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Cutting Forces Calculation At Diamond Grinding Of Brittle Materials

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Abstract. A method of calculation of cutting forces at diamond grinding of brittle materials is proposed in article. The cutting forces: normal, tangential and fracture, acting to single grain are calculated. Total grinding forces are defined by average number of grain in contact zone. Calculating values of forces are compared with result of experimental approximation of measuring force at grinding of glass-ceramic workpiece. Grinding forces increase with increasing of diamond grains wear and can be indicative of grinding wheel blunting.

Introduction.

Increase of performance and quality of diamond grinding of brittle materials is an urgent issue for contemporary optronic and optical fields of industry. In its turn, the condition of diamond grinding wheel directly affects these values. Wear of the diamond wheel is related to that of the grains on its surface [1]. Due to increase of the diamond grains wear the contact area between the workpiece and the grinding wheel also increases which leads to increase of forces in the cutting zone. Consequently, the degree of blunting and frequency of the wheel dressing can be determined by continuous control of the forces in the grinding area [2].

Calculation of cutting forces for single diamond grain. To calculate the forces in the cutting zone it is necessary to consider the forces affecting a single diamond grain. Since a diamond grain features complicated spacial shape with multiple cutting edges, a simplified model will be considered. For instance, the works [2, 3, 4] established that the most precise description of the diamond grain can be described by an ellipsoid of revolution with constant ratio of semiaxes, .

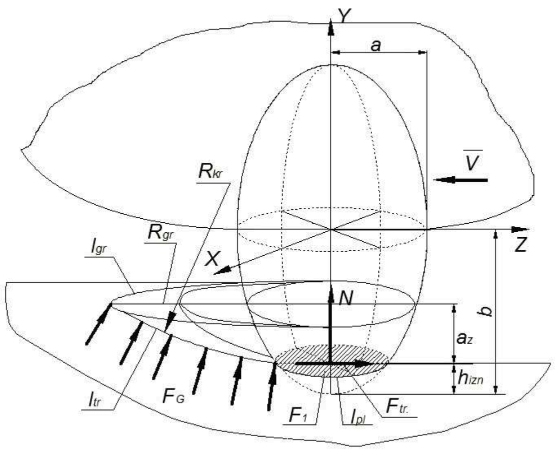

Fig. 1. The forces affecting a single worn diamond grain

Fig. 1 shows:

N - reaction force of the machined material affecting the diamond grain on the wear area F_1 .

$$N = \sigma_n F_1, \tag{1}$$

where σ_n - normal stress on the wear area of the diamond grain (equal to hardness of the machined material) [5];

F_{tr} - friction force acting on the grain wear area:

$$F_{tr} = \mu N, \tag{2}$$

where μ - friction coefficient between the machined material and the diamond grain.

Since during processing of brittle amorphous materials removal of allowance is performed by chipping in the cutting zone [6], there is a crack occurs at the first moment of contact of the diamond grain with the machined material on the machined surface. Then the size of the crack becomes crucial, the material is broken and removed. The force leading to crucial crack can be calculated by the formulae based on the values of the stresses in the cutting zone and area of chipping. The stresses and, consequently, the fracturing force are directed perpendicularly to the chipping surface. There is an assumption that the direction of the crack propagation coincides with the cutting trajectory of a single grain.

Thus, tangential and radial aspects of the cutting force affecting a single diamond grain are equal:

$$F_{z_r} = F_{tr} + F_{Gz} = N\mu + F_{Gz} = \sigma_n F_1 \mu + F_{Gz} \approx HV \cdot F_1 \mu + F_{Gz}$$

$$F_{y_r} = N + F_{Gy} = \sigma_n F_1 + F_{Gy} \approx HV \cdot F_1 + F_{Gy}.$$

The fracturing force can be expressed as follows:

$$F_G = \sigma_k S_{sk}, \tag{3}$$

where σ_k - stress producing crucial crack in the cutting zone; S_{sk} - chip area of the machined material.

The stress producing crucial crack depends on the length of the crack and can be defined by the formula borrowed from the source [7]:

$$\sigma_k = \sqrt{\frac{2\gamma E}{\pi l_{tr}}} \tag{4}$$

where γ - intensity of the surface energy of the machined material; E - Young's modulus; l_{tr} - length of the crack produced in the cutting zone.

Calculation of total grinding forces. The number of the cutting grains contacting the machined material can be calculated by the proposal of A.N. Reznikov [2] corrected by the defined conditions of grinding in the work of the authors [2] as the following formula:

$$n_p \approx 0,047 \cdot \beta \frac{K_0(1-\varepsilon)}{\pi \alpha^{3/2} b^2} \cdot \frac{1}{\sqrt{VK_0(1-\varepsilon)^3}} \cdot S \cdot \sqrt{\frac{t}{D}} \cdot S_c, \tag{5}$$

where β^* - allowance for asymmetry of location of the peaks of the grains (distribution of the grains peaks on the wheel surface is subject to regular law);

K_0 - concentration of the diamond grains in the diamond part of the wheel, %;

ε - relative crucial embedding of the grain defined by the depth of the grain embedding in the string at the moment when it is not held on the wheel surface;
b - value of the major semiaxis of the ellipsoid of rotation, micron;
V - grinding speed, m/s; S - speed of workpiece movement, m/minute;
t - allowance ground by the wheel per one stroke, mm;
D - diameter of grinding wheel, mm;
S_c - footprint area of the contact of the grinding wheel and the workpiece, mm^2.
Aggregate cutting forces at diamond grinding of brittle amorphous materials are calculated by the formulas:

$$F_{z_r} \approx \left(HV \cdot F_1 \mu + F_{Gz}\right) \cdot n_p$$

$$F_{y_r} \approx \left(HV \cdot F_1 + F_{Gy}\right) \cdot n_p$$

Testing of calculation. The calculated dependences of the cutting forces at diamond grinding of brittle materials were verified by empirical power dependences demonstrated in the reference source [8].

$$F_{y_e} = 27.49 \cdot t^{0.46} \cdot s^{0.31} \cdot v^{-0.29}$$

$$F_{z_e} = 1.26 \cdot t^{0.12} \cdot s^{0.47} \cdot v^{-0.08}$$

The power dependencies were obtained for the conditions of flat diamond grinding by the wheel periphery of the ceramized glass workpieces (grade AC-418). The grinding wheel 1A1 200x10x3x76 A250/200-4-M2-01 was used in the experiments. The modes of grinding varied within the following limits: wheel speed $V = 23 - 41$ m/s, feed $S = 1.1 - 4.47$ m/minute, cutting depth $t = 0.1 - 0.4$ mm.
The mechanical performance of the ceramized glass is: Young's modulus – 85,000 MPa; Poissons ratio – 0,25; micro hardness H_μ = 8,500 MPa; limit of transverse strength – 110 MPa, compression – 1450 MPa, elongation – 60 MPa. The rest of the initial parameters necessary for calculation are specified in Table 1.

Table 1. Initial parameters of diamond grinding

Parameters	Values
Machined material	Ceramized glass SO-418
Concentration of diamond grains in a string, %	100
Ratio of the ellipsoid axes producing the grain shape α	0,6
Ratio of the diamond grain embedded in the string ε	0,5
Grinding wheel diameter D, mm	200
Grinding wheel grit size, µm	200/250
Maximum wear of single-point diamond h_{izn} µm	140
Coefficient of friction between the machined material and the grain, μ	0,1

Figures 2, 3 and 4 show the curves of dependencies of cutting forces at diamond grinding at maximal blunting of the grains from the common parameters of the process: feed, depth, speed of grinding.

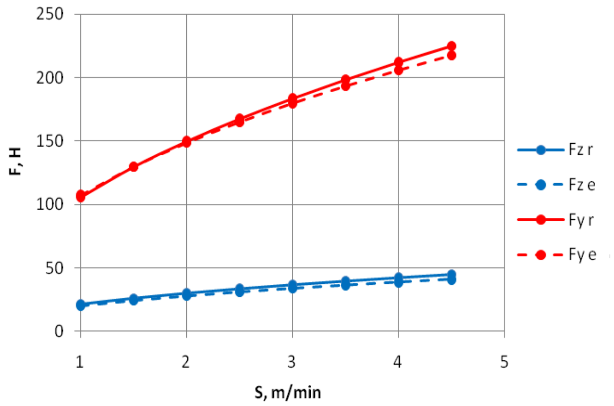

Fig. 2. Dependencies of the grinding forces from speed of the workpiece feed ($t = 0{,}1\,мм$, $V = 20\,м/с$).

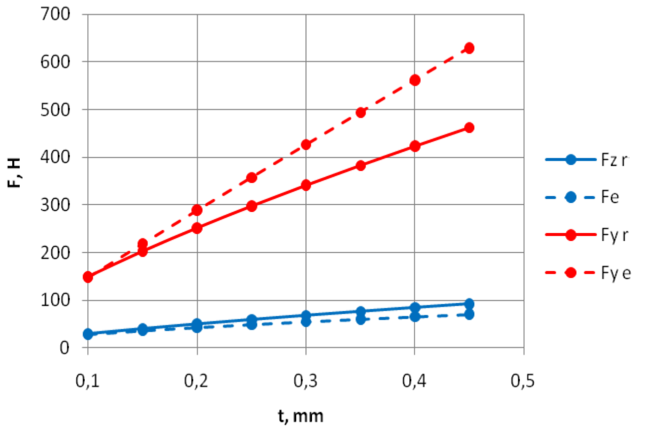

Fig. 3. Dependencies of the grinding forces from the allowance taken off per one turn ($S = 2\,м/мин$, $V = 20\,м/с$)

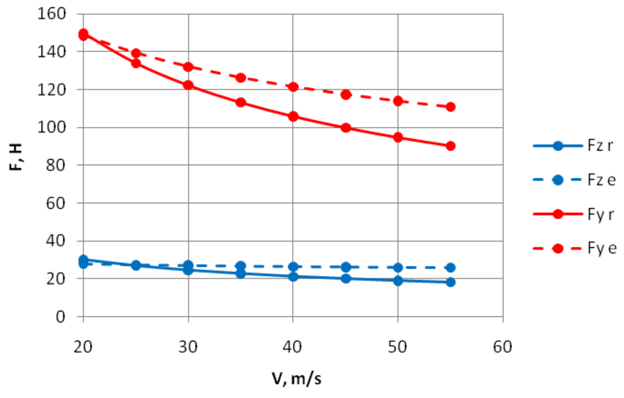

Fig. 4. Dependencies of the grinding forces from the grinding wheel speed ($S = 2\,м/мин$, $t = 0{,}1\,мм$)

Application of model. Relative discrepancy among the forces calculated by power dependencies and by the calculation formulas is from 0 to 26%, which can be deemed acceptable.

The shown model of calculation the forces in the cutting zone at diamond grinding of brittle materials allows to find the dependence between the cutting forces and grain wear on the wheel surface. If this dependency is known, it is possible to assign the extreme value of wear and calculate the cutting force when wheel dressing should be necessary.

Since the quality of the machined surface directly depends on the wheel wear [9], the values of wear for rough and finishing grinding will be different. Thus, for rough grinding the grain wear may be 30-40% from the average diameter of the grain, and for the finishing grinding – 10-20%.

Figure 5 shows the graphical dependence of the cutting forces from the wheel wear for various brittle amorphous materials: optical glass K8, ceramized glass AS-418. The properties of the materials are shown in Table 2. The rest of the initial parameters necessary for calculation are specified in Table 3. The values of the forces are limited by the assigned average wear of the diamond grains on the surface of the wheel, equal to 35%.

Thus, the tangent aspect of the grinding force for the considered brittle materials has been increased by 65% in average.

Table 2. Physical and mechanical properties of the materials.

Machined material	Hardness, MPa	Young's modulus, MPa	Intensity of surface energy, $*10^{-3}$N/mm
Optical glass K8	4,980	83,330	0,5
Optical glass LK51	5,210	68,470	0,3
Ceramized glass SO-418	8,500	85,000	0,5

Table 3. Calculation parameters

Process parameter	Parameter value
Concentration of diamond grains in a string, %	100
Ratio of the ellipsoid axes producing the grain shape α	0,6
Ratio of the diamond grain embedded in the string ε	0,5
Grinding wheel diameter D, mm	200
Grinding wheel grit size, µm	200/250
Maximum wear of single-point diamond h_{izn} µm	45
Coefficient of friction between the machined material and the grain, μ	0,1
Allowance t, mm	0,1
Wheel speed V m/s	20
Workpiece feed rate S m/min	2

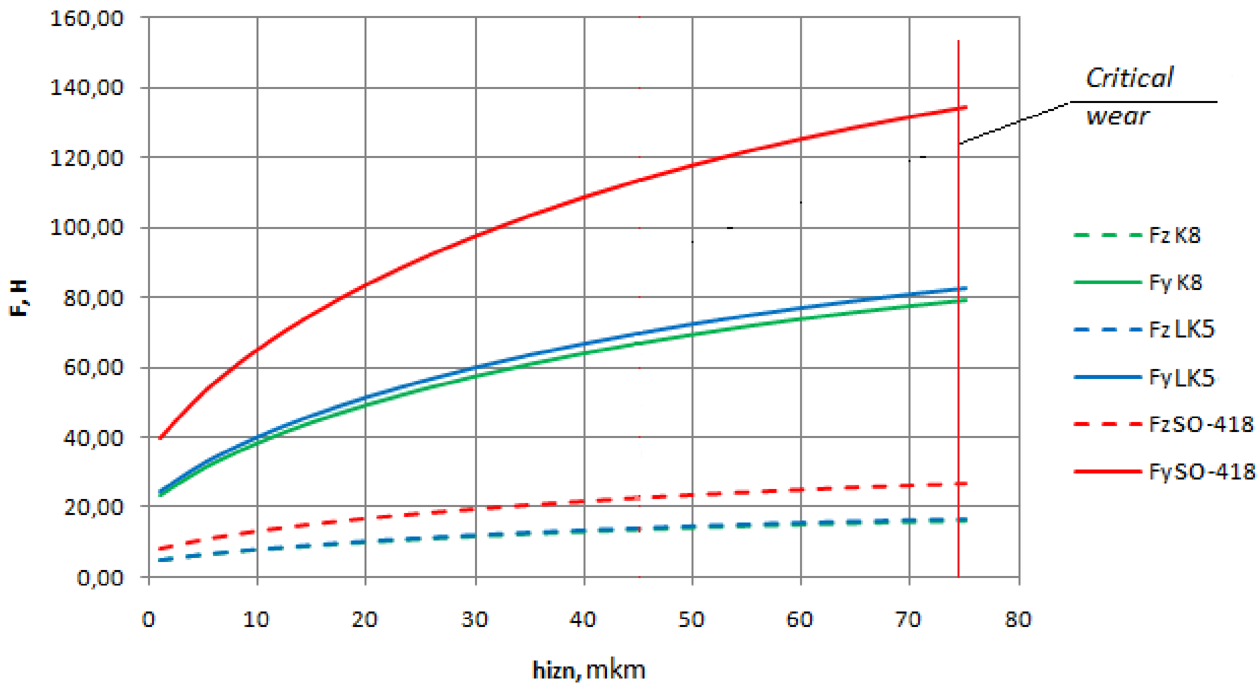

Fig. 5. Dependence of cutting forces on the wheel wear for various materials

Summary.

The continuous control of the tangent aspect of the grinding force, e.g., via the drive power allows to control wear and assign the durability period of the diamond wheel for various parameters of the process, type of machining, parameters of the wheel and properties of the machined material. Thus, the process can be optimised, and the percentage of reject reduced at finishing processing of the surfaces of brittle optical materials.

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