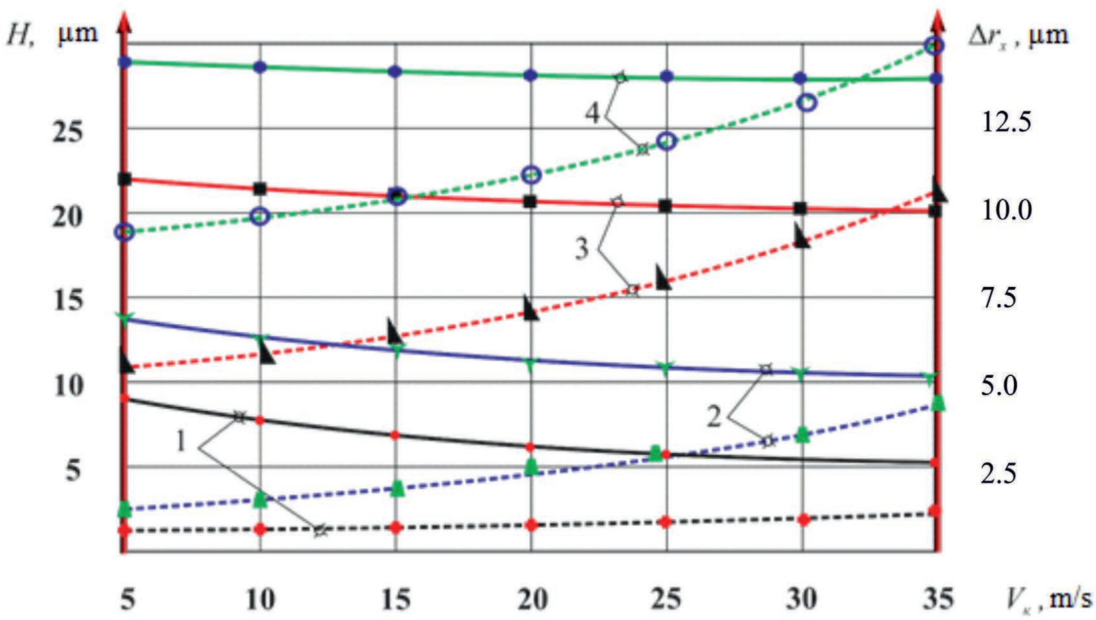

Fig. 7. Effect of wheel speed on material removal (– – –), caused by brittle fracture and on layer thickness with current surface roughness (__):

1 – t_f = 9.22 μm, 2 – t_f = 14.65 μm; 3 – t_f = 23.76 μm, 4 – t_f = 30.58 μm

In the studied range, the thickness of the layer with the current surface roughness changes almost proportionally to t_f. So, for wheels with a grain size of F90, with an increase of t_f by almost 2 times (from 9.22 μm to 14.65 μm at V_k = 35 m/s) the thickness of the layer with the current roughness increases by 1.92 times (from 5.2 μm to 10.01 μm). The radial removal of the material increases more significantly with an increase in the depth of micro-cutting than the thickness of the layer with the current surface roughness. Thus, with an increase of t_f by 1.59 times (from 9.22 μm to 14.65 μm) (Fig. 5), the radial removal increases by 3.1 times (from 2.38 μm to 7.34 μm). This effect of the depth of micro-cutting on the radial removal is explained by the fact that with increasing t_f not only the thickness increases, but also the length of individual sections, the brittle component of the removal increases.

With an increase in the speed of the wheel, the radial removal increases, the thickness of the layer with the current surface roughness decreases. With an increase in the speed of the workpiece at t_f = const, the radial removal of the material decreases, the thickness of the layer with the current surface roughness increases.

Results and discussion

For the purpose of experimental verification of the obtained dependencies, experiments were conducted on grinding samples during internal grinding of the hole. Samples (hole diameter – 150 mm, length – 250 mm) were ground on a machine *RSM M 500 CNC* by the tool *AW 60×25×13 63C F90 M 7 B A 35 m/s* (the grinding head speed – 35 m/s, the workpiece speed – 0.262 m/s). In order for each point of the surface to meet the wheel once in one pass, the longitudinal feed per revolution of the workpiece was chosen equal to the width of the grinding head *bs* (Fig. 8).

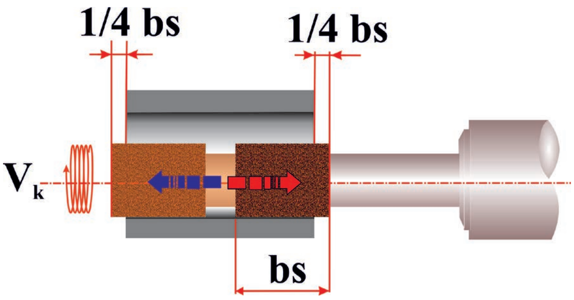

Fig. 8. Diagram of the internal grinding process

According to the obtained experimental results, the maximum depth of micro-cutting and the thickness of the layer with the current surface roughness were calculated. The thickness of the specified layer was compared with the experimental data obtained using a profilogram of the polished surface.

The obtained dependences of the removal of the material and the thickness of the layer with the current surface roughness on the transverse feed are similar to those available in the literature. If we approximate it with equations of the form $H = \Delta_H S_y^n$, then the exponent for S_y will be equal to 0.44, which is in good agreement with the experimental data of other authors [17].

A comparison of the calculated and experimental data indicates its compliance with almost all feed values. The slope of the calculated curve is slightly different (the largest deviation is 21.34 % of the calculated values from the experimental ones) with a transverse feed of 0.5 μm/stroke. With an increase in the transverse feed, the differences in the calculated and experimental values of the surface roughness decrease. Minor differences between experimental and theoretical values in the feed range of 1 ... 2 μm/stroke can be explained by the fact that the number of vertices on the surface of the wheel is assumed to be constant during calculations, while according to research data [17–20] it increases with a decrease in the intensity of metal removal and transverse feed. But even if the number of abrasive grains remains constant, equations (8) and (10) model the real process of grinding holes made of brittle non-metallic materials quite well.

Conclusions

The developed mathematical models allow us to calculate the radial removal of the material and the thickness of the layer in which the current roughness is distributed when grinding brittle non-metallic materials. The proposed dependencies show the regularity of the removal of particles of brittle non-metallic

Table 2

Influence of cross feed on micro-cutting depth, radial material removal and surface roughness

№	Cross feed rate S_y, μm/stroke	Actual depth t_f, μm	Radial material removal, μm		Layer thickness with current roughness H, μm		
			Δr_p	Δr_x	experimental	accounting	deviation, %
1	0.5	10.47	4.68	2.324	6.382	8.114	21.34
2	1.0	17.83	9.27	6.389	12.451	14.95	16.71
3	2.0	22.34	12.18	9.363	16.872	19.52	13.57
4	4.0	26.38	14.83	12.2	26.01	23.75	8.69
5	8.0	32.16	18.65	16.38	27.904	29.89	6.64

material by radial removal and the distribution of the current roughness formed after each radial removal in the contact zone.

The proposed analytical dependences are valid for a wide range of grinding modes of holes in sitall blanks, the characteristics of wheels and a number of other technological factors [18, 19, 20].

The obtained expressions allow us to find the maximum depth of micro-cutting and the thickness of the layer with the current surface roughness when grinding brittle non-metallic materials. A comparison of the calculated and experimental data indicates its compliance with almost all feed values, which confirms the adequacy of the obtained equations, which model the real process of grinding holes made of brittle non-metallic materials quite well.

References

1. Novoselov Yu.K. *Dinamika formoobrazovaniya poverkhnostei pri abrazivnoi obrabotke* [Dynamics of surface shaping during abrasive processing]. Sevastopol, SevNTU Publ., 2012. 304 p. ISBN 978-617-612-051-3.

2. Kassen G., Werner G. Kinematische Kenngrößen des Schleifvorganges [Kinematic parameters of the grinding process]. *Industrie-Anzeiger = Industry Scoreboard*, 1969, no. 87, pp. 91–95. (In German).

3. Malkin S., Guo C. *Grinding technology: theory and applications of machining with abrasives*. New York, Industrial Press, 2008. 372 p. ISBN 978-0-8311-3247-7.

4. Hou Z.B., Komanduri R. On the mechanics of the grinding process. Pt. 1. Stochastic nature of the grinding process. *International Journal of Machine Tools and Manufacture*, 2003, vol. 43, pp. 1579–1593. DOI: 10.1016/S0890-6955(03)00186-X.

5. Lajmert P., Sikora V., Ostrowski D. A dynamic model of cylindrical plunge grinding process for chatter phenomena investigation. *MATEC Web of Conferences*, 2018, vol. 148, pp. 09004–09008. DOI: 10.1051/matecconf/20181480900.

6. Leonesio M., Parenti P., Cassinari A., Bianchi G., Monn M. A time-domain surface grinding model for dynamic simulation. *Procedia CIRP*, 2012, vol. 4, pp. 166–171. DOI: 10.1016/j.procir.2012.10.030.

7. Sidorov D., Sazonov S., Revenko D. Building a dynamic model of the internal cylindrical grinding process. *Procedia Engineering*, 2016, vol. 150, pp. 400–405. DOI: 10.1016/j.proeng.2016.06.739.

8. Zhang N., Kirpitchenko I., Liu D.K. Dynamic model of the grinding process. *Journal of Sound and Vibration*, 2005, vol. 280, pp. 425–432. DOI: 10.1016/j.jsv.2003.12.006.

9. Ahrens M., Damm J., Dagen M., Denkena B., Ortmaier T. Estimation of dynamic grinding wheel wear in plunge grinding. *Procedia CIRP*, 2017, vol. 58, pp. 422–427. DOI: 10.1016/j.procir.2017.03.247.

10. Garitaonandia I., Fernandes M.H., Albizuri J. Dynamic model of a centerless grinding machine based on an updated FE model. *International Journal of Machine Tools and Manufacture*, 2008, vol. 48, pp. 832–840. DOI: 10.1016/j.ijmachtools.2007.12.001.

11. Tawakolia T., Reinecke H., Vesali A. An experimental study on the dynamic behavior of grinding wheels in high efficiency deep grinding. *Procedia CIRP*, 2012, vol. 1, pp. 382–387. DOI: 10.1016/j.procir.2012.04.068.

12. Jung J., Kim P., Kim H., Seok J. Dynamic modeling and simulation of a nonlinear, non-autonomous grinding system considering spatially periodic waviness on workpiece surface. *Simulation Modeling Practice and Theory*, 2015, vol. 57, pp. 88–99. DOI: 10.1016/j.simpat.2015.06.005.

13. Yu H., Wang J., Lu Y. Modeling and analysis of dynamic cutting points density of the grinding wheel with an abrasive phyllotactic pattern. *The International Journal of Advanced Manufacturing Technology*, 2016, vol. 86, pp. 1933–1943. DOI: 10.1007/s00170-015-8262-0.

14. Guo J. Surface roughness prediction by combining static and dynamic features in cylindrical traverse grinding. *The International Journal of Advanced Manufacturing Technology*, 2014, vol. 75, pp. 1245–1252. DOI: 10.1007/s00170-014-6189-5.

15. Soler Ya.I., Le N.V., Si M.D. Influence of rigidity of the hardened parts on forming the shape accuracy during flat grinding. *MATEC Web of Conferences*, 2017, vol. 129, p. 01076. DOI: 10.1051/matecconf/201712901076.

16. Soler Ya.I., Khoang N.A. [Influence of the depth of cut on the height roughness of tools made of U10A steel during surface grinding with cubic boron nitride wheels]. *Aviamashinostroenie i transport Sibiri:* sbornik materialov IX Vserossiiskoi nauchno-prakticheskoi konferentsii [Aircraft engineering and transport of Siberia. Proceedings of the 9th All-Russian Scientific and Practical Conference]. Irkutsk National Research Technical University. Irkutsk, 2017, pp. 250–254. (In Russian).

17. Gusev V.V., Moiseyev D.A. Iznos almaznogo shlifoval'nogo kruga pri obrabotke keramiki [Wear of a diamond grinding wheel when processing ceramics]. *Progressivnye tekhnologii i sistemy mashinostroeniya = Progressive Technologies and Systems of Mechanical Engineering*, 2019, no. 4 (67), pp. 25–29.

18. Bratan S.M., Roshchupkin S.I., Kharchenko A.O., Chasovitina A.S. Veroyatnostnaya model' udaleniya poverkhnostnogo sloya pri shlifovanii khrupkikh nemetallicheskikh materialov [Probabilistic model of surface layer removal when grinding brittle non-metallic materials]. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2021, vol. 23, no. 2, pp. 6–16. DOI: 10.17212/1994-6309-2021-23.2-6-16.

19. Bratan S.M., Roshchupkin S.I., Kharchenko A.O., Chasovitina A.S. Modelirovanie s"ema pripuska v zone kontakta pri vnutrennem shlifovanii khrupkikh nemetallicheskikh materialov [Simulation of the stock removal in the contact zone during internal grinding of brittle non-metallic materials]. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2021, vol. 23, no. 2, pp. 31–39. DOI: 10.17212/1994-6309-2021-23.2-31-39.

20. Bratan S., Roshchupkin S., Kolesov A., Bogutsky B. Identification of removal parameters at combined grinding of conductive ceramic materials. *MATEC Web of Conferences*, 2017, vol. 129, p. 01079. DOI: 10.1051/matecconf/201712901079.

Conflicts of Interest

The authors declare no conflict of interest.