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Influence of the shape of the toroidal flank surface on the cutting wedge angles and mechanical stresses along the drill cutting edge

Petr Pivkin [a, *], ***Artem Ershov*** [b], ***Nikita Mironov*** [c], ***Alexey Nadykto*** [d]

Moscow State University of Technology “STANKIN”, 3a Vadkovski Lane., Moscow, 127055, Russian Federation

[a] https://orcid.org/0000-0002-7547-4652, PMPivkin@gmail.com; [b] https://orcid.org/0000-0003-3966-7032, a.ershov@stankin.ru;
[c] https://orcid.org/0009-0002-4205-6996, dzr1380im@gmail.com; [d] https://orcid.org/0000-0003-3652-7421, a.nadykto@stankin.ru

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ABSTRACT

Introduction. Drilling holes with standard tolerance varying from *IT8* to *IT12* is widely used in industrial production. However, at present time, there are neither comprehensive studies, nor scientifically justified recommendations for the rational choice of the geometry of the cutting part of drills with a toroidal flank surface. Therefore, the computer-aided design (*CAD*) of new drill designs with a toroidal flank surface and finite element modeling (*FEM*) of the stressed state of its cutting part are important tasks. **The purpose of the work** is reducing both the range of change in the rake angle and the wedge angle of the cutting wedge along the cutting edge from the periphery to the center and the equivalent stresses in the cutting wedge. In this paper we investigate changes in the rake and wedge angles of the cutting wedge depending on the radius of the generatrix line of the toroidal flank surface as well as changes in equivalent stresses in the cutting wedge, which depend on changes in the radius of the generatrix line of the toroidal flank surface. **The research methods** include the fundamentals of the theory of cutting, *CAD* methods, and the *FEM*, which was applied in this work to new drill designs. **Results and discussion.** It is found that the range of changes in the rake angle and the wedge angle of the cutting wedge of the drill decreases compared to the standard design with decreasing radius of the generatrix line of the flank surface. A *CAD* system for drills with a toroidal flank surface is developed. As a result, the range of changes in the rake angle along the cutting edge decreased by 86 % for a drill with a minimum radius of the generatrix line of the toroidal surface compared to that with the conical flank surface, the range of the wedge angle of the cutting wedge decreased by 56 %, and the maximum equivalent stresses decreased by 2.13 times. It is also important to note that in this case, the wedge angle is close to constant for half of the drill tooth. These indicators exceed those for existing designs of the twist drills that indicate the key achievement of this paper.

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Introduction

Hole drilling is widely used in most essential industries. The twist drill is most common drill design. The advantages of twist drills include good removal of chips from the hole being machined, simplicity of design and, therefore, low labor costs of sharpening and high positioning accuracy in the hole due to the presence of calibration tapes [1]. The main cutting edges of the drill are located on a conical cutting part with an angle of 2φ. Angle 2φ acts as a cutting edge angle and varies from 70° to 135° [2].

*** Corresponding author**
Pivkin Petr M., Ph.D. (Engineering), Associate Professor
Moscow State University of Technology “STANKIN”,
3a Vadkovsky Lane,
127055, Moscow, Russian Federation
Tel.: +7 (903) 231-66-80, **e-mail:** PMPivkin@gmail.com

At the same time, there are a number of disadvantages in the design of twist drills: a decrease in the rake angle along the cutting edge (*CE*) up to negative when approaching the center; rake angles at the periphery are too large. To reduce and, if possible, completely eliminate these disadvantages, a design solution for a drill with a gash in the center has been proposed. The gash is made either to reduce the area with negative rake angle values [3] or with a positive rake angle along the entire gash [4]. Also in tool production, there are solutions with the gash along the entire cutting edge [5]. However, the implementation of such a design is possible only at small rake angles, which can lead to increased cutting forces and accelerated drill wear [6].

To reduce the rake angle at the periphery, a drill design with two conical sections with different generatrix angles φ is used. At the periphery, the cone has a smaller angle, for example, for 2φ it is equal to 118°, the second conical section has an angle of 70° [7]. As a result, for this drill design, the rake angle at the periphery can be reduced by 7–8°, which will relieve the load on the areas most susceptible to wear. As a result of reducing the angle φ, the chip thickness decreases, the chips width increases and heat dissipation drastically improves, which allows increasing the tool life by more than 3 times [1]. However, this design has a flaw in the form of an uneven change in the width of the cut layer and the formation of a stress concentrator in the transition zone. These problems can be resolved by using a twist drill with a toroidal flank surface instead of a conical one. 3D analysis algorithms provide more complete and accurate rake angle data along the drill cutting edge compared to analytical models [8]. Currently, modeling of specialized automated algorithms is used to estimate the geometric parameters of various classes of cutting tools. Therefore, the rationale for the choice of geometric parameters of the class of drills being considered in this work is formed based on the *CAD* new designs of drills with a toroidal flank surface. In addition, some critically important operational parameters of drills, such as stresses in the cutting wedge, which are difficult to obtain experimentally, can be easily predicted using the finite element method (*FEM*) [9–11]. When computer modeling metalworking processes, two main problems arise while developing models using *FEM*. The first is the material model, which should adequately reflect the deformation under loading with different intensities and directions of stresses applied to the structure in a wide range of typical operating conditions and take into account the nature of internal stress in the structure [12–14]. The second is related to the modeling and numerical implementation of changes in the configuration of the cutting part during the shaping process depending on the state of the technological system [15, 16]. Computer modeling of machining processes is complicated due to multiple areas of contact between the cutting wedge and the material being processed [17, 18]. These problems cannot be solved using standard *FEM* [19]. Currently, many studies focused at solving these problems regularly appear in the computer modeling of cutting processes [20, 21]. Although many studies have been conducted on the use of *FEM* to predict operational parameters in machining a wide range of workpiece materials [22], currently there does not exist a unified *FEM* model that could be used for toroidal flank drills.

The literature review shows that although today there are several types of drill designs with a spherical or toroidal flank surface, however there are neither its comprehensive studies nor recommendations on its cutting part geometry and parameters used to assess its efficiency. In addition, no *CAD* systems for drills with a toroidal flank surface and established mechanisms for computer modeling of the stress state of the cutting part are available at the present time. In this regard, the **main purposes of this study** are reducing the range of changes in the rake angle and the sharpening angle of the cutting wedge along the cutting edge from the periphery to the center, and lowering the equivalent stresses in the cutting wedge through the use of drills with a toroidal flank surface with rational geometric parameters.

To achieve these purposes, the following tasks should be solved:

1) to develop a *CAD* system for drills with a toroidal flank surface;

2) to investigate changes in the value of the rake angle and the sharpening angle of the cutting wedge depending on the radius of the generatrix of the toroidal flank surface;

3) to study changes in equivalent stresses in the cutting wedge depending on changes in the radius of the generatrix of the toroidal flank surface.

Methods

Based on the study of the geometric and operational drill parameters, a *CAD* system for a wide range of designs was developed. The *CAD* algorithm includes design methods for both standard designs and advanced ones with a toroidal flank surface, separated into two different subsystems. The initial parameters for drill design are shown in table 1.

Table 1

Initial parameters for drill design

Parameter identifier	Parameter name
R	Drill radius
d_s	Core diameter
α	Clearance angle
γ	Rake angle
b	Wedge angle
γ_k	Flute profile rake angle
ω	Helix angle
R_t	Radius of the generatrix of the toroidal flank surface
φ	Point angle
κ	Displacement of the generatrix of the toroidal flank surface relative to the drill axis
η	The angle between the point of tangency of the circle defining the toroidal generatrix and the point of intersection of the circle with the periphery
L	Drill length
l_r	Drill body
f	Margin
ν	The value that specifies the point of contact of the toroidal generatrix relative to the drill axis
r	Radius of the back profile of the helical flute of the drill
r_{p}	The radius of the circle that specifies the control section that determines the values of the drill clearance angle
$R_{\min}$	Minimum radius of the toroidal flank surface of the drill
l_t	The length of the main cutting edge at the reference point, measured from the starting position. The initial position of the edge is set at the intersection point of the main and transverse cutting edges
l	Total length of main cutting edge

Automated design of twist drills is based on initial data that determines a set of technological, physical, mechanical and operational indicators and its relationships with construction feature as the basis of the design methodology. Automated design of drills is carried out via a sequential methodology based on the impact of the most important elements and restrictions on the development of detailed engineering drawings. The creation of such a system plays an important role in the development of cutting tools and industrial *R&D*, which can greatly improve the efficiency of drill design and its quality, help designers of various scientific fields to use efficient technologies and methods to develop innovative design schemes greatly improving the efficiency of design and product development. To improve the efficiency of technological innovations, the key parameters such as rake angle changes and internal equivalent stresses in the cutting wedge of the drill, were analyzed in the first instance. In order to accomplish this task, certain restrictions were imposed on the design results in the form of recommended ranges and reference values of the key parameters. Analysis of the relationships between structural elements and geometric parameters of a twist drill with a toroidal flank surface was carried out with accounting for the workpiece and tool material, cutting conditions and interdependent design components. Since no formalized dependencies in analytical, numerical and algorithmic form between the parameters of the technological environment and the parameters of the drill exist at the present time, a comprehensive methodology for designing drills with a toroidal flank surface is proposed in this work for the first time. The comprehensive *CAD* methodology for the design of twist drills is based on classical approaches to drill design and is divided into sub-elements of modeling (fig. 1). The first design block includes a structural base of initial data in accordance with *GOST 17275-71* (R, ds, α, γk, ω, R_t, φ, κ, η, L, l_r, f, ν).

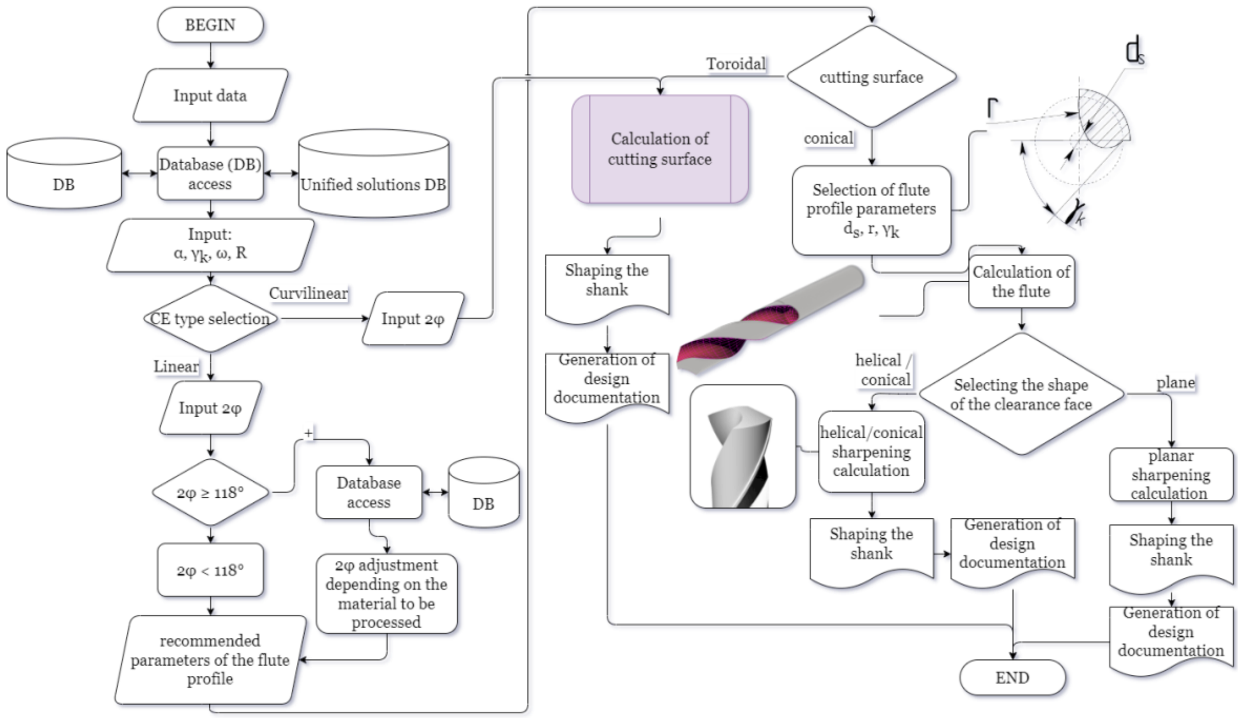


Fig. 1. Complex *CAD* block schematic diagram of twist drills

Depending on the shape of the cutting edge, the design methodology includes two groups of cutting edge designs. The system generates conditions for searching for a rational flute shape to form a straight cutting edge of a drill with a conical cutting surface [7] (fig. 2).

The definition of the helical projection of the cutting edge is described by the following equation:

$$\mathrm{Pr}_y = -RK\Xi_{ty}\cos\left(\frac{B+\tan\left|\sqrt{RK\Xi_{tx}{}^2+RK\Xi_{ty}{}^2}\right|}{\tan(\omega)\pi Dd}\right)+$$

$$+RK\Xi_{tx}\sin\left(\frac{B+\tan(\varphi)\left|\sqrt{RK\Xi_{tx}{}^2+RK\Xi_{ty}{}^2}\right|}{\tan(\omega)\pi\left|\sqrt{RK\Xi_{tx}{}^2+RK\Xi_{ty}{}^2}\right|}\right); \qquad (1)$$

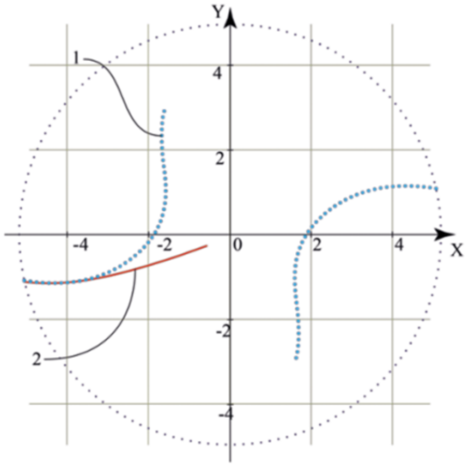


Fig. 2. Defining the profile of the spiral flute (*1*) and the profile element of flute on the rake surface (*2*)

$$\mathrm{Pr}_x = -RK\Xi_{tx}\cos\left(\frac{B+\tan(f)\left|\sqrt{RK\Xi_{tx}^{\ 2}+RK\Xi_{ty}^{\ 2}}\right|}{\tan(\omega)\pi\left|\sqrt{RK\Xi_{tx}^{\ 2}+RK\Xi_{ty}^{\ 2}}\right|}\right)-$$

$$-RK\Xi_{ty}\sin\left(\frac{B+\tan(f)\left|\sqrt{RK\Xi_{tx}^{\ 2}+RK\Xi_{ty}^{\ 2}}\right|}{\tan(\omega)\pi\left|\sqrt{RK\Xi_{tx}^{\ 2}+RK\Xi_{ty}^{\ 2}}\right|}\right). \quad (2)$$

The next stage of the design methodology consists of a modeling of the spiral flute and its corresponding cutting surface. Depending on the diameter of the drill, the shape of the flank surface is assigned and a *Boolean* operation is formed that defines the flank surface, while maintaining the shape of the cutting edge and the specified geometric parameters in the control sections (α, γ*k*, ω, φ, κ, ν). This design stage generates design documentation for traditional types of twist drill designs.

In this work, a new technique for *CAD* design of drills with a toroidal flank surface is proposed for the first time. The block schematic diagram of this technique and its detailed view are shown in fig. 3 in

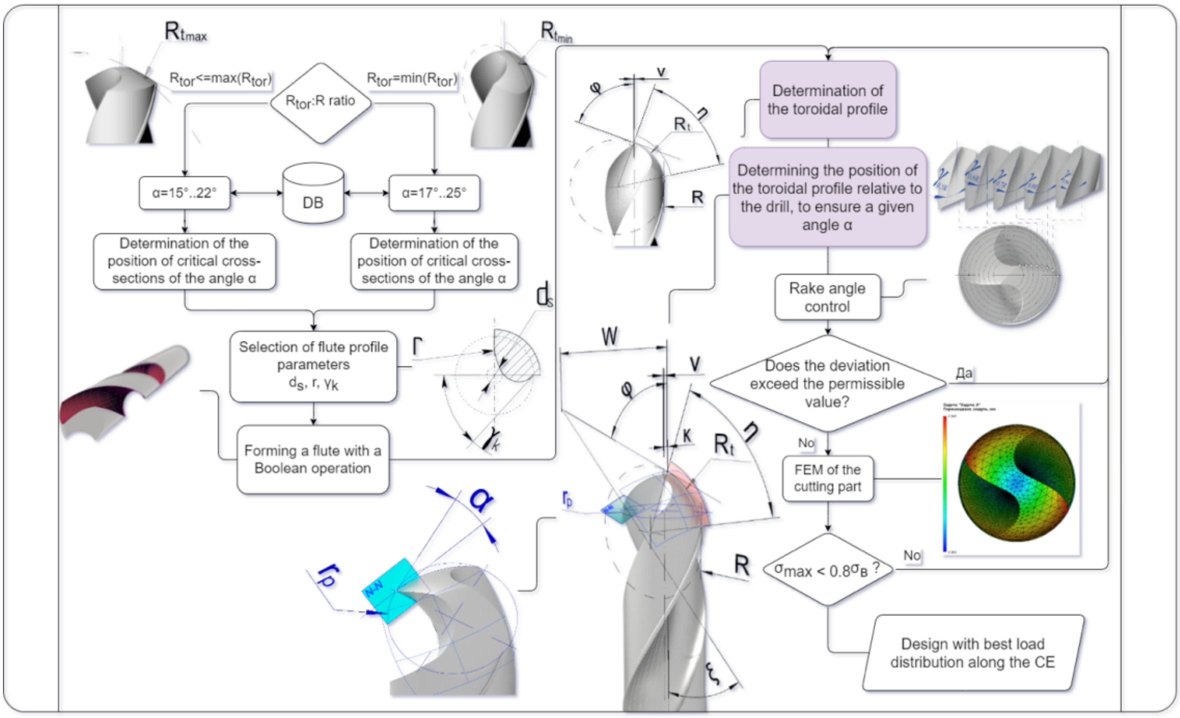


Fig. 3. CAD block schematic diagram of twist drills with toroidal flank surface

the form of a separate algorithm. The first stage of design is the formation of an actual set of initial data (*R*, *ds*, α, γ*k*, ω, *Rt*, φ, κ, η, *L*, *lr*, *f*, ν). The range for assigning the radius of the generatrix of the toroidal flank surface is consistent with the range for assigning the clearance angles and is compared with the established design database, which has a number of typical relationships between the geometric parameters of the drill. As a result, the algorithm determines the position of the section in which the value of the clearance angle α is set, or α is set manually. At the next stage, the profile of the chip flute is formed based on the specified values of the core diameter d_s, back radius *r* and radial rake angle γ_k. Based on the profile data of the spiral flute of a twist drill, a *Boolean* operation is generated that specifies a 3D model of the workpiece with a spiral flute.

An important stage in developing a drill model is the formation of the cutting surface. The geometric parameters that define the *Boolean* operation are presented in the second operator of the algorithm. The tangent to the generatrix of the generating surface imposes a strict limitation, ensuring constant contact of the generatrix of the entire set of drill structures at a certain angle in terms of φ. The center-to-center distance between the axis of the toroidal flank surface and the axis of the drill is specified by the parameter *v*. The angle between the point of contact of the circle defining the toroidal generatrix and the point of intersection of the circle with the periphery η regulates the possibility of assigning a parametric and structurally related angle to the radius of the flank surface of the generatrix in terms of φ with a known radius of the toroidal surface *Rt*.

The final task in developing a parametric model of a twist drill with a toroidal flank surface is the formation of the flank surface. The flank surface is a toroidal surface obtained by rotating the profile of the *Boolean* "subtraction" operation around an axis located at an angle ε to the drill axis and the position of the intersection point of these axes at a distance *W* from the drill axis. Moreover, the angle between the tangent to the flank surface and the tangent at a given point on the cutting edge of the drill with radius r_p is the clearance angle α.

A comprehensive *CAD* methodology allows producing both the most common and specialized designs of twist drills (fig. 4). Based on the work of *CAD* and the resulting designs with a toroidal flank surface, a comprehensive study of the distribution of the rake angle along the cutting edge, deformations and stress state using the finite element method along the cutting edge for structures with different types of sharpening

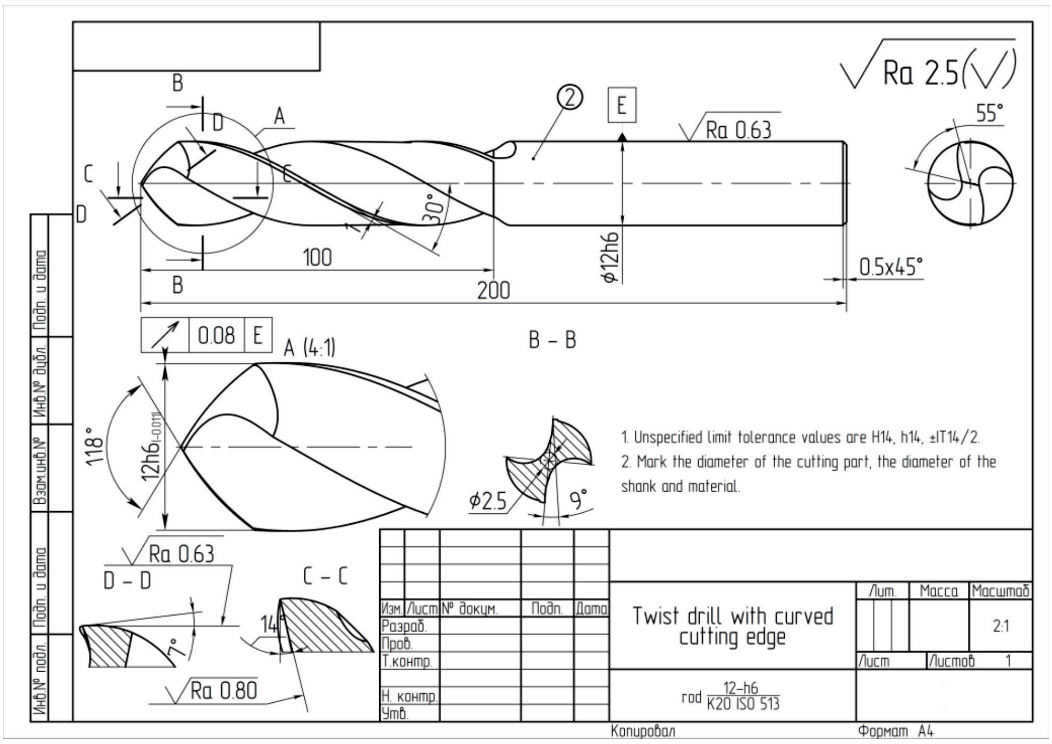


Fig. 4. Technical drawing of a twist drill with toroidal flank surface

of the flank surface: conical and toroidal with different radii of the generatrix of the toroidal surface R_t ($R_{t\ \min}$, 1.25 R, 2.5 R) was carried out. The radius of the toroidal flank surface varied from 2.5 R (the drill design is comparable in geometry to a drill with a conical sharpening) to the minimum possible radius of the generatrix of the toroidal flank surface $R_{t\ min}$. The minimum radius of the flank surface generatrix $R_{t\ min}$ was determined by the following equation:

$$R_{t\ \min} = \frac{R\,\mathrm{ctan}(\varphi / 1)}{\sin(\varphi)}. \qquad (3)$$

The investigation of geometric parameters along the cutting edge was carried out by determining the angle between the tangent to the rake (flank) surface at the control point and the perpendicular (tangent) to the flank surface at the control point (fig. 5).

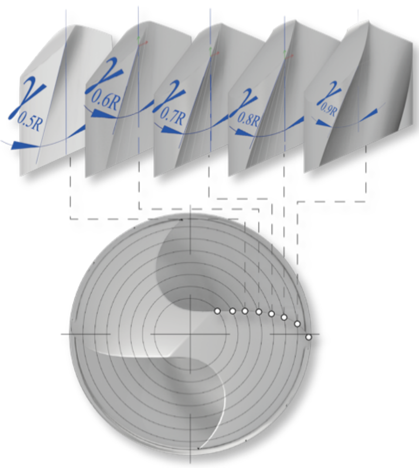


Fig. 5. Defining the rake angle on a drill with the toroidal flank surface

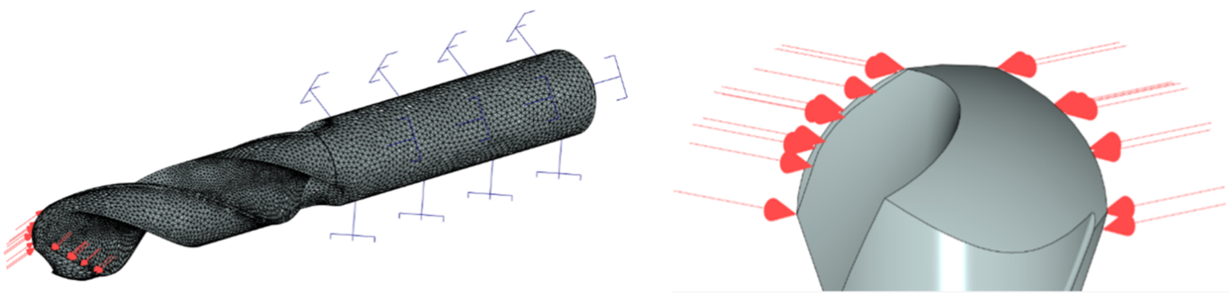
Analysis of the drill-to-workpiece contact zones was a major aspect for determining the rake height directly affected by the resulting mechanical loads in the *SolidWorks Simulation CAE* system (fig. 6). Mechanical forces were applied to this region in *FEM* simulations. Therefore, the load in this analysis was applied at an angle that is set tangent to the trajectory of the cutting wedge in the zone of feed per revolution *f* (0.2 mm/rev). The zone of cutting forces application was reshaped depending on the width of the cut layer at different radii of curvature of the cutting edge at a constant feed. The tool was fixed along a cylindrical surface.

The minimum mesh element size should be at least three times smaller than the chip thickness to simulate chip formation that corresponds to a very fine local mesh.

Since the shape of the axial section of the drill varies in the work, the shape of the uncut chip also changes. Therefore, to set the loading zone, it is important to analyze the cut layer with one constant feed ($\boldsymbol{S}$ = 0.2 mm/rev) for different profile shapes of the producing surfaces (table 2).

In the obtained diagrams, a significant decrease in the uncut chip at the periphery is observed with a decrease in the radius of curvature of the generatrix of the flank surface, which indicates a decrease in the forces acting on the cutting edge and the formation of more favorable conditions for the cutting process.

In this work, to carry out *FEM*, the model mesh was three-dimensional polyhedral – tetrahedrons. While such mesh elements are capable of providing a high degree of adaptation to the complex geometry of the cutting part of a drill with a toroidal flank surface, its use is associated with high computational complexity of the calculation. Also, to obtain reliable results, it is necessary that the size of the mesh elements more than three times smaller than the thickness of the chips being removed. Due to these limitations, the mesh size was chosen to be 0.02 mm in order to obtain reliable results of stresses on the cutting part of various drill designs (fig. 7).

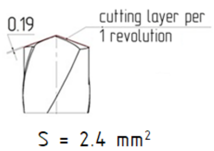
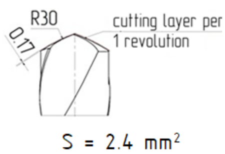
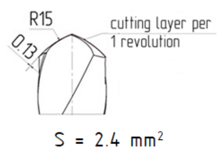
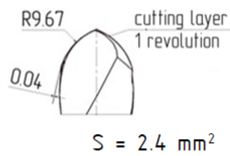


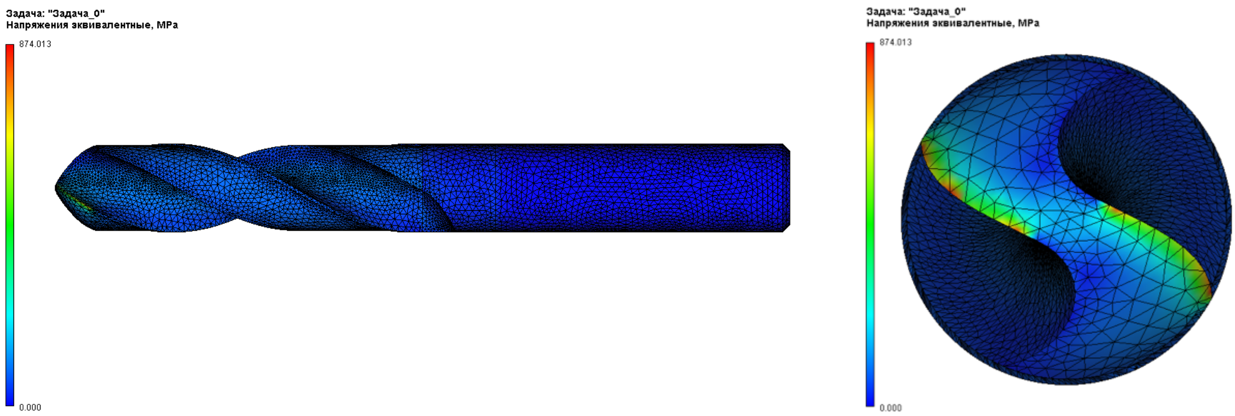
a *b*

Fig. 6. Model of a drill with the toroidal flank surface in the *SolidWorks Simulation CAE* system:
a – isometric view of the model with a mesh; *b* – side view of applied loads

Table 2

Comparison of the shape of the cut layer using twist drills with different parameters of the flank surface

Parameter	Conical flank surface	Toroidal flank surface (2.5 *R*)	Toroidal flank surface (1.25 *R*)	Toroidal flank surface ($R_{t\,min}$)
Width of uncut chip on periphery	$t = 0.19$ mm	$t = 0.17$ mm	$t = 0.13$ mm	$t = 0.04$mm
Diagram of uncut chip				



a *b*

Fig. 7. Epure of equivalent stresses of a drill with a toroidal flank surface:
a – side view; *b* – end view

Hard alloy *VK6* (*WC* 94 %-*Co* 6 %) was chosen as the material of the cutting tool, due to its effective use in processing materials in which abrasive wear predominates, such as cast iron. The physical and mechanical properties of the *VK6* material for creating a material model are shown in table 3.

After solving the problem, diagrams of equivalent stresses and displacements of drills with conical and toroidal sharpening of the flank surface were plotted.

Table 3

Physical and mechanical properties of hard alloy

Property	Value
Bending strength, MPa	≥ 1,500
Compressive resistance, MPa	≥ 4,300
Material density, g/cm^3	≥ 14.6
Hardness of material *HRA*	≥ 88.5

Results and discussion

Using the method described in the last paragraph, we obtained control measurements of the rake (fig. 8, *a*) and clearance angles (fig. 8, *b*) for 4 designs of twist drills – one design with a conical sharpening of the flank surface and three designs with a toroidal sharpening of the flank surface with varying the radius of the toroidal generatrix surface R_t ($R_{t\,\min}$, 1.25 *R*, 2.5 *R*). The initial values of the angles for toroidal sharpening of the flank surface are: rake angle $\gamma = 30°$, $\gamma_N = 25°$, when moving to a gash $\gamma_p = 2°$, clearance angle $\alpha = 8°$, $\alpha_N = 8°$, °, at transition to gash $\alpha_p = 22°$.

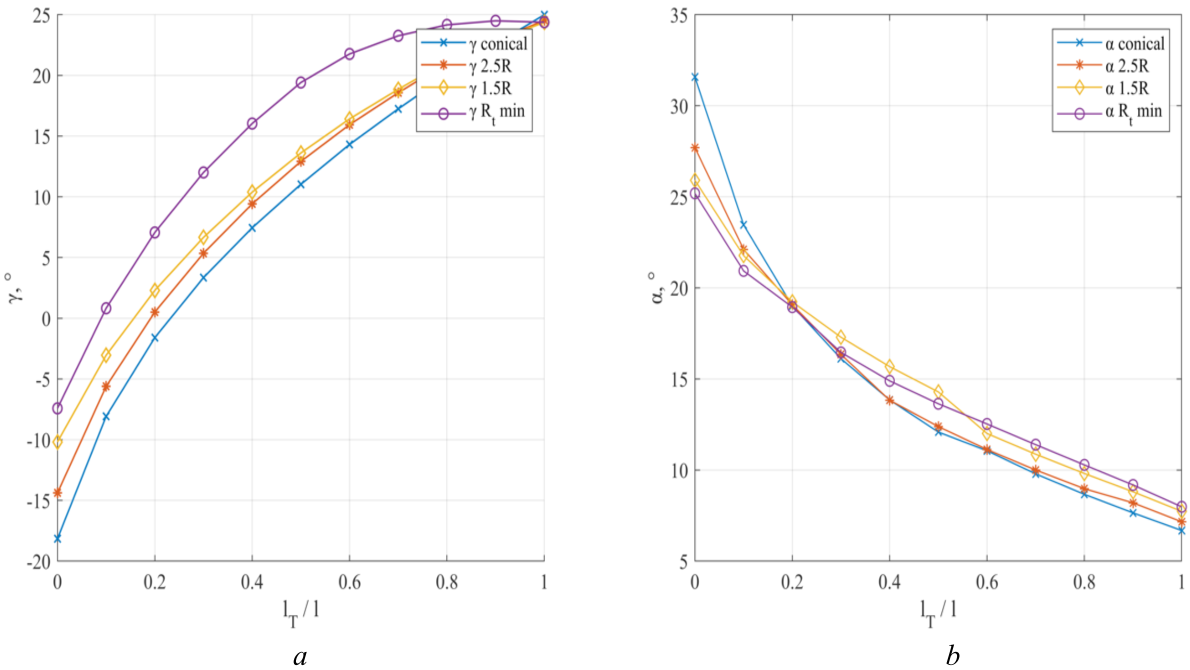


Fig. 8. Graphs of the dependence of the rake (*a*) and clearance (*b*) angles of various drill designs on the ratio of the length of the main cutting edge at the measurement point from the initial position, to the total length of the main cutting edge

Based on the analysis of the graphs, it is found that drills with toroidal sharpening of the flank surfaces have a more uniform decrease in the rake angle from the periphery to the center. The nature of the change in the front and clearance angles of drills with toroidal sharpening of the rear surface is identical to the nature of the change in the geometric parameters of drills with conical sharpening. The rake angle γ takes on the greatest values, and the clearance angle α is the smallest at the periphery of the drill. The range of variation of the rake angle decreased from [−18°; 25°] to [2°; 25°], which indicates a decrease in range by 86 %. With a decrease in the radius of the generatrix of the rear toroidal surface, a decrease in the intensity of a decrease in the front angle and an increase in the rear angle are revealed. This tendency makes the change in the sharpening angle of the cutting wedge from the periphery to the center more uniform. The range of changes in the sharpening angle of the cutting wedge decrease from [58°; 77°] to [56°; 68°], which indicates a decrease in range by 56 %. The design of drills with sharpening of the flank surface with a minimum radius of the generatrix has the best distribution of the rake angle and the rake angle has a positive value along almost the entire cutting edge. This will allow the use of such drill designs without additional sharpening in the center with performance indicators comparable to those of drills with sharpening in the center.

A graph of the dependence of the sharpening angle of the cutting wedge β on the ratio of the length of the main wedge at the control point, measured from the initial position, to the total length of the main wedge is presented in fig. 9. According to the graph, it is found that the use of drills with sharpening of the flank surface with a minimum radius of the generative provides a uniform angle sharpening of the cutting wedge up to 0.45 of the length of the twist drill, precisely in the zone that is subjected to the most intense loading.

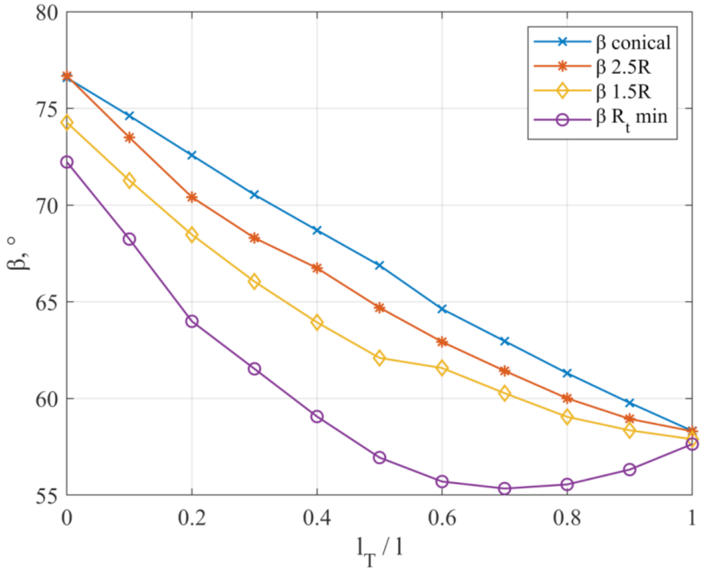


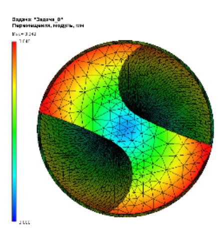
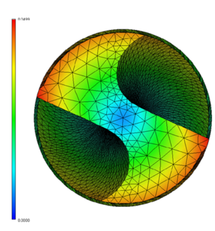
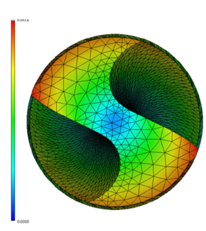
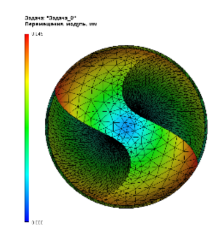
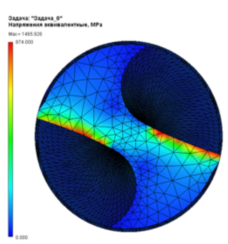
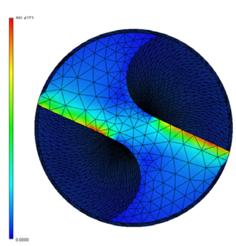
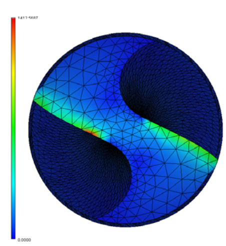
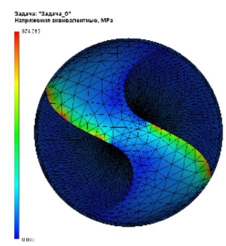
Fig. 9. Graph of the dependence of the cutting wedge taper angle β on the ratio of the length of the main cutting edge at the inspection point measured from the initial position, to the total length of the main cutting edge

For the diagram of equivalent stresses and displacements of drills with conical and toroidal sharpening of the rear surface, an *FEM* analysis is carried out using the above-mentioned method. The results of elastic displacements and equivalent stresses in the cutting wedge of drills with different sharpening shapes are shown in table 4.

Analysis of the obtained results shows that the maximum stress for a drill with a minimum radius of the generative of the flank surface is the minimum of all the drill designs being considered here, which indicates a more rational distribution of width of uncut chip and geometric parameters along the cutting edge. The cutting wedge along the cutting edge has a cross-sectional area that is closest to constant, which allows us to identify the best strength characteristics of a drill with a toroidal sharpening with a minimum radius of the generatrix $R_{t\ min}$, which forms the rear surface. The stresses at points of the cutting edge equidistant from each other are considered, and the angular values of the position of these points from the drill axis are measured according to the design method for drills with a toroidal flank surface. The results obtained are

Table 4

Results of an epure of the maximum equivalent stresses and displacements in the cutting wedge for drills with different parameters of the flank surface

Type of *FEM* analysis	Conical flank surface	Toroidal flank surface (2.5 *R*)	Toroidal flank surface (1.25 *R*)	Toroidal flank surface ($R_{t\ min}$)
Movements				
	max = 0.049 mm	max = 0.052 mm	max = 0.050 mm	max = 0.045 mm
Equivalent stresses				
	max = 1465.926 MPa	max = 1412.569 MPa	max = 991.473 MPa	max = 874.013 MPa

shown in table 5 and on its basis a graph of the dependence of stress on the angular position of the control point on the cutting edge in the instrumental coordinate system is plotted (fig. 10, 11).

It is found that in the case, when the radius of the generatrix of the flank surface reduces, the length of the cutting edge increases, which leads to an integral decrease in stresses in the cutting wedge along the entire cutting wedge and proves a more rational assignment of geometric parameters along the cutting edge.

Table 5

Results of an epure of equivalent stresses and displacements along the cutting edges of drills with different parameters of the flunk surface

Conical flank surface			Toroidal flank surface (2.5 *R*)			Toroidal flank surface (1.25 *R*)			Toroidal flank surface ($R_{t\,min}$)		
σ, MPa	Ψ,°	λ,°	σ, MPa	Ψ,°	λ,°	σ, MPa	Ψ,°	λ,°	σ, MPa	Ψ,°	λ,°
1064.85	29.0289	5.8	740.4581	32.0511	0.891	557.1906	36.3369	17.82	499.1	46.81	60
1039.035	27.825	3.8	741.7603	29.9989	0.956	558.1982	33.0369	10.63	462.4	40.6211	40.52
802.4772	25.7869	1.33	694.3632	27.3139	1.052	424.1168	29.4411	5.36	217.7	34.7439	24.7
681.772	22.1639	1.2	622.1755	23.2369	1.124	433.9531	24.7761	2.13	207.4	28.6361	5.26
595.8291	15.1731	2.33	585.3223	15.8989	1.112	722.0529	17.0239	2.09	390.2	20.065	0.75
460.658	0	4	458.2239	0	1.326	654.7368	0	1.016	226.3	0	1.5

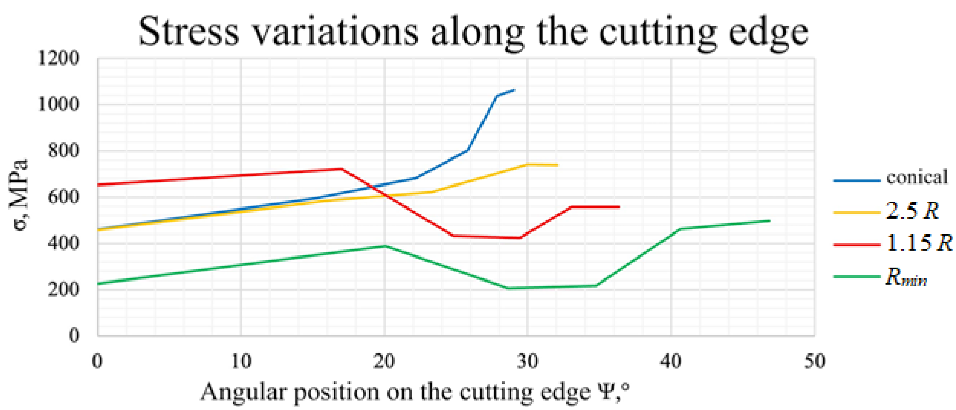


Fig. 10. Graph of variance in internal stresses of the drill structure relative to the angular position of the measurement point on the cutting edge

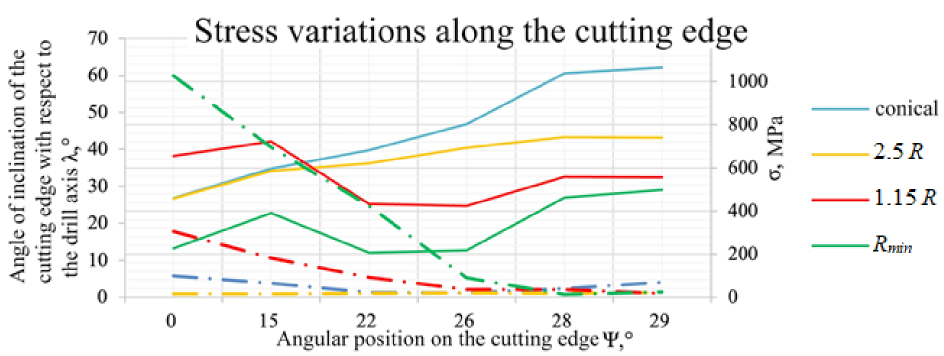


Fig. 11. Combined graph of the dependence of the cutting edge angle and equivalent stresses in the drill design on the angular position on the cutting edge

It is shown that the design of a drill with a cutting wedge part and a cutting edge with a large value λ can have both positive and negative effects on the tool life. With a short duration of such a section, the element of the cutting wedge acts as a stress concentrator and takes a significant part of the bending load, while in the case of a longer section with a smooth change in angle, the forces are evenly distributed over the cutting wedge. Therefore, later design can significantly increase the resistance to brittle fracture. This effect can be enhanced by the uniformity of cross-sectional area of the cutting wedge along the cutting edge. The established patterns serve as the basis for the design methodology for drills with a toroidal flank surface and as a prerequisite for the development of a comprehensive *CAD* for twist drills. This work is important for understanding the geometric design features of drills with a non-standard flank surface shape. After confirming the relevance of using drill designs with a new sharpening form, the logical development of this work would be revealing the analytical relationships between the shape of the cutting edges, the helical flute and the shape of the flank surface.

Conclusions

1. In this study, a comprehensive methodology for designing drills with a toroidal flank surface is proposed in this work for the first time, including the development of new designs of drills with a toroidal flank surface. The *CAD* algorithm for toroidal flank drills is discussed in detail when designing each functional surface in the solid-state modeling system.

2. A comprehensive study of the effect of changing the radius of the generatrix of the flunk surface on the value of the rake angles in order to identify the best geometric parameters of the tool on various designs of drills with a toroidal flank surface and its application field is carried out. It is pointed out that with a decrease in the radius of the generatrix of the flank surface, the range of changes in the rake angle and the sharpening angle of the cutting wedge decreases compared to the design of drills with conical sharpening of the flank surface. It is also found that a tool with a minimum permissible radius of the generative of the flank surface has the best distribution of rake angles and sharpening angles of the cutting wedge along the entire cutting edge. The range of variation of the rake angle decreased from [−18°; 25°] to [2°; 25°], which indicates a decrease in range by 86 %. The range of changes in the sharpening angle of the cutting wedge decrease from [58°; 77°] to [56°; 68°], which indicates a decrease in range by 56 %. Drills with such sharpening of the flank surface can be used without additional sharpening to the center, since the rake angle is in the positive range of values up to the section where the main cutting edge transitions into the chisel edge. It is proved that the sharpening angle of the cutting wedge has a value close to constant up to 0.45 ***lt***/l, while the range of the sharpening angle decreased from [58°; 68°] to [56°; 58°], which indicates an improvement in geometric parameters up to 5 times. These indicators exceed those for all the existing twist drill designs.

3. Based on *FEM*, it is shown that the equivalent stresses in the cutting wedge reduced from 4644.62 MPa to 2003.1 MPa due to the use of drills with a toroidal flank surface with a minimum generatrix radius, indicating a stress reduction by a factor of 2.31. At the same time, the maximum equivalent stresses decreased from 1064.85 MPa to 499.1 MPa , indicating a stress reduction by ~ 2.13 times.

References

1. Kozhevnikov D.V., Grechishnikov V.L., Kirsanov S.V., Kokarev V.I., Skhirtladze A.G. *Rezhushchii instrument* [Cutting tool]. Moscow, Mashinostroenie Publ., 2007. 528 p. ISBN 978-5-217-03373-7.

2. Semenchenko I.I., Matyushin V.M., Sakharov G.N. *Proektirovanie metallorezhushchikh instrumentov* [Design of cutting tools]. Moscow, Mashgiz Publ., 1963. 952 p.

3. Zeng T., Chen Z.C., Liu Z., Yi Z., Wang S. An applied explicit mathematical model of conical drill point geometry without flank rubbing. *The International Journal of Advanced Manufacturing Technology*, 2020, vol. 106 (9–10), pp. 3707–3720. DOI: 10.1007/s00170-019-04759-y.

4. Petukhov J.E., Vodovozov A.A. *Spiral'noe sverlo s krivolineinymi rezhushchimi kromkami* [Twist drill with curvilinear lip]. Patent RF, no. 2528593, 2014.

5. Yavuz M., Gökçe H., Çiftçi İ., Gökçe H., Yavaş Ç., Şeker U. Investigation of the effects of drill geometry on drilling performance and hole quality. *The International Journal of Advanced Manufacturing Technology*, 2020, vol. 106 (9–10), pp. 4623–4633. DOI: 10.1007/s00170-019-04843-3.

6. Abele E., Fujara M. Simulation-based twist drill design and geometry optimization. *CIRP Annals*, 2010, vol. 59 (1), pp. 145–150. DOI: 10.1016/j.cirp.2010.03.063.

7. Pirtini M., Lazoglu I. Forces and hole quality in drilling. *International Journal of Machine Tools and Manufacture*, 2005, vol. 45 (11), pp. 1271–1281. DOI: 10.1016/j.ijmachtools.2005.01.004.

8. Ren K., Ni J. Analyses of drill flute and cutting angles. *The International Journal of Advanced Manufacturing Technology*, 1999, vol. 15 (8), pp. 546–553. DOI: 10.1007/s001700050100.

9. Pivkin P.M., Grechishnikov V.A., Ershov A.A., Nadykto A.B. A new method for the precise determination of rational geometric parameters of the helical groove and cutting part of high-performance tri-flute. *Proceedings of SPIE*, 2020, vol. 11540, p. 1154014. DOI: 10.1117/12.2574392.

10. Grigor'ev S.N. Volosova M.A. Complex surface hardening of oxide-carbide ceramic cutting tools. *Russian Engineering Research*, 2005, vol. 25 (9), pp. 7–12.

11. Baumann A., Oezkaya E., Biermann D., Eberhard P. Geometry modifications of single-lip drills to improve cutting fluid flow. *The International Journal of Advanced Manufacturing Technology*, 2022, vol. 121 (3–4), pp. 1689–1695. DOI: 10.1007/s00170-022-09400-z.

12. Grigor'ev S.N., Myachenkov V.I., Kuzin V.V. Automated thermal-strength calculations of ceramic cutting plates. *Russian Engineering Research*, 2011, vol. 31 (11), pp. 1060–1066. DOI: 10.3103/S1068798X11110086.

13. Wang J., Zhang X., Fang F., Xu F., Chen R., Xue Z. Study on nano-cutting of brittle material by molecular dynamics using dynamic modeling. *Computational Materials Science*, 2020, vol. 183, pp. 109851. DOI: 10.1016/j.commatsci.2020.109851.

14. Chen D., Wu S., He Y., Luo Y., Wang X. A review of simulation and experiment research on cutting mechanism and cutting force in nanocutting process. *The International Journal of Advanced Manufacturing Technology*, 2022, vol. 121 (3–4), pp. 1533–1574. DOI: 10.1007/s00170-022-09051-0.

15. Yang D., Wei F., Wang W., Zhang Y., Zeng L. Finite element modelling and experimental validation of the graphite cutting process. *Processes*, 2023, vol. 11 (9), p. 2546. DOI: 10.3390/pr11092546.

16. Wang J., Fang F., Li L. Cutting of graphite at atomic and close-to-atomic scale using flexible enhanced molecular dynamics. *Nanomanufacturing and Metrology*, 2022, vol. 5 (3), pp. 240–249. DOI: 10.1007/s41871-022-00128-8.

17. Wang J., Fang F. Nanometric cutting mechanism of silicon carbide. *CIRP Annals*, 2021, vol. 70 (1), pp. 29–32. DOI: 10.1016/j.cirp.2021.04.068.

18. Lei X., Wang L., Shen B., Sun F., Zhang Z. Effect of boron-doped diamond interlayer on cutting performance of diamond coated micro drills for graphite machining. *Materials*, 2013, vol. 6 (8), pp. 3128–3138. DOI: 10.3390/ma6083128.

19. Agapiou J.S., DeVries M.F. On the determination of thermal phenomena during drilling. Part I. Analytical models of twist drill temperature distributions. *International Journal of Machine Tools and Manufacture*, 1990, vol. 30 (2), pp.203–215. DOI: 10.1016/0890-6955(90)90130-B.

20. Biermann D., Iovkov I., Blum H., Rademacher A., Taebi K., Suttmeier F.T., Klein N. Thermal aspects in deep hole drilling of aluminium cast alloy using twist drills and MQL. *Procedia CIRP*, 2012, vol. 3, pp. 245–250. DOI: 10.1016/j.procir.2012.07.043.

21. Pivkin P.M., Minin I.V., Volosova M.A., Romanov V.B., Nadykto A.B. Image processing of advance milling cutters to automate the measurement of the geometric parameters of the cutting edge on optical measuring systems. *SPIE Proceedings*, 2021, vol. 11914, p. 1191412. DOI: 10.1117/12.2605754.

22. Wang Q., Wang D., Fang Y. Research on chip mechanism of Inconel 718 with ultrasonic assisted drilling by step drill. *The International Journal of Advanced Manufacturing Technology*, 2023, vol. 126 (5–6), pp. 2579–2594. DOI: 10.1007/s00170-023-11212-8.

Conflicts of Interest

The authors declare no conflict of interest.

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