PHYSICO-GEOMETRIC INTERPRETATION OF MICROCUTTING TO DEVELOPMENT OF THE THEORETICAL THERMOMECHANICS OF GRINDING

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Abstract: *A technical concept for the development of new technological solutions of the high-performance grinding with a significant increase in processing productivity under a slight increase in thermomechanical tension of the cutting process is proposed and considered. A conditional cutting stress is noted and considered among the factors of influence on the thermo-mechanics of grinding in research. The parametric structure of this factor accepted for consideration to a certain extent includes the angular characteristics of the geometry of the cutting grain and its friction with the material that is processed in. The implementation of the concept follows from the possibilities of a significant reduction in the conditional cutting stress and, correspondingly, the energy intensity of the treatment, which is consistent with practical data. Attention to the phase of elastic-plastic deformation without the formation of chips with the initial introduction of cutting grain into the processed material is drawn, and also at very small depths of intervention in the microcontacts between the cutting grain and object of processing too. The performed analysis is based on the previous author's development of the probabilistic approach to the formation of the maximum thickness of the cut. Analytical modeling is performed for conical and spherical models of cutting grain. The simulation results are compared, and recommendations on the application of the completed analytical development in further theoretical studies and calculations of technological projects of high-performance grinding operations are given.*

Keywords: high-performance grinding, thermomechanics of machining, model of microcutting, maximum cut thickness, conditional cutting stress, energy intensity of processing.

1. INTRODUCTION

In work [1] the dependence of the cutting temperature in grinding θ with an analytically established central role of the conditional cutting stress in the formation of the thermo-mechanical load of the treatment process was presented:

$$\theta = \frac{\sigma}{c \cdot \rho} \cdot \frac{2}{\left[\sqrt{1 + \frac{2 \cdot B \cdot \lambda \cdot \sqrt{D_c}}{c \cdot \rho \cdot Q \cdot t^{0,5}}} + 1\right]}, \tag{1}$$

where σ – conditional cutting stress (energy intensity of treatment), N/m^2; c – specific heat of the processed material, J/(kg·K); ρ – density of the processed material, kg/m^3; B – width of grinding, m; λ − coefficient of thermal conductivity of the processed material, W/m·K;

D_c – diameter of the grinding wheel, m; Q – processing productivity, m^3/s; t – depth of grinding, m.

Ibid ([1]) noted the importance of execution an in-depth theoretical analysis of the patterns of σ change in order to develop of energetically more profitable technological transitions, operations, processes and productions.

In connection with this, in the present work we continue to develop the approach to the theoretical analysis of the thermomechanics of the diamond grinding process which was considered [1].

2. ANALYTICAL RESEARCH

It was established in [2] that in grinding σ is described by an analytical dependence:

$$\sigma = \frac{\sigma_{ct}}{tg\left[45^0 - \frac{(\psi+\gamma)}{2}\right]}, \quad (2)$$

where σ_{ct} – the compressive strength of the processed material, N/m^2; ψ – conditional friction angle of cutting grain with the processed material, in degrees; γ – negative front angle of the cutting grain, in degrees.

As seen, the conventional cutting stress (machining energy consumption) σ can be reduced by reducing the angles ψ and γ, i.e. due to decrease the intensity of friction of the cutting grain with the processed material and increase the sharpness of the cutting grain.

It should be noted that the analytical dependence (2) is obtained without consideration of a bond friction of the grinding wheel with the treated material, that when worn and blunt grains, and wheel as a whole usually determine the intensity of friction in the grinding zone and accordingly the temperature of cutting θ during grinding. However, it is difficult to establish this friction component analytically, it can only be determined experimentally for specific grinding conditions. Therefore, when analyzing the strength and thermal intensity of the grinding process, it is sufficient to initially confine oneself to considering only the intensity of friction of the cutting grain with the processed material that is taken into account in relation (2) by the angle ψ.

If we consider a cutting grain in the form of a sphere (Fig. 1), a negative rake angle γ of the cutting grain is determined by the dependence:

$$sin\gamma = 1 - \frac{a}{R}, \quad (3)$$

where a – thickness of the cut, m; R – radius of cutting grain, m.

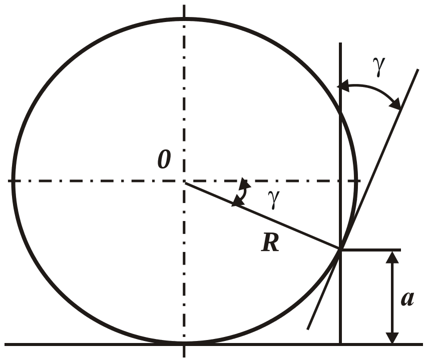

Fig. 1. The design scheme of the parameters of the microcutting process with a unit grain

With an increase in the a/R ratio γ angle decreases, it leads to a decrease of the conditional cutting stress (energy intensity of the treatment) σ and to an increase of the efficiency of chip formation during cutting. As a result, the power and thermal strength of the grinding process reduce.

The calculated values of the γ angle and σ/σ_{ct} ratio obtained by the use of the dependences (3) and (2) are shown in Table 1 with a/R ratio increasing.

***Table 1**: The calculated values of the angle γ and ratio σ/σ_{ct}*

a/R	0	0.1	0.2	0.3	0.5
γ, ^{0}	90	65	54	45	30
σ/σ_{ct} for ψ =0	∞	4.54	3.08	2.44	1.75
σ/σ_{ct} for ψ =10^0	–	7.4	4.34	3.12	2.14
σ/σ_{ct} for ψ =20^0	–	25	7.14	4.54	2.75

As can be seen, the σ/σ_{ct} ratio decreases with a/R increasing and takes values greater than unity. In the same time, the σ/σ_{ct} ratio increases with an increase in the conditional friction angle ψ of cutting grain with processed material. Consequently, consideration of the cutting grain friction with the cutting material leads to a significant increase in the ratio σ/σ_{ct}, and taking into account the friction of the bond of the grinding wheel with the processed material will lead to even greater values of the σ/σ_{ct} ratio, which is consistent with the grinding practice [3].

To simplify the calculations and ease of use of the dependence (2), it can be converted to the form [4]:

$$\sigma = \frac{\sigma_{ct}}{\left(\sqrt{\frac{a}{2 \cdot R}} - tg\,\frac{\psi}{2}\right)}. \qquad (4)$$

The calculated values of the σ/σ_{ct} ratio obtained by the use of the dependences (4) are shown in Table 2 with a/R ratio increasing.

Table 2: The calculated value of the σ/σ_{ct} ratio

a/R	0	0.1	0.2	0.3	0.5
σ/σ_{ct} for $\psi=0$	∞	4.54	3.125	2.56	2.0
σ/σ_{ct} for $\psi=10^0$	–	7.35	4.37	3.33	2.42
σ/σ_{ct} for $\psi=20^0$	–	22.73	6.94	4.67	3.09

Comparison of the calculated values of the σ/σ_{ct} ratio given in Table 1 and Table 2 shows to their slight discrepancy (within 8 %), which indicates the correctness of the transformed dependence (4). In this case, it is necessary to make the calculation of the σ/σ_{ct} ratio taking into account the conventional friction angle ψ of cutting grain with a processed material, which has a significant effect on the σ/σ_{ct} ratio.

The calculated values of the σ/σ_{ct} ratio valid for the microcutting of a single grain. To analyze the conditional cutting stress (energy intensity of the treatment) σ and σ/σ_{ct} attitude when diamond grinding, as a parameter it should be regarded a maximum probability (reduced) cut thickness H_{max} that corresponds to grain form of Fig. 2=4, and it is defined by the dependence [5]:

$$H_{max} = \sqrt[3]{\frac{630\cdot\pi\cdot\overline{X}^3\cdot V_{det}\cdot\sqrt{t\cdot\rho}\cdot(1-\eta)^2}{tg\gamma\cdot m\cdot V_c\cdot(1+\eta)}}, \qquad (5)$$

where $\overline{X}$ – the granularity of the diamond wheel, m; m – volume concentration of grains in the diamond wheel, in relative units; V_c – speed of the wheel, m/s; $\rho = 1/R_c + 1/R_{det}$, R_c, R_{det} – radiuses of a wheel (circle) and a workpiece (detail), m; V_{det} – speed of the workpiece, m/s; $\eta = x/H$ – dimensionless coefficient that determines the degree of blunting grain ($\eta = 0$ for sharp-cut grain, $\eta \to 1$ for blunted grain); x – value of linear wear of grain, m; H – the maximum conditional depth of the introduction of grain into the processed material (from the top of the grain before wear, and for the grain with maximum elevation above level of bond), m.

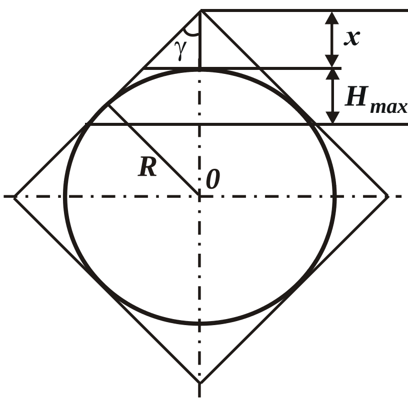

Fig. 2. The design scheme of the parameters of the microcutting in grinding process

If we consider a cutting grain in the form of a sphere with radius R, it should be expressed a dimensionless coefficient η in relation (5) in terms of the radius R. For this, quantity $x = \frac{R}{sin\gamma} - R$ is equal to the distance from the vertex of the square to the inscribed circle with the radius R, and it follows from condition $\frac{R}{R+x} = sin\gamma$. For $\gamma = 45^0$ we have $x = 0{,}414 \cdot R$. From the conditions $H = \frac{x}{\eta}$ and $H = x + H_{max}$ we have $H_{max} = 0{,}414 \cdot R \cdot \left(\frac{1}{\eta} - 1\right)$. From here $\frac{H_{max}}{R} = 0{,}414 \cdot \left(\frac{1}{\eta} - 1\right)$ or

$$\eta = \frac{1}{\left(1 + 2{,}415 \cdot \frac{H_{max}}{R}\right)}. \tag{6}$$

The values of the dimensionless coefficient η calculated on dependence of (6) are shown in Table 3.

***Table 3**: The calculated values of the dimensionless coefficient* η

H_{max} / R	0	0.1	0.2	0.3	0.5	0.6
η	1	0.8	0.674	0.58	0.45	0.41

As can be seen, a dimensionless coefficient η decreases with an increase in the H_{max} / R ratio, assuming values less than unity. According to the known experimental data of the professors Kragelsky I.V. and Bogomolov N.I., with H_{max} / R<0,2 (respectively $0{,}7 < \eta < 1$) it is a process of elasto-plastic deformation of the processed material without chip forming, and at H_{max} / R>0,2 (respectively $\eta < 0{,}7$) – a process of chip formation when cutting.

Elation $\frac{(1-\eta)^2}{(1+\eta)}$, which enters into the dependence (5), with account of dependence (6) takes the form:

$$\frac{(1-\eta)^2}{(1+\eta)} = \frac{5{,}83 \cdot \left(\frac{H_{max}}{R}\right)^2}{\left(1 + 2{,}415 \cdot \frac{H_{max}}{R}\right) \cdot \left(2 + 2{,}415 \cdot \frac{H_{max}}{R}\right)}. \tag{7}$$

Since the ratio of H_{max} / R<1, then the relation (7) can be simplified:

$$\frac{(1-\eta)^2}{(1+\eta)} = 2{,}915 \cdot \left(\frac{H_{max}}{R}\right)^2. \tag{8}$$

Substituting (8) into (5), we have:

$$\frac{H_{max}}{R} = \frac{1836{,}45 \cdot \pi \cdot \overline{X}^3 \cdot V_{det} \cdot \sqrt{t \cdot \rho}}{m \cdot V_c \cdot R^3}. \quad (9)$$

In contrast to the analogous dependence (5) obtained for the conical shape of the grain, when grinding of a wheel with grains having the shape of a sphere, the grinding parameters included in the dependence (9) have a much greater effect on the ratio H_{max} / R. In this case, the dependence (9) is simplified, since it does not contain an indefinite dimensionless coefficient η.

For the newly dressed diamond wheel it is correct condition $\overline{X} = 2 \cdot R$, and condition $\overline{X} < 2 \cdot R$ is correct when blunted wheel, because parameter R in this case defines the radius of rounding of the cutting edge of the diamond grain, which is usually more than the radius of the grain. In the case $\overline{X} = 2 \cdot R$, the dependence (9) is simplified because there are no parameters $\overline{X}$ and R:

$$\frac{H_{max}}{R} = \frac{14{,}7 \cdot 10^3 \cdot \pi \cdot V_{det} \cdot \sqrt{t \cdot \rho}}{m \cdot V_c}. \quad (10)$$

Based on the relation (9) and for the raw data V_c / V_{det} =60; m =0.25; t =20·10^{-6} м; $\overline{X} / R$ =2; R_c =0.4 m; R_{det} =0.05 m we have H_{max} / R=0.175. In this case, according to the known experimental data of Professors Kragelsky I.V. and Bogomolov N.I., the process of chip formation takes place during cutting. At lower values H_{max} / R the chip-forming process passes into the process of elastic-plastic deformation of the processed material without the formation of chips and, accordingly, without material removal. Therefore, it is necessary to increase ratio H_{max} / R in order to increase the efficiency of the cutting process during the grinding. Based on the dependence (9), this is achieved by increasing the speed of the workpiece V_{det} and the depth of grinding t. For example, with increasing V_{det} and t in 2 times the ratio H_{max} / R = 0.5, which corresponds to a stable process of chip formation during cutting.

Taking into account the dependence (9) and condition $a = H_{max}$, dependence (4) for determining the conditional cutting stress (energy intensity of processing) σ when grinding, taking into account the dependence (9) and condition $a = H_{max}$ becomes:

$$\sigma = \frac{\sigma_{ct}}{\left(\sqrt{\frac{918{,}25 \cdot \pi \cdot \overline{X}^3 \cdot V_{det} \cdot \sqrt{t \cdot \rho}}{m \cdot V_c \cdot R^3}} - tg\frac{\psi}{2}\right)}. \quad (11)$$

It can be reduced σ by an increase of parameters V_{det} and t , and a decrease m and V_c, since $\overline{X} = 2 \cdot R$ when grinding with a wheel with non-wound cutting grains. There is no doubt that a value R has a significant impact on the nature of the change in attitude H_{max} / R due to the deterioration of the grains and the increase in the radius of their rounding.

On condition $Q = B \cdot V_{det} \cdot t = \text{const}$ dependence (11) is expressed by:

$$\sigma = \frac{\sigma_{ct}}{\left(\sqrt{\frac{918{,}25 \cdot \pi \cdot \overline{X}^3 \cdot Q}{m \cdot V_c \cdot R^3 \cdot B}} \cdot \sqrt{\frac{\rho}{t}} - tg\frac{\psi}{2}\right)}. \quad (12)$$

In this case, the depth of grinding t slightly affects on σ, and increase of processing productivity Q leads to a decrease σ. However, with an increase Q, obviously, the value of R increases too, that leads to only a slight decrease of σ. Therefore, with increase of processing productivity Q, the second multiplier will dominate in dependence (1) that causes an increase in cutting temperature θ when grinding [6].

Thus, using relation (1), taking into account relation (12), it becomes possible theoretical analysis of the dependences of change of cutting temperature θ when grinding and producing the scientifically justified rational choice of processing conditions.

3. CONCLUSION

It is established that the maximum value of the cutting temperature during grinding depends mainly on the energy intensity of the treatment. Under these conditions, it is possible to reduce the cutting temperature by increasing the cutting ability of the grinding wheel and reducing the friction intensity in the grinding zone. Technical solutions in this direction open up new technological possibilities for reducing the heat stress of the grinding process and increasing the processing productivity without actually increasing the cutting temperature. This approach can be implemented under significantly reduce of the conditional cutting stresses (energy intensity of processing), which is consistent with practical data.

The obtained theoretical solutions should be used to improve technologies of forming the high functional hard-to-work materials by diamond wheel on metal bonds operating in the mode of the electro-erosive dressing [7]. The solution of practical problems of increasing of energy efficiency, productivity and quality of processing requires of scientifically substantiated determination of rational cutting regimes in the context of the analytical dependence given in the paper for determining the grinding temperature and the study presented here.

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