Simulation of the process of creep-feed diamond grinding of hardmetals

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Abstract. To determine the efficiency of diamond grinding of hardmetals, which is characterized by specific metal removal rate, it is necessary to determine the volume of chip removed by the one grain taking into consideration its curvilinear. A scheme for calculating the chip area in the longitudinal cross section with taking into consideration of its curvilinear was developed. According to the obtained equations, the volume of chips removed was determined, which provide a way to calculate the maximum force acting on the grain with higher accuracy. Comparative analysis of the motion trajectory of the grain obtained by the simulation in SolidWorks and by the calculating using the equations showed that the error between the coordinates no more than 2%.

1. Introduction
Features of the grinding process are significantly different from cutting process. There are several directions to simulate this process. One of these is to compare the grinding process with milling, but it does not take into account grain spacing, their random location on the grinding wheel, etc. The second direction describes the process for one grain with the subsequent summation of grinding with all grains [1, 2]. In the context of simulation of the grinding process the second direction is the nearest to the description of all the laws that taking place in this process. In grinding, to increase the efficiency of the process, creep-deep grinding is used. The creep-feed grinding is characterized by low feed speeds and high depths of cut [3]. Most of the papers on creep-feed grinding are devoted to abrasive grinding, while on diamond grinding there is much less papers [3-7]. One of the important factors determining the efficiency of the grinding and tool life of the diamond wheel is the wear-resistance of the diamond grains, which depends on its characteristics, mechanical properties of the tool and the workpiece and processing conditions.

2. Formulation of the problem
The main indicator that characterizes the grinding efficiency is the specific metal removal rate, which depends on dimensions of the diamond wheel and its characteristics, as well as on processing conditions [8]. To determine the maximum force acting on the grain it is necessary to determine the volume of chips removed. In the study [8] cut chip thickness when surface grinding with one grain is determine (Figure 1).
When using this scheme, the longitudinal cross section of the chip will be in the form of a «comma».

The cut chip thickness calculated using following equation:

\[ a_z = 2 \cdot S_z \cdot \frac{t}{D} \]  

where \( S_z \) is the traverse feed motion per revolution (mm/rev), \( t \) is the cutting depth (mm), \( D \) is the diameter of the motion trajectory of the grain.

The variants of the chip shape depending on the grain shape are determined (Fig. 2).

![Figure 1. The scheme of device for intermittent microcutting with one abrasive grain](image)

**Figure 2.** The variants of the chip shape produced using intermittent microcutting with one abrasive grain: a – triangular pyramid; b – prism, c – quadrangle pyramid

The calculation of the cut chip thickness depending on its shape is carried out using equations (2-4).

For the triangular pyramid shape (Fig. 2, a):

\[ a_z = 2.08 \cdot S_z \cdot t^2 / D \]  

(2)

For the prism shape (Fig. 2, b):

\[ a_z = \sqrt{3} \cdot S_z \cdot t^2 / D \]  

(3)

For the quadrangle pyramid shape (Fig. 2, c):
These equations allow calculating the maximum cut chip thickness of a one abrasive grain. The shapes of the chips removed by one grain in a longitudinal cross section, as noted above, are curvilinear, while in this case it is straight and have a shape of a pyramid or prism. In this case, it is worth considering the cutting by a group of grains on the arc of contact, and not just one abrasive grain. It is also necessary to calculate the chip area with taking into consideration of its curvilinear.

3. Theory
Consider the scheme of the surface creep-feed diamond grinding (Fig. 3), taking into consideration the cutting of a group of grains on the arc of contact with a grain size «a» and a space between grains «b».

The total number of grains that are on the arc of contact at the end face of the abrasive wheel is calculated by following equation:

\[
N = \frac{\pi \cdot D}{a + b},
\]

where \( D \) - external diameter of the abrasive wheel (mm).

In grinding, the cutting is produce at the cutting depth \( t \) on the arc of a contact \( l \), and the angle of the arc of contact is expressed as \( \phi \). The total number of grains that are on the arc of a contact \( l \) is calculated by following equation:

\[
N_\theta = \frac{l}{a + b},
\]

where \( a \) – averaged size of a grain (mm), \( b \) – averaged space between grains.

The arc length is calculated by the following equation:

\[
l = \frac{\phi}{360},
\]

The angle of the arc of contact is calculated by the equation:
\[ |\phi| = \arccos \left( \frac{D - 2t}{D} \right), \]  

(8)

Substituting equation (8) into (7) we get:

\[ l = \frac{\pi \cdot D \cdot \arccos \left( \frac{D - 2t}{D} \right)}{360}, \]

(9)

The maximum cut chip thickness cutting by a one grain is calculated using following equation:

\[ h = \frac{S_l}{N_i}, \]

(10)

where \( S_l \) - the traverse motion for its rotation at the angle \( \phi \) (mm).

The traverse motion of a wheel per revolution is calculated by the equation:

\[ S_o = S_l \cdot \frac{360}{\varphi}, \]

(11)

The traverse feed motion is calculated using following formula:

\[ S_{\text{прод}} = S_o \cdot n, \]

(12)

where \( n \) – wheel rotation speed (rpm).

Then the equation for calculating the traverse feed motion will take the form:

\[ S_{\text{прод}} = \frac{h \cdot \pi \cdot D \cdot n}{a + \delta}, \]

(13)

Depending on the diamond powder concentration in the diamond layer, the space between grains “b” may vary in the range indicated in Table 1.

| Diamond powder concentration (%) | The volume of diamond grains in the diamond layer (%) | Dependence b on a |
|----------------------------------|----------------------------------------------------|------------------|
| 25                               | 6.25                                               | \( b \approx 16 \cdot a \) |
| 50                               | 12.5                                               | \( b \approx 8 \cdot a \) |
| 75                               | 18.75                                              | \( b \approx 5.33 \cdot a \) |
| 100                              | 25                                                 | \( b \approx 4 \cdot a \) |
| 150                              | 37.5                                               | \( b \approx 2.67 \cdot a \) |

To determine the chip area of a one abrasive grain, taking into account the curvilinear surfaces, consider the scheme shown in Figure 4.
Figure 4. The scheme for determining the chip area

The motion trajectory of the grain is located from point 1 to point 2 along a certain curve. Calculating the angle between two adjacent grains $\alpha$ (Fig. 3):

$$\alpha = \arccos\left(1 - 2\left(\frac{\alpha + \delta}{2R - \alpha}\right)^2\right),$$

(14)

where R – radius of the abrasive wheel (mm)

In the considered scheme, the coordinates of the point are calculated by equations 15 and 16:

$$x = \cos \beta (R + h),$$

(15)

$$y = \sin \beta (R + h),$$

(16)

Suppose that the curve passing through the points 1 and 2 is described by the parabola equation:

$$y = kx^2 + A,$$

(17)

Then the equation for point 1 will look like:

$$-R = 0 + A,$$

(18)

It follows thence:

$$A = -R,$$

(19)

Then the equation (16) takes the form:

$$y = kx^2 - R,$$

(20)

Substituting (15) and (16) in (20) we get:

$$\sin(R + h) = k \cos^2 \beta (R + h)^2 - R,$$

(21)

From here we express $k$:

$$k = \frac{\sin \beta (R + h) + R}{\cos^2 \beta (R + h)^2}.$$
Given the above equations, the final parabola equation will take the form:

\[ y = \frac{\sin \beta (R + h) + R}{\cos^2 \beta (R + h)^2} x^2 - R, \]  

(23)

To calculate the chip area in the longitudinal cross section, use the following relation:

\[ S = \int_0^{\cos \beta (R+h)} (x) dx - S_{sect} - S_\Delta, \]  

(24)

where \( \int_0^{\cos \beta (R+h)} (x) dx \) – area of the sector \( \langle O_{124} \rangle \) (mm²); \( S_{sect} \) – area of the sector \( \langle O_{24} \rangle \) (mm²); \( S_\Delta \) – area of the sector \( \langle O_{13} \rangle \) (mm²);

Substituting (17) into (24) we get:

\[ S = \int_0^{\cos \beta (R+h)} (R + hx^2) dx - \frac{\pi R^2 \alpha}{360^\circ} - \frac{1}{2} xy, \]  

(25)

As a result of integration, we obtain:

\[ S = (Rx - k \frac{x^3}{3}) \left[ \cos \beta (R + h) - \frac{\pi R^2 \alpha}{360^\circ} - \frac{1}{2} \cos \beta (R + h) \sin \beta (R + h) \right], \]  

(26)

After reexpression, the chip area takes the following form:

\[ S = \frac{2}{3} R \cos \beta (R + h) - \frac{5}{12} \sin 2 \beta (R + h)^2 - \frac{\pi R^2 \alpha}{360^\circ}. \]  

(27)

The amount of chip removed by one grain is calculated by the following equation:

\[ V = S \cdot a', \]  

(28)

where \( a' \) – the grain size in a transverse cross section (mm).

4. Experimental results

To check the adequacy of the obtained equations, the grinding process simulation was performed using the SolidWorks to determine the motion trajectory of the grain (Fig. 5).
Figure 5. The scheme of a grinding process: 1 – abrasive wheel, 2 – diamond layer; 3 – machined surface; 4 – workpiece surface; 5 – grinding zone; 6 – abrasive grain

Figure 6 shows the motion trajectory of the grain during grinding at different periods of time.

Comparative analysis of the motion trajectory, obtained as a result of simulation in SolidWorks and the calculated trajectory obtained as a result of using the equation (22) showed that the error between the coordinates is not more than 2%.

5. Discussion
The resulting equation actually corresponds to the simulation results, which allows to conclude that the equation can be used to calculate the cut chip thickness. The error between coordinates obtained using simulation and calculated by the equation (22) can be interpreted as the error of the SolidWorks graphic editor.

6. Conclusion
The obtained equations for calculating the cut chip thickness can be used both for calculating the chip thickness removed by one grain or by a group of grains cutting in a certain time in the arc contact. In future, to determine the maximum depth of cut for creep-feed grinding, it is necessary to calculate the force on the diamond grain, which will allow you to select the conditions and characteristics of the abrasive wheel, taking into account ensuring maximum efficiency and longer wheel life.

References
[1] Composite authors 1967 Razvitiye nauki o rezanii metallov (The development of the science of cutting metals) (Moscow: Machinebuilding) p 416
[2] Vasin S A, Vereszhaka A S, Kushner V S 2001 Rezaniye materialov: Termomekhanicheskiy podkhod k sisteme vzaimosvyazey pri rezanii (Cutting materials: Thermomechanical approach to the system of interconnections during cutting) (Moscow: Moscow State Technical University named after N.E. Bauman Press) p 448

[3] Ortega N, Bravo H, Pombo I, Sánchez J A, Vidal G 2015 Thermal analysis of creep feed grinding Procedia Engineering 132 1061-8

[4] Masih Paknejada, Amir Abdullaha, Bahman Azarhoushangb 2017 Effects of high power ultrasonic vibration on temperature distribution of workpiece in dry creep feed up grinding Ultrasonics – Sonochemistry 39 392-402

[5] Al-Mokhtar O. Mohamed, Robert Bauer, Andrew Warkentin 2013 Application of shallow circumferential grooved wheels to creep-feed grinding J of Mater. Proc. Technol. 213 700-6

[6] Bhaduri D, Soo S L, Novovic D, Aspinwall D K, Harden P, Waterhouse C, Bohr S, Mathieson A C, Lucas M 2013 Ultrasonic assisted creep feed grinding of Inconel 718 Procedia CIRP 6 612-20

[7] Hood R, Aspinwall D K, Voice W 2007 Creep feed grinding of a gamma titanium aluminide intermetallic alloy using SiC abrasives J of Mater. Proc. Technol. 191 210-4

[8] Reznikov A N, Gavrilov G M 1974 Approksimatsiya raspredeleniya razmerov zeren v almaznykh poroshkakh (Approximation of the grain size distribution in diamond powders) Synthetic diamonds 4 10-3