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Simulation of the stock removal in the contact zone during internal grinding of brittle non-metallic materials

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ABSTRACT

Introduction. Finishing operations, in particular, cylindrical grinding, essentially form the quality parameters of products, its performance characteristics and functional suitability. At the same time, the cost of grinding work increases significantly in comparison with grinding metals, reaching an average of 20...28 % of the total cost of manufacturing products. The selection of the optimal parameters of the technological system based on the process simulation can improve the reliability, productivity and economic efficiency. To describe the processing of brittle nonmetallic materials, empirical dependences are mainly used, and the existing analytical models do not take into account the stochastic nature of the grinding operation and the combination of microcutting and brittle chipping when removing particles of brittle nonmetallic material and wear of the surface of the grinding tool. **Purpose of the work**: simulation of stock removal in the contact zone during internal grinding of brittle non-metallic materials. The task is to study the features and patterns of change in the probability of material removal when the treated surface comes into contact with an abrasive tool. In the work, the theoretical and probabilistic models are obtained, allowing to reveal the patterns of material removal in the contact zone. The models make it possible to trace the regularities of the interaction of cutting and piercing grains on the surface of the workpiece and the process of removing the allowance in the contact zone due to a combination of the phenomena of microcutting and brittle chipping, considered as a random event. **The research methods** are mathematical and physical simulation using the basic provisions of the theory of probability, the laws of distribution of random variables, as well as the theory of cutting and the theory of a deformable solid. **Results and discussion**. Data are obtained that provide a clear illustration of the patterns of material removal along the contact zone at various levels. Analysis of the results obtained shows that the peripheral speed of the tool and the rotation speed of the workpiece, which are directly included in the equation for calculating the probability of material removal, significantly affect the rate of material removal. The cross feed also has a significant effect on stock removal. A qualitative picture of the change in the probability of material removal in the contact zone during grinding of holes in brittle nonmetallic materials is obtained. The obtained patterns of change in the probability of material removal when the machined surface is in contact with an abrasive tool and analytical dependences are valid for a wide range of grinding modes, tool characteristics and other technological factors.

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Introduction

Products made of such non-metallic materials as ceramics, rubies, sapphires, glass, quartz, sitalls, ferrites, despite its high fragility, which complicates its processing during manufacture, are widely used in various industries due to its high indicators of hardness, strength and wear resistance. Finishing operations, in particular, cylindrical grinding, essentially form the quality parameters of products, its performance

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characteristics and functional suitability. At the same time, the cost of grinding work increases significantly in comparison with the grinding of metals, reaching an average of 20...28 % of the total cost of manufacturing products [1].

The complex stochastic nature of the grinding process [2] leads to a decrease in reliability and productivity, a scatter of product quality indicators, and a decrease in economic efficiency. The selection of the optimal parameters of the technological system based on the process simulation can improve reliability, productivity and economic efficiency. A large number of works [3–15] are devoted to the creation of dynamic models for grinding processes. However, all the obtained models have a limited field of application and are suitable only for simulation the processing of metal products. To describe the processing of brittle nonmetallic materials, empirical dependences are mainly used, and the existing analytical models do not take into account the stochastic nature of the grinding operation and the combination of microcutting and brittle chipping when removing particles of brittle nonmetallic material and wear of the surface of the grinding tool.

The aim of the work is to simulate the stock removal in the contact zone during internal grinding of brittle non-metallic materials. The task is to study the features and regularities of change in the probability of material removal, when the treated surface comes into contact with an abrasive tool.

Simulation of the process

To describe the interaction of a grinding tool with the surface of a workpiece made of brittle non-metallic materials, the authors have developed probabilistic-theoretical models that make it possible to identify the regularities of material removal in the contact zone. The models make it possible to trace the regularities of the interaction of cutting and piercing grains on the surface of the workpiece and the process of stock removal in the contact zone due to a combination of the phenomena of microcutting and brittle chipping, considered as a random event. The probability of removal when grinding brittle non-metallic materials is calculated by the formula:

$$P(M) = P_1(\overline{M}) \cdot P_2(\overline{M}), \tag{1}$$

where $P_1(\overline{M})$ – is the probability at which the processed material is not removed due to the microcutting process; $P_2(\overline{M})$ – the probability, that the material to be processed is not removed by the brittle chipping process.

Dependence (1) can be described by the following expression:

$$P(M) = 1 - \exp\left(-a_0 - a_1(y,\tau) - a_2(y,\tau)\right), \tag{2}$$

where a_0 – an indicator, characterizing the initial state of the surface of the workpiece in a given section before the start of the grinding process; $a_1(y,\tau)$ – an indicator, characterizing the change in the area of the depressions formed due to the mechanical cutting process; $a_2(y,\tau)$ – an indicator, characterizing the change in the area of depressions formed due to the process of brittle chipping; y – distance from the outer surface of the workpiece to the current level; τ – the moment in time of the event.

The previously accepted models of grain peaks and densities of its depth distribution [16, 17] allow us to proceed to the establishment of functional relationships between the probability of non-removal the material and technological factors.

To calculate the indicator characterizing the change in the area of the depressions formed due to the mechanical cutting process, the expression is obtained:

$$a_1(y,z)=\frac{3\pi k_c\sqrt{2\rho_z}(V_k\pm V_u)n_z(1-P_0)(t_f-y)^2}{8V_uH_u^{\frac{3}{2}}}\times\left(z-\frac{2z^3}{3\sqrt{L_y}}+\frac{z^5}{5L_y}+\frac{8}{15}L_y\right)+$$

$$+\frac{3\pi k_c\sqrt{2\rho_z}(V_k\pm V_u)n_z(t_f-y)^4}{16V_uH_u^{3/2}t_f^2}\times\left(z+\frac{z^9}{9L_y^2}-\frac{4z^7}{7L_y^{\frac{3}{2}}}+\frac{6z^5}{5L_y}-\frac{4z^3}{3\sqrt{L_y}}+\frac{8}{20}L_y\right), \qquad (3)$$

where n_z – is the number of grains per unit area of the working layer of the tool; V_k – peripheral speed of the tool; V_u – the peripheral speed of the workpiece; H_u – thickness of the layer of the working surface of the tool in contact with the workpiece; t_f – actual depth of cut; L_y – the length of the contact zone from the conditional outer surface of the tool to the main plane; P_0 – the probabilistic characteristic of chipping of brittle non-metallic chipping material; z – coordinate directed along the contact zone; ρ_z – radius of rounding of the top of the grain.

The dependence for calculating the indicator $a_2(y,\tau)$ is as follows:

$$a_2(y,z)=\frac{3\pi k_c\sqrt{2\rho_z}(V_k\pm V_u)n_z(1-P_0)(t_f-y)^2}{8V_uH_u^{\frac{3}{2}}}\left(z-\frac{2z^3}{3\sqrt{L_y}}+\frac{z^5}{5L_y}+\frac{8}{15}L_y\right)+$$

$$+\frac{0.05k_c\sqrt{2\rho_z}(V_k\pm V_u)n_z(t_f-y+\Delta r_x)^4}{V_uH_u^{1.3}(t_f+\Delta r_x)^2}\left(z+\frac{z^9}{9L_y^2}-\frac{4z^7}{7L_y^{3/2}}+\frac{6z^5}{5L_y}-\frac{4z^3}{3\sqrt{L_y}}+\frac{8}{20}L_y\right), \qquad (4)$$

where Δr_x – is the increment in material removal in the process of brittle cleavage of brittle non-metallic material.

Results and discussion

Let's calculate the probability of non-removal and the probability of removing material when grinding holes with a diameter of 150 mm in workpieces made of glass (AC-370) with the AW 60 × 25 × 13 63C F90 M 7 BA tool 35 m / s (at a wheel speed of 35 m / s, workpiece speed – 0.25 m / s, longitudinal feed – 33 mm / s, cross feed – 0.008 mm / stroke). From the calculation of the balance of displacements [18], we determine that for the given processing conditions $t_f=9,04\cdot10^{-6}$, m. Based on the research data [17, 20, 21], we accept: $k_c=1,0$; $\rho_z=7,31\cdot10^{-6}$ mm; $n_z=15,86$ grains / mm2. For the considered conditions $L_y=0,002$ m, $P_0=0,5$, $\Delta r_x=0,1\cdot t_f$. The calculation is performed according to equations (2), (3), (4) for level $y=1\cdot10^{-6}$ m at $z=-0,1\dfrac{L_y}{2}$:

$$a_1(y,z)=\frac{3\pi1,0\cdot\sqrt{2\cdot7,31\cdot10^{-6}}(35+0,25)15,86\cdot10^6(1-0,5)(9,04\cdot10^{-6}-1\cdot10^{-6})^2}{8\cdot0,25(9,04\cdot10^{-6})^{3/2}}\times$$

$$\times\left(-0,1\cdot10^{-3}\cdot0,001-\frac{2(-0,1\cdot10^{-3}\cdot0,001)^3}{3\sqrt{0,53\cdot10^{-3}}}+\frac{(-0,1\cdot10^{-3}\cdot0,001)^5}{5\cdot0,53\cdot10^{-3}}+\frac{8}{15}\cdot0,53\cdot10^{-3}\right)+$$

$$+\frac{3\pi1,0\cdot\sqrt{2\cdot7,31\cdot10^{-6}}(35+0,25)15,86\cdot10^6(9,04\cdot10^{-6}-1\cdot10^{-6})^4}{16\cdot0,25(9,04\cdot10^{-6})^{3/2}\cdot(9,04\cdot10^{-6})^2}\times$$

$$\times\left(-0,1\cdot 10\quad\cdot 0,001+\frac{(-0,1\cdot 10^{-3}\cdot 0,001)^9}{9(0,53\cdot 10^{-3})^2}-\frac{4(-0,1\cdot 10^{-3}\cdot 0,001)^7}{7(0,53\cdot 10\quad)^{\frac{3}{}}}+\frac{6(-0,1\cdot 10^{-3}\cdot 0,001)^5}{5\cdot 0,53\cdot 10^{-3}}-\right.$$

$$\left.-\frac{4(-0,1\cdot 10\ ^{3}\cdot 0,001)^3}{3\sqrt{0,53\cdot 10}}+\frac{8}{20}\cdot 0,53\cdot 10\quad\right)=2,701$$

$$a_2(y,z)=\frac{3\pi 1,0\cdot\sqrt{2\cdot 7,31\cdot 10^{-6}}(35+0,25)\cdot 15,86\cdot 10^6(1-0,5)(9,04\cdot 10^{-6}-1\cdot 10^{-6})^2}{8\cdot 0,25(9,04\cdot 10^{-6})^{3/2}}\times$$

$$\times\left(-0,1\cdot 10^{-3}\cdot 0,001-\frac{2(-0,1\cdot 10^{-3}\cdot 0,001)^3}{3\sqrt{0,53\cdot 10^{-3}}}+\frac{(-0,1\cdot 10^{-3}\cdot 0,001)^5}{5\cdot 0,53\cdot 10^{-3}}+\frac{8}{15}\cdot 0,53\cdot 10^{-3}\right)+$$

$$+\frac{0.05\cdot 1,0\cdot\sqrt{2\cdot 7,31\cdot 10^{-6}}\cdot 35,25\cdot 15,86\cdot 10^6(9,04\cdot 10^{-6}-1\cdot 10^{-6}+0,1\cdot 9,04\cdot 10^{-6})^4}{0,25(9,04\cdot 10^{-6})^{1,3}(9,04\cdot 10^{-6}+0,1\cdot 9,04\cdot 10^{-6})^2}\times$$

$$\times\left(-0,1\cdot 10^{-3}\cdot 0,001+\frac{(-0,1\cdot 10^{-3}\cdot 0,001)^9}{9\cdot(0,53\cdot 10^{-3})^2}-\frac{4\cdot(-0,1\cdot 10^{-3}\cdot 0,001)^7}{7\cdot(0,53\cdot 10^{-3})^{\frac{3}{2}}}+\right.$$

$$\left.+\frac{6\cdot(-0,1\cdot 10^{-3}\cdot 0,001)^5}{5\cdot 0,53\cdot 10^{-3}}-\frac{4\cdot(-0,1\cdot 10^{-3}\cdot 0,001)^3}{3\sqrt{0,53\cdot 10^{-3}}}+\frac{8}{20}\cdot 0,53\cdot 10^{-3}\right)=2,701$$

To determine the index, profilograms were used, taken from a sample of the workpiece (sitall AS-370) after rough grinding [22]. The probability of an event characterizing the removal of the surface layer at the level $y=0,004$ of mm at the value of the indicator $a_0=0,546$ is calculated by the equation (2):

$$P(M)=1-e^{-(a_0+a_1+a_2)}=1-e^{-0,546-2,7-2,701}=0,997\,.$$

The probability of no material removal, as an opposite event, can be determined from the total probability formula:

$$P_1(\overline{M})=1-P(M)=1-0,997=0,003\,.$$

For other levels of the considered example, the calculated data on the probability of material removal are given in Table and Fig. 1.

Analysis of the data obtained (Table) provides a clear illustration of the regularities of material removal along the contact zone at various levels.

Calculations by formula (2) show that the probability of removal at values $z=-3,38$, $y=0,8\cdot t_f$, $t_f=9,04\cdot 10^{-6}$ m is equal to 0.71. This means that 71 % will be removed, and 29 % of the processed material will remain on the surface in the form of microroughnesses.

This is explained by the fact that in the process of grinding, single grains leave traces in the form of scratches, which are superimposed on each other, while some of the grains do not cut, as it fall into the trajectory of the previous grain. Some of the grains will partially contact the material being processed, that is, the contact will not extend over the entire width of the grain. Chipping can occur under the scratch when processing brittle non-metallic materials. With an increase in the number of grains in contact with the surface of the workpiece, the number of scratches overlapping each other increases.

The proposed dependences make it possible to calculate changes in the probability of material removal when processing brittle non-metallic materials during grinding operations. The above analytical models can

Values of the probability of material removal when grinding holes in workpieces made of sitall

z	Values of the parameters of the contact zone in the radial direction (levels y)								
	$y = 0.1t_f$	$y = 0.2t_f$	$y = 0.3t_f$	$y = 0.4t_f$	$y = 0.5t_f$	$y = 0.6t_f$	$y = 0.7t_f$	$y = 0.8t_f$	$y = 0.9t_f$
–6.76	0.998	0.993	0.98	0.95	0.895	0.806	0.687	0.559	0.459
–5.07	1	0.999	0.999	0.994	0.975	0.92	0.806	0.642	0.486
–3.38	1	1	1	0.999	0.994	0.967	0.88	0.71	0.512
–1.69	1	1	1	1	0.999	0.986	0.926	0.764	0.536
0	1	1	1	1	1	0.994	0.954	0.809	0.56
1.69	1	1	1	1	1	0.998	0.972	0.845	0.582
3.38	1	1	1	1	1	0.999	0.983	0.874	0.603
5.07	1	1	1	1	1	1	0.989	0.898	0.623
6.76	1	1	1	1	1	1	0.993	0.917	0.642

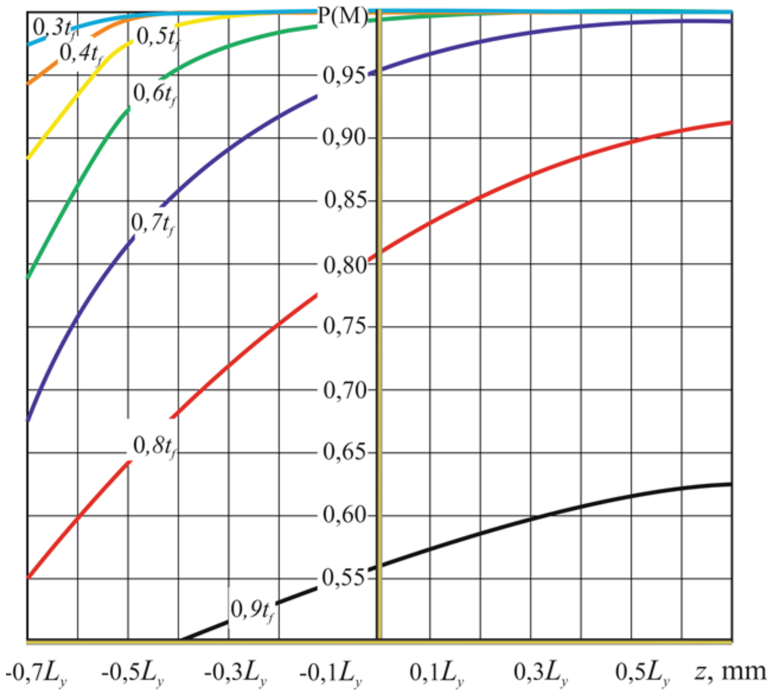

Fig. 1. Change in the likelihood of material removal when grinding holes in sitall workpieces (hole diameter – 150 mm, tool AW 60 × 25 × 13 63C F90 M 7 BA 35 m / s, wheel speed – 35 m / s, workpiece speed – 0.25 m / s, $t_f = 0,00904$ mm , at levels: $y = 0,3t_f \ldots 0,9t_f$)

be used for flat, cylindrical external and internal grinding schemes. Models provide an adequate description of the phenomena of stock removal for a wide range of cutting modes, the characteristics of the abrasive tool when grinding workpieces made of brittle non-metallic materials.

Illustration of material removal when grinding holes in workpieces made of sitall (AC-370) with the AW 60 × 25 × 13 63C F90 M 7 BA tool 35 m / s (at a circle speed of 35 m / s, a workpiece speed of 0.25 m / s, longitudinal feed – 33 mm / s, cross feed – 0.008 mm / stroke) is shown in Fig. 1.

Analysis of the data obtained shows that the peripheral speed of the tool and the rotation speed of the workpiece, which are directly included in the equation for calculating the probability of material removal, significantly affect the rate of material removal. The lateral feed also has a significant effect on stock removal, which is not represented directly in equations (2), (3) and (4), but determines the maximum microcutting depth t_f and is calculated through the equation of the balance of displacements [17].

Fig. 2 shows a qualitative picture of the change in the probability of material removal in the contact zone when grinding holes in brittle non-metallic materials.

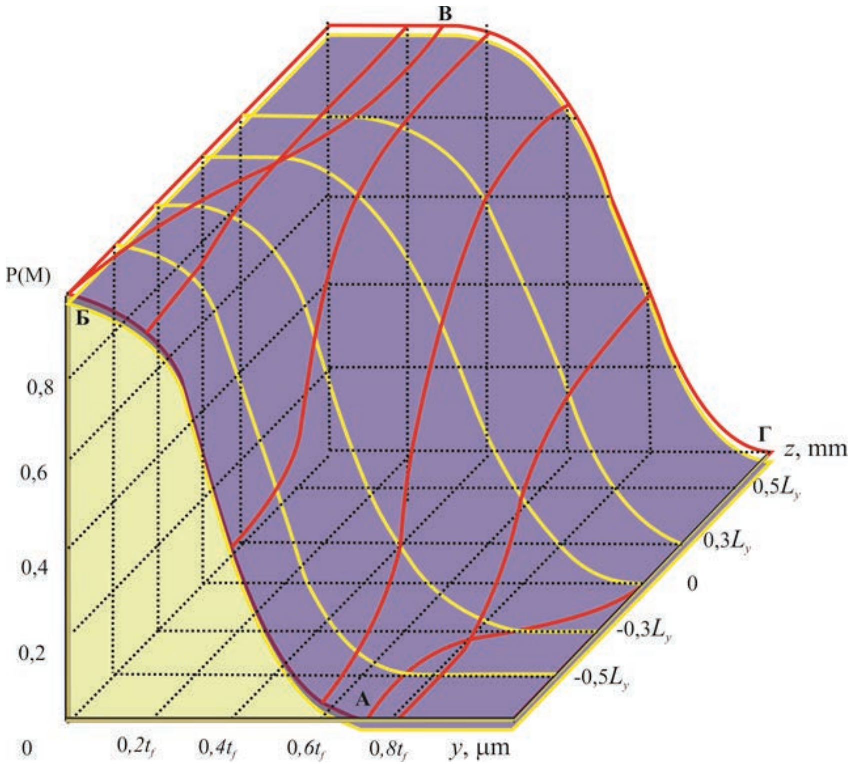

Fig. 2. Change in the probability of removing the allowance in the contact zone when grinding holes in brittle non-metallic materials

In Fig. 2, the position of the *AБ* line corresponds to the ratio of the removed and not removed parts of the material, taking into account the initial roughness of the workpiece surface. The position of the *ВГ* line makes it possible to trace the regularity of the change in the values of the probability of material removal after the end of the contact of the tool with the workpiece. The regularities of changes in the probability of material removal at fixed levels along the length of the contact zone are reflected in planes parallel to the plane $P(M)$, z.

The position of the *БВ* line determines the pattern of stock removal at the level of probability $P(M) = 0,997$.

Analysis of the data obtained allows us to draw the following conclusion. As the surface of the tool comes into contact with the workpiece material, as the actual depth of cut increases, the likelihood of material removal at all levels y increases. The highest probability value corresponds to the coordinate $z = 0$ (the position of the section of the contact zone along the main plane), since in this position the actual cutting depth is maximum.

Conclusions

Expressions (2) (3) and (4) make it possible to find the material removal values Δr, respectively, for the schemes of internal, flat and circular external grinding. To solve the considered equations, it is necessary to know the magnitude of the increment in removal Δr_x due to brittle fracture during the development of microcracks in the surface layer. The developed mathematical models make it possible to trace the effect on the removal of the allowance of the imposition of single cuts when grinding holes in brittle non-metallic materials. The obtained regularities of change in the probability of material removal upon contact of the treated surface with an abrasive tool and analytical dependences [21, 23] are valid for a wide range of grinding modes, tool characteristics and other technological factors.

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Conflicts of Interest

The authors declare no conflict of interest.