The role of the friction process in abrasive grain micro cutting technology

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Abstract. The process of micro-cutting with abrasive grain - complicated tribological phenomenon. The removal of the chip-shaped material from the surface of the semi-finished product is accompanied by elastic and plastic deformations of the surface, with heat releases and phase changes. One of the features of the grinding process and other types of abrasive processing, is that the removal of the chip especially takes place with negative front angles. According to [1] the average value of the front cutting angle values is within the limits - (46.6… 56.9). To the geometric parameters of the distant layer that characterizes the cutting process can be attributed: the thickness and width of the cut and the shrinkage of the chip. A series of scientific and manual works on cutting materials can be objected to the fact that in the process of deformation at cutting which is characterized by the coefficient of shrinkage of the chip a physical-mechanical influence has the characteristic of the processed material, the value of advance, depth of cutting and other parameters.

1. Introduction

Even in the middle of the last century, the authors [1, 2] remarked that when analyzing the mechanics of cutting materials, there is a wrong physical explanation of the phenomena and an incorrect determination of the main influencing factors. The authors assumed that the main role in the value of plastic deformation belongs to the coefficient of friction. The influence of cutting regimes and physical-mechanical properties of materials on the value of plastic deformation of the removed layer, determined by the shrinkage of the chip, can be expressed only by the corresponding influence on changing the coefficient of friction of the chip on the cutting surface of tools.

Experimental research [3, 4] confirms the above. In the development of the above we can add that the local value of the coefficient of friction within the contact area "tool-chip" is not constant. Depending on the purpose of the research, we can examine only the most requested areas of contact of the abrasive grain with the chip. Because, the discussion takes place about the formation of the chip, so the main role is given to the plane of separation of the front and back surface of the granule, ie - the cutting edge of the tool.

The results of experimental research related to the determination of the shear force at grinding are known [5]. Models of cutting forces are known [6, 7] they have an essential value in determining the friction force, and can explain the processes of friction, cutting and the formation of wrinkles on the surface of the part (figure 1) [8]. The increase of the cutting depth is accompanied by the increase of the cutting forces, as a result tempering increases and there are changes in the structure and hardness
of the part, attempts have been made to describe mathematically [9] the value of the influence of cutting forces on the process of forming residual stresses. 

Decreasing the cutting forces and the cutting depth leads to an increase in the influence of friction [10]. Consequently, the volume of heat in the cutting area increases, which leads to the appearance of thermal stresses, which can be determined by the expression [10, 11]:

$$\sigma = \frac{E}{1-\mu} \lambda(t_\phi - t)$$  \hspace{1cm} (1)

where: $E$ - Young module; $\mu$ - Poisson's ratio; $\lambda$ - thermal coefficient; $t_\phi$ - average temperature; $t$ - current surface temperature.

It is known that along the cutting line the normal stresses reach the maximum values and the tangential ones are equal to zero, i.e. the friction forces are missing.

After the transformation the expression (2) will have the form:

$$\frac{\mu_1+\mu_2}{1-\mu_1\mu_2} < \frac{\eta\cos \gamma}{1-\eta \cos \gamma}.$$  \hspace{1cm} (2)

2. Mathematical model

In the paper [3] it was demonstrated that the rotating hyperboloid is a figure that better fits the shapes of the abrasive grain and can be used to model geometry. This is also mentioned in the authors' work [3]. Then the value of the front angle on the surface of the abrasive granules and in the plane of the main sections at the level of the semi-finished section can be determined from the following expression [4]:

$$1 \cos \gamma = \pm \sqrt{\frac{\rho^2}{a^2(2\rho + a_z \tan^2 \gamma_3)} + \tan^2 \gamma_3 + 1},$$  \hspace{1cm} (3)

where: $\rho$ - radius of rounding of the cutting edge (radius of the tip of the hyperboloid); $a_z$ - depth of purchase with a single grain; $\gamma_3$ - the front angle of the abrasive granule, determined by the position of the asymptotes of the hyperboloid - the model of the granule section ($\gamma_3 = \varepsilon / 2$, $\varepsilon$ - the angle between the asymptotes).

By transforming expression (2), it follows that,

$$\pm \sqrt{\tan^2 \gamma + 1} = \pm \sqrt{\frac{\rho^2}{a^2(2\rho + a_z \tan^2 \gamma_3)} + \tan^2 \gamma_3 + 1},$$

$$\frac{1}{\cos \gamma} = \pm \sqrt{\tan^2 \gamma + 1} = \pm \sqrt{\frac{\rho^2 + 2\rho a_z \tan^2 \gamma_3 + a_z \tan^4 \gamma_3}{a_z(2\rho + a_z \tan^2 \gamma_3)}},$$

$$\tan \gamma = \frac{\rho + a_z \tan^2 \gamma_3}{\sqrt{a_z(2\rho + a_z \tan^2 \gamma_3)}}.$$  \hspace{1cm} (4)

$$\tan \gamma = \frac{(\rho + a_z \tan^2 \gamma_3)^2}{a_z(2\rho + a_z \tan^2 \gamma_3)}, \gamma = -\arctg \left( \frac{\rho + a_z \tan^2 \gamma_3}{\sqrt{a_z(2\rho + a_z \tan^2 \gamma_3)}} \right),$$

where $\gamma = \varepsilon \left( \frac{\pi}{2} ; 0 \right)$  \hspace{1cm} (5)
By replacing the expression (5) in the inequality (2) we obtain the possibility, depending on the cutting depth $a_2$ and the groove geometry, to determine the maximum possible value of the generalized friction coefficient, at which the displacement deformations take place.

As a criterion, which characterizes the existence or lack of chip formation in the process of interaction of abrasive granules and chip processing can serve the ratio $a_z / \rho$, the parameter of chip formation, the value of which in different works is measured in a wide range - from 0.01 to at 1.0. The formulas for determining this value in the literature sources are missing, and the data presented are as a rule the results of experimental research. We will try to solve this problem.

We return to expression (4) and highlight the parameter of chip formation $x = a_z / \rho$, dividing the denominator and the numerator by $\rho^2$. Preparation:

$$\tan^2 \gamma = \frac{1 + 2 \tan^2 \gamma_3 + (\tan^2 \gamma_3)^2}{2x + (\tan^2 \gamma_3)^2},$$

After transformations we obtain:

$$2 \tan^2 \gamma + x \tan^2 \gamma_3 = 1 + 2 \tan^2 \gamma_3 + x^2 \tan^4 \gamma_3,$$

$$\tan^2 \gamma_3 (\tan^2 \gamma - \tan^2 \gamma_3)x^2 + 2(\tan^2 \gamma_3 - \tan^2 \gamma)x + 1 = 0.$$ We will note differently $\tan^2 \gamma_3 - \tan^2 \gamma = K$:

$$K \tan^2 \gamma_3 x^2 + 2Kx + 1 = 0.$$ We solve this quadratic equality with respect to $x$.

$$x = -\cot^2 \gamma_3 \left(1 - \frac{\tan \gamma}{\sqrt{-K}}\right),$$

The necessary root is found in the expression:

that is, the chip formation parameter can be expressed by the angle $\varepsilon$ at the top of the abrasive grains (because $\gamma_3 = \varepsilon/2$) and current front angle $\gamma$ following relationship:

$$\frac{a^2}{\rho} = -\cot^2 \gamma_3 \left(1 - \frac{\tan \gamma}{\sqrt{\tan^2 \gamma - \tan^2 \gamma_3}}\right)$$

(6)

At the denominator on the left side of the expression (6) we have the parameter $\rho$ - the radius of the hyperboloid vertex. But in this case it is more correct to examine not the radius at the top of the hyperboloid, but the radius of curvature $r$ at the point at the level of the semi-finished plane. There is a dependency between them:

$$r = \frac{\rho}{\cos^3 \alpha},$$

(7)

where $\alpha$ - the angle between the normal at the exaninate point and the radius of the vector, descended from the "focus" of the hyperboloid to the given point.

Taking into account this fact, expression (6) will have the form:

$$\frac{a^2}{\rho} = -\cot^2 \gamma_3 \left(1 - \frac{\tan \gamma}{\sqrt{\tan^2 \gamma - \tan^2 \gamma_3}}\right) \times \cos^3 \alpha.$$ (8)

The value of the front angle in relation (8) can be determined from expression (1) according to the formula [5]:

$$\gamma = \arcsin \left[ \frac{1}{1 + \mu^2} \left( \frac{\mu^2}{\eta} - \sqrt{1 + \mu^2 - \left(\frac{\mu}{\eta}\right)^2} \right) \right]$$

(9)
Using (9) and the expression (6) or (8) we will have the possibility to determine the chip formation parameter. In fig. 1 shows the influence of the generalized friction coefficient $\mu$ and the chip contraction coefficient $\eta$ at the value $\alpha_r/\rho$ - the results of the calculations according to the relations (9) and (7). The top angle of the granule is equal to the angle between the asymptotes of the hyperboloid and accepted as $1*10^9$.

The presented curves show that the value of the chip formation parameters can vary in a very wide spectrum. Obviously, that in the literature sources the data are obtained for concrete processing conditions and have a connection with the friction coefficients, the cutting speed, the processed material, which in turn determines the compression value of the chip. The influence of external and internal friction coefficients on the chip formation parameter as seen is extremely high within the values of 0.1… 0.4 when grinding [6]. This fact can be clarified by the fact that, for the abrasive granule, the external and internal friction - this is an externally directed load, which determines the possibility of exceeding it depending on the direction of the applied force vector. Some authors propose that [6] the internal friction angle equals the texture angle, which is logical and correct. Which allows all forms of basic loads on abrasive grains to be presented in angular units. Since the projection of the resultant of the cutting force following the texture plane must be positive [7], then the inequality must be fulfilled:

$$\Sigma = \beta_1 + \xi + \psi - \gamma < \frac{\pi}{2}$$

(10)

where: $\Sigma$ - load on the abrasive grain in angular units; $\beta_1$ - travel angle; $\xi$ - external friction angle; $\psi$ - internal friction angle (texture angle); $\gamma$ - the front angle next to the cutting edge line in the plane of the main section (figure 2).

The value of the internal friction coefficient in angular units $\mu_2 = \tan \psi$ can be determined from formulas, presented in [7]:

$$\mu_2 = \frac{2\Delta}{\Delta + \sqrt{\Delta^2 + 4}}$$

(11)

where: $\Delta = \cot \beta_1 + \tan (\beta_1 - \gamma)$ – displacement relative to the transformation of the cut layer into chips.
\[\tan(\beta_1 - \gamma) = \frac{\tan\beta_1 - \tan\gamma}{1 + \tan\beta_1 \tan\gamma} \]
\[\tan\beta_1 = \frac{\cos\gamma}{\eta - \sin\gamma}\]

Given the fact that after these transformations we get:

\[\Delta = \eta^2 + 1 - 2\tan\gamma.\]

From the point of view of the interaction of contact at atom level, the external and the internal friction have a similar nature. The idea of this theory is based on the fact that each discrete elementary act of sliding atomic layers towards each other is accompanied by a sudden (inevitable) rupture of the bonds between the atoms of contacted bodies and elsewhere, as well as the formation of new bonds. “Additive lava”. Internal friction - the dissipation of wave energy elastic at the expense of internal processes in the solid body, has its peculiarities and can be caused by different forms of processes [8].

3. The results obtained

The reduction of internal and external friction is a perspective direction in tribology, especially applied for mechanical processing of abrasive grain materials. It will allow the reduction of the energy consumption quota, consumed for the plastic deformation on the given surface of the abrasive grain and to increase the energy quota for the movement within the front plane. The position of the cutting edge line, of course, has changed, because the micro-cutting process - synergistic process.

The influence of friction in the cutting area on the chip formation process is considerable, especially when a thin layer is removed from the surface of plastics. This refers to different types of abrasive processing, and for grinding in particular. A maximum influence on the chip formation process is exerted by the coefficient of friction on the front plane of the tool near the cutting edge.

The paper [10, 11] presents the mechanism of influence of the coefficient of friction on the position of the cutting-edge line at micro-cutting with unitary abrasive granule of hyperboloid shape. The spatial configuration of the edge determines the real shape and surface of the front abrasive grain, and correspondingly the geometric parameters of the chip, which ultimately affects the volume of the metal removed and the productivity of the process.

The volume of the chip, removed from a single grain, taking into account the plastic deformation process, can be calculated according to the formulas obtained in the works [12, 13]. Based on the regressive analysis, the presented formulas can be substantially simplified, if to examine particular cases, ie to link them to concrete processing conditions, and as variable values to choose the most essential ones. As an example, depending on the influence of the coefficient of friction (\(\mu\)) and the coefficient of compression (\(\eta\)) on the volume (\(V\)) of the chip can be presented as follows:

\[V = 0.074 \frac{0.033}{\mu} - \frac{0.253}{\eta}.\] (12)

Expression (12) obtained by a nonlinear regression for the initial parameters: diameter of the abrasive disc - 250 mm; accepted cutting depth - 0.01 mm; the apex angle of the abrasive granules - 83… 143°; peak radius - 7 - 50 \(\mu\)m; cutting speed 35.5 m / s, longitudinal feed - 10 m / min.

The curves of the dependence of the volume of chips, removed by a single chip, on the coefficient of friction at different compression coefficients of the chip are shown in figure 2.

The figure shows that if the compression coefficient of the chip has small values, then the coefficient of friction obtains high values, in this case the chip will not be possible to be removed (\(V<0\) - the field in which only the plastic deformation accompanied by friction takes place without metal removal).

When grinding in the contact area of the abrasive and semi-finished disc, complicated physical-mechanical and chemical processes take place, among them we can highlight the adhesion, the elastic
and the plastic deformation, and the phase transformations. According to the law of conservation of kinetic energy, the energy of the granules of the abrasive disc and the semi-finished product is transmitted to the chips and is transformed into thermal energy, including by elastic deformation and the mechanism of plastic deformation - double sliding and displacement between granules. Some of the energy goes to change the internal state of the semi-finished product, which is manifested by the deformation of the crystal lattice, the accumulation of internal stresses and the structure becomes unstable.

In the conditions when high required contact voltages take place, the thermal energy momentarily causes different forms of phase transformations, even until the metal melts. The momentary high temperature, on the one hand, increases the plasticity of the deformed metal and improves the conditions for chip formation by abrasive grains, on the other hand - causes structural transformations in the surface layer and promotes the appearance of tensile stresses in the given layer [13]. At the same time, the main mechanism of plastic deformation becomes slipping. Simultaneously, the processes of diffusion, polygonization, recrystallization and other similar effects take place, which tend to increase the stability of the structure [14].

The temperature in the cutting area, in the local sounds, can reach 1100... 1500°C, and this is much higher than the temperature of the critical points (as for example for steel 35 - it is 730°C and 810°C). In other areas the temperature can be much lower, which leads to the non-uniformity of the structure of the processed material and the appearance of a number of phases with different physical-mechanical properties. On the outside it is expressed by the appearance of burns, the formation of micro cracks (in case of critical internal stresses), the formation of unstable thermodynamic phases (such as the formation of austenite with large granules), which pass into other phases (e.g. pearlite) or subsequent destruction. Worsen the quality of the outer layer [15-19].

To control the processes, caused by the non-uniformity of the thermal fields, at rectification it is practically impossible, as well as to measure the temperature in the local points in the conditions of the rapid thermodynamic processes. But the measures, which allow to reduce the temperature in the cutting area, in some cases are extremely effective, refer to the rational choice of cutting regimes.

We can talk about the fact that the thermal tension takes place in the cutting area due to the analysis of the chip composition, collected after grinding the semi-finished products, composed of deformed chips, molten metal elements, in the form of balls of various sizes (figure 3), abrasive dust and others dispersion product (ground granule, binder, chipped metal) [20-25].

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**Figure 3.** The shape of the sludge under the microscope (you can see the chips and molten metal balls).
4. Conclusions
The respective mathematical apparatus and the possibilities of the current calculation technique allow the modelling of different technological processes and the processing of experimental data according to known methods. At the same time, the time for carrying out scientific research is reduced, but there is also the possibility of finding an optimal solution, which is not obvious after carrying out the research.

A considerable influence on the section plane of the sharpening element of the abrasive grain is exerted by its penetration depth, at the same time the influence of its rounding radius and the angle at the top is much smaller but approximately equal to each other; The influence of different factors on the value of the plastic deformation of the removed layer can be expressed by the corresponding influence on the modification of the coefficient of external friction of the chip on the outer surface of the cutting tool and internal friction of the processed material near the cutting edge line; The $a_p/r$ chip formation parameter in reality can vary in a very wide spectrum of values, determined, to a large extent, by the value of the external and internal friction coefficient and by the compression of the chip; As a result of decreasing the external friction coefficient increases the number of granules that remove the chip and decreases the number of granules that deform the surface layer, which leads to reduced grain wear, increases tool life, productivity and machining accuracy. Using the results of the sludge analysis, we can determine the thermal stress of the grinding process and optimize the processing regimes (for example, the advance value) so as to lower the temperature in the cutting area, which will have a positive effect on reducing unwanted tensile stresses and increase fatigue resistance of the obtained surface.

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