Investigation of Technological Parameters for Machining Toroidal Section of Solid Ceramic End Mills

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Abstract. Solid ceramic mills are a promising technological solution for cutting heat-resistant materials. Although nanostructured cutting ceramics has a number of valuable physical and mechanical properties providing high operational performance of mills, it has low strength. The design of a solid ceramic mills is formed by smooth surfaces without stress concentrators to ensure operability and to reduce the probability of failure. The most important structural element of solid ceramic end mill is a helical groove with a negative rake angle needed to increase surface strength. This groove can be machined with standard grinding wheels of type 1A1 or 1V1. However, the application of grinding wheels of a standard shape requires the use of reduced cutting parameters to prevent chipping on the forming sections of the cutter. Chipping can be caused by too short length of the contact line and the stress concentration at the end point of the profile of the grinding wheel, which is typically fully responsible for shaping the front surface and its transition to the tooth back. In this paper, in order to increase the contact line, we develop a new approach to designing grinding wheels for machining helical grooves of solid mills and determining rational technological and operational parameters for their use. A new approach is developed based on the fundamental principles of analytical geometry and linear algebra, numerical methods and basic axioms of the shaping theory. In this study, we have identified the key relationships between parameters determining the position of the grinding wheel relative to the workpiece and the geometrical parameters of a solid ceramic mills. The developed approach allowing to determine the specific design of the grinding wheel, depending on the initial parameters of the mill and the trajectory of the axis of the wheel relative to the mill, was implemented in the MathCAD environment.

1. Introduction
Unique physical and mechanical properties such as low plasticity, high corrosion resistance, low density and high hardness even at very high temperatures open up wide prospects for ceramics as a material for cutting tools [1-3].

Heat-resistant materials are widely used in various industries. Cutting ceramics is an ultimate choice for processing heat-resistant materials [4,5] and is widely used in indexable tools. In the aerospace industry, a large fraction of total production is represented by products made of heat-resistant materials with a small varying surface curvature [6-10]. The use of indexable tools for processing of such surfaces is quite limited due to the large size that can cause the undesirable interference of the surface being processed with the tool [11, 12].
In the view of these circumstances, the development of the theoretical foundation of design of and new technologies for the production of unique ceramic mills is very important and highly promising. A number of contactless processes such as laser [13], plasma [14-18], electron beams [19, 21], electrochemical [22], ultrasonic [23-25] and water-jet [24] methods, with the preparation of the front surface via applying wear-resistant coatings [25-28], are widely used for producing ceramic cutting tools. However, in most cases ceramic cutting tools are produced by grinding with diamond grinding wheels with small abrasive grain [29-33] that helps to reduce the degree of chipping of the cutting edges [34].

Our group has carried out in-depth studies of the geometric parameters of mills and has developed a new mill design, described in detail in Patent 2019145011/02(086799) under approval. The cutting edge on the toroidal section of the cutting part of the mill is a complex line in 3D space, which can be represented as the intersection of the helical surface of the chip groove and the toroidal cutting surface. Based on the distribution of the normal rake angle along the cutting edge obtained from a mathematical model of the cutting part of the mill, which was developed based on the revealed functional relationships between the main geometric parameters of the end ceramic cutter with a toroidal cutting part with a radius of curvature Rt = 1 mm, it was found that the rake angle varies along the cutting edge from -14 ° to -35 ° and that the helical groove at γ = -14, Dserd = 3.34 mm and w = 30 degrees uniformly transits into the toroidal part. [35-37].

In order to implement the trajectory using the control program on a CNC machine, it is necessary to perform transformations in the tool coordinate system in such a way as to make the design system universal [38-41].

The geometrical properties of the helical groove directly affects the tool strength, tool rigidity, chip forming, directions of cutting forces and cutting conditions. Science the groove profile of the end mill [35] has a complex shape, determining the parameters of the parameters of the grinding wheel is quite a complicate task. The groove can be properly shaped using a newly designed grinding wheel of complex with taking into account its position relative to the mill.

Petukhov have made a valuable contribution to the solution of this problem, having discovered many new approaches to the determination of the parameters of the grinding wheel relative to the mill using numerical methods with the three key parameters such as the angle of intersection of the axes, the distances between axes and the position of the point of intersection of the axes [42-45]. Guochao Li [46,47] and Radzevich [48, 49] proposed to use vector algebra for determining the shape of a second-order tool along the normals to the helical surface with minimal curvature. Semenchenko [50], Grechishnikov [51] and Rodin [52] were among the first to develop such an approach, based on the presence of a common normal between the machined surface and the cutting surface of the grinding wheel, known as the second condition of shaping, and to apply it to machining of the helical groove. Karpuschewski et al. [53] proposed a method for determining the position of the grinding wheel of 1A1 type relative to the workpiece. The mathematical model of Karpuschewski et al. allows to uniquely set the position of the grinding wheel via the four key parameters such as movements along two axes and the angles of rotation of the wheel around these axes. Wei Ji and Lihui b Wang developed an extended numerical model of determining the shape of the grinding wheel while machining helical grooves using circular projections, which is based on angular positioning on the radial section on the grinding wheel [54].

Grooves of a solid ceramic mills with a negative geometry of the front surface have points with intermittent changes in the positions of the normals along the profile in the cross section. This complicates profiling of the grinding wheel using the envelope method and limits the validity range of numerical methods. No analytical solution to the problem of profiling of the grinding wheel for a helical groove with a sharp drop in the curvature radius exists at the present time.

In this paper, the following tasks have been accomplished:

The key features of the design of solid ceramic mills have been analyzed;

Initial setting parameters for positioning of the axis of the grinding wheel relative to the workpiece have been identified;
A new mathematical model of the dependence of the shape of the grinding wheel; A new approach to determine the profile of the grinding wheel using the analytical method with the increased accuracy due to the exclusion of discontinuities at points with sharp changes in curvature has been developed; The efficiency and performance of the newly developed model and approach to the design of the grinding wheel have been thoroughly evaluated. The key advantage of the new mathematical model and approach over the existing ones is their ability to reveal new functional relationships and new key parameters controlling forming that can be used to improve the design of ceramic mills. Other advantage of the aforementioned model and approach is the ability to determine the shape of the grinding wheel based on setting conditions with sudden jump-like changes in the curvature radius that cannot be done by the existing numerical and analytical models. The developed mathematical model is easy to use and the amount of analytical transformations and calculations needed to execute the model and, hence, computational costs, are greatly reduced compared to widely used numerical methods of circular projections and combined sections. The developed model is more universal compared to competitors and allows identifying new functional relationships between the setting parameters of the grinding wheel and the shape of the helical groove without developing numerical algorithms for each specific case.

2. Results and Discussion

2.1. Analysis of surfaces of solid ceramic mill being machined
The primary reason for the failure of solid ceramic mills is the low strength. The helical surface of the cutting part, passing from the cylindrical periphery to the rake surface, has a uniform load distribution without stress concentrators on the toroidal section of the cutting surface (see Fig.1). Changes in the rake, clearance and wedge angle along the profile on the toroidal section affect the distribution of cutting forces and residual stresses in the cutting material. The geometric parameters of the toroidal part are controlled by the helical groove profile. The solid ceramic mill has negative rake surface.

The front surface of a solid ceramic milling cutter is formed in a radial section based on the recommended negative values of the rake angle. The profile of the front surface \( F_{pp1}(X) \) and the back surface \( F_{pp1}(G) \) in the XOY coordinate system is represented by dependences (1), based on which the helical front surface with a step \( T \) is expressed by equations (2):

\[
F_{pp1}(X) = b(y) - \sqrt{2 \cdot a(y) \cdot X - X^2 + R_{pp} - a(y)^2};
\]

\[
F_{pp1}(G) = b_1 - \sqrt{2 \cdot a_1 \cdot G - G^2 + R_{pp} - a_1^2}
\]

\[
F_{pp}(X, v) = \begin{cases} 
X \cdot \cos(v) - \sin(v) \cdot \left( b(y) - \sqrt{R_{pp}^2 - X^2 + 2 \cdot a(y) \cdot X - a(y)^2} \right) \\
\cos(v) \cdot \left( b - \sqrt{R_{pp}^2 - X^2 + 2 \cdot a(y) \cdot X - a(y)^2} + X \cdot \sin(v) \right) \\
\left( \frac{T}{2\pi} \right) \cdot v + L_z
\end{cases}
\]

\[
F_{pp}(G, v) = \begin{cases} 
G \cdot \cos(v) - \sin(v) \cdot \left( b_1 - \sqrt{2 \cdot a_1 \cdot G - G^2 + R_{pp} - a_1^2} \right) \\
\cos(v) \cdot \left( b_1 - \sqrt{2 \cdot a_1 \cdot G - G^2 + R_{pp} - a_1^2} + G \cdot \sin(v) \right) \\
\left( \frac{T}{2\pi} \right) \cdot v + L_z
\end{cases}
\]
Figure 1. Main geometrical parameters of toroid-shaped solid ceramic end mill.

2.2. Mathematical model of the position of the grinding wheel relative to the machined surface

The coordinate system of the grinding wheel $O_{Xw}Y_{w}Z_{w}$ is fixed to the grinding wheel so that the axis of the wheel corresponds to the axis $OZ_{w}$, and in the initial position is aligned with the tool coordinate system $OXYZ$ (Fig. 2). The position of the grinding wheel relative to the ceramic mill is controlled by three parameters: the distance between axes $A$, which is determined by the radii of the core of the mill and the grinding wheel, the angle of intersection of the axes $\varepsilon$ and the position $L_{z}$ of the axis of the grinding wheel relative to the initial profile of the mill groove. Change in the distance $L_{z}$ allows varying the position of the maximum diameter of the grinding wheel profile along the axis $OZ_{w}$.

Figure 2. Scim of degerming grinding weal profile.
The location of the grinding wheel relative to the helical surfaces of the back and the front surface of the cutter is described by the following parametric relationships:

\[
F_r(x, y) = \begin{cases}
\cos(\Psi) \cos(y) \sin(\psi) \left( X - \frac{R_p F_w X}{2} + 2 a \cos(\Psi) \frac{x}{2} \right) - \frac{R_p F_w X}{2} \cos(\Psi) \\
\cos(\Psi) \cos(y) \sin(\psi) \left( X - \frac{R_p F_w X}{2} + 2 a \cos(\Psi) \frac{x}{2} \right) - \frac{R_p F_w X}{2} \cos(\Psi) \\
\cos(\Psi) \cos(y) \sin(\psi) \left( X - \frac{R_p F_w X}{2} + 2 a \cos(\Psi) \frac{x}{2} \right) - \frac{R_p F_w X}{2} \cos(\Psi)
\end{cases}
\]

2.3 Search for a mathematical model determining the profile of the grinding wheel

The profile of the grinding wheel is the envelope of the profiles of the helical front surface Zk0 (X, \Psi), Yk0 (C, \Psi) and the back surface Zk (G, \Psi), Yk (G, \Psi) in the axial sections of the grinding wheel OWyZw in the plane OXwYwZw.

\[
F_{w}(X, y) = -\cos(\Psi) \cos(x) \sin(y) \left( \frac{R_p F_w X}{2} - \frac{R_p F_w X}{2} \right) - X \cos(y) - \frac{R_p F_w X}{2} \cos(\Psi) \left( \frac{a}{2} - X \sin(y) \right) - \frac{R_p F_w X}{2}
\]

The solution of the aforementioned equation has been performed using the Newton method (see Figs 3 and 4).

![Graph 3](image1.png)  \quad ![Graph 4](image2.png)

The screw parameter \( v_t \), defining the profile of the screw groove \( F_{w}(X, v_t) \), \( F_w(G, v_t) \) the envelope of which determines the shape of the grinding wheel with improved properties for machining a helical groove.

\[
v_t(X) = \frac{v_p R_p + \cos(\Psi) \cos(x) \sin(y) \sin(\psi)}{\cos(\Psi) \cos(x) \sin(y) \sin(\psi) - \frac{a}{2} - X \sin(y)}
\]

After the substitution of the obtained screw parameter \( v_t \) into the contact equation of the screw surface, we obtain the parametric equations \( F_{w}(X, v_t) \) \( F_w(G, v_t) \). By varying the rotation angle of the axial section of the grinding wheel \( \Psi \) we determine the set of shape-forming profiles of the screw surface \( F_{w}(X, v_t) \), \( F_w(G, v_t) \), the envelope of which determines the shape of the grinding wheel with improved properties for machining a helical groove (Fig. 5).
Figure 5 Scheme of determining the profile of a grinding wheel implemented in the MathCad environment.

\[
F_{w_1}(X, v_t) = \cos(\Psi) \cdot \left( \cos(v) \cdot \left( b(y) - \sqrt{R_{pp}^2 - X^2 + 2 \cdot a(y) \cdot X - a(y)^2} \right) - A + X \cdot \sin(v) \right) - \sin(\Psi) \cdot (\cos(v) \cdot (\sin(v) \cdot (b(y) - \sqrt{R_{pp}^2 - X^2 + 2 \cdot a(y) \cdot X - a(y)^2} - X \cos(v)) + \sin(\xi) \cdot (L_z + \frac{v \cdot \pi}{2})) \right)
\]  

(7)

\[
F_{w_2}(X, v_t) = \cos(\xi) \cdot \left( L_z + \frac{v \cdot \pi}{2} \right) \cdot v - \sin(\xi) \left( \sin(v) \left( b(y) - \sqrt{R_{pp}^2 - X^2 + 2 \cdot a(y) \cdot X - a(y)^2} \right) - X \cos(v) \right)
\]  

(8)

2.4 Discussion on the mathematical model for determining the profile of the grinding wheel

It is clear that the use of a special grinding wheel can significantly increase the length of the contact line between the wheel and the helical surface. This will provide an improvement in the depth of cutting along the grinding wheel profile.

To verify the accuracy of the proposed mathematical model, the obtained profile \( F_{w_1}(X, v_t) \) was specified in the T-Flex CAD system. An array of model grinding wheels with the profile \( F_{w_1}(X, v_t) \) was formed in accordance with the forming conditions and shapes of the model grinding wheels in the cross section of the model grinding wheel. The controllable profile of the helical groove in the cross section represents the envelope of profiles of these grinding wheels. It was found that maximum deviation of less than 0.01 mm has been achieved after the fifth iteration of the Newton method (Fig. 6-7).
3. Conclusions
Based on the shaping theory, analytical geometry, linear and vector algebra, the cutting theory and some knowledge of computer graphics, a new approach to the design of grinding wheels under rational installation conditions was developed. The inverse profiling problem solved in T-Flex CAD proves evidence of the viability of the newly developed approach and its applicability to the design of grinding wheels for machining solid ceramic mills.

The present study leads us to the following conclusions:
1. New design of the grinding wheel allows to increase the length of the contact line between the grinding wheel and the machined helical surface, which provide a more uniform distribution of the cutting depth along the profile of the wheel, which in turn increase the cutting parameters without compromising the quality of the surface being machined.
2. The developed mathematical model provides an analytical description of shaping, which may be an important instrument of finding new dependencies in shaping of the screw surfaces of solid ceramic mills.
3. The precise determination of the shape of the forming profiles depends on the screw parameter, groove profile parameter in the cross section, set conditions such as A, Eps, H, the radius of the grinding wheel and the angle of inclination of the helical groove.
4. It was found that the greatest influence on the groove processing is played by the ratio of the angle of inclination of the helical groove and the angle of installation of the grinding wheel relative to the workpiece and also by the angle of intersection of the axes of the grinding wheel and solid ceramic mill.
5. It was found that the main contribution to the accuracy of forming the profile of the front surface is made by the profile section of the grinding wheel with the length of less than 30%.

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