UDC 629.73.002
DOI: 10.15587/1729-4061.2022.254555

FORMING THE GEOMETRIC ACCURACY AND ROUGHNESS OF HOLES WHEN DRILLING AIRCRAFT STRUCTURES MADE FROM POLYMERIC COMPOSITE MATERIALS

Kateryna Maiorova
PhD, Head of Department*
Iurii Vorobiov
Corresponding author
Doctor of Technical Sciences, Professor*
E-mail: i.vorobiov@khai.edu
Oleksii Andrieiev
Doctor of Technical Sciences, Chief Engineer
Antonov Company
Tupolieva str., 1, Kyiv, Ukraine, 03062
Borys Lupkin
Doctor of Technical Sciences, Professor*
Valeriy Sikulskiy
Doctor of Technical Sciences, Professor*
*Department of Technology of Aircraft Manufacturing
National Aerospace University «Kharkiv Aviation Institute»
Chkalova str., 17, Kharkiv, Ukraine, 61070

The subject of this study is indicators of the quality, geometric accuracy, and roughness of holes in aviation structures (AS) made from polymeric composite materials (PCM) produced by drilling. The indicators of quality, geometric accuracy, and roughness of PCM holes were investigated by using kinematic hole drilling schemes and the creation of PCM chips. A kinematic scheme has been built of the cutting forces operating in PCM when drilling with the distribution of zones from 0° to 360°. Experimental studies on the establishment of characteristic shrinkage zones in the drilling of PCM, as well as their values, have been implemented. The methods used are the analysis of the quality indicators of PCM holes, and the method of expert assessments. The following results were obtained. Based on the analysis and synthesis, it was found that with incorrectly selected geometric parameters for drills involving the work accompanied by the wear of drills on the back surface, stratification, cracks, or chips of PCM may appear. It is shown that the decisive factor is a comprehensive assessment, which is determined not only by the quality, accuracy, and roughness but also by the condition of the holes at the input and output of the drill. Features and characteristic contact zones for PCM drilling were identified. It has been established that within the drill operating areas from 0° to 90° and from 180° to 270° the cutting forces are reduced while the indicators of surface quality, roughness, and geometric accuracy of a PCM hole are improved. In zones from 90° to 180° and from 270° to 360° – on the contrary, low quality of the machined surface is assumed. The calculation of the required cutting forces and calculation of the height of roughness of drilling holes in PCM have been proposed, taking into consideration the bearing of chips under the action of the wedge. The results of experimental studies on the establishment of characteristic shrinkage zones when drilling PCM confirmed the adequacy of the results of theoretical studies on the kinematic schemes of drill operation in PCM

Keywords: aviation structure, polymeric composite materials, drilling, hole roughness, geometric accuracy, hole shrinkage

Received date 07.03.2022
Accepted date 08.04.2022
Published date 28.04.2022

How to Cite: *Maiorova, K., Vorobiov, I., Andreev, O., Lupkin, B., Sikulskiy, V. (2022). Forming the geometric accuracy and roughness of holes when drilling aircraft structures made from polymeric composite materials. Eastern-European Journal of Enterprise Technologies, 2 (1 (116)), 71–80. doi: https://doi.org/10.15587/1729-4061.2022.254555*

1. Introduction

In the modern world, polymeric composite materials (PCM) replace metal ones due to their excellent properties such as high specific strength, which ensures reliability and low wear rate with an extension of the service life [1]. The accumulated experience of operating PCM in responsible highly loaded aircraft structures (AS) showed significant advantages compared to metal structures. These include a decrease in the mass of the structure by 30–50 %, a prolongation of the service life by 2–5 times, a decrease in the complexity of production, by 20–40 %, and in the material intensity of the structure to 50 % [1, 2]. In the Ukrainian aircraft industry, as regards the An-70 aircraft, the volume of applied PCM is up to 22 % of the mass of the airframe. The total volume of PCM in the Ukrainian aircraft An-148/158 and An-178 is 17 % of the mass of the airframe; applying them makes it possible to reduce the weight of the aircraft by 2550 kg [3].

Among the methods of cutting AS parts from PCM, the most common is mechanical blade machining, which produces a surface layer on parts made from PCM, which significantly affects their physical and mechanical properties. Heterogeneity of the structure and varying characteristics of the strength of the components of PCM contribute to the formation of microcracks and chips in the process of blade machining [4]. In the machining of PCM, it is necessary to use tools with special carbide and diamond coatings of the cutting edge of the tool [5].

One of the mass processes of mechanical blade treatment in the manufacture of AS parts from PCM is drilling, which accounts for 70...80 % of the total complexity of the machining process. The requirements for the accuracy of the holes of vital AS made from PCM are 7–8 qualifiers, and, for all others do, not exceed 11–12 qualifiers at the surface roughness parameter Rz≥20 μm. The quality of the holes along the input and output edges, the accuracy and cleanliness of the surface of the cylindrical part of the hole are extremely important in terms of reliability, durability, and performance of the structure.

It should be noted that the parameters of the process of drilling holes in PCM vary depending on the properties of the reinforcing material. Scientific experience related to this issue is associated with very contradictory information on the technology of drilling holes in PCM regarding cutting modes, technological transitions, geometric parameters of the cutting tool, etc. With incorrectly selected geometric parameters of drills and when operating a drill with wear on the back surface, stratification, cracks, or chips of PCM may appear, especially in the direction perpendicular to reinforcing fibers. The quality (purity) of the hole surface in PCM depends on the number of revolutions of the tool and the feed. When the feed is too high, the roughness of the hole increases because drills tend to pull the fibers instead of cutting them (fibers rupture occur). At high spindle speeds, the temperature in the cutting zone increases, and the connector is destroyed. First, the boundary layer «matrix – fiber» loosens, and then PCM completely collapses. There is also melting of the matrix, which leads to a decrease in roughness. However, if the fibers are extracted from the matrix, then this causes damage, thereby increasing the roughness.

Therefore, it is a relevant task to conduct a comprehensive study into the quality of holes in PCM, made by drilling, which is determined not only by the quality and roughness but also by the condition of the holes at the input and output of the drill.

2. Literature review and problem statement

An important role in ensuring the quality of the hole surface in PCM belongs to the stability and geometric shape of the cutting edges of the tool, as shown in [6]. According to work [7], the main defects arising in the machining of PCM are the cracking of a binder, stratification, pulling of fibers, non-cutting of fibers, thermal destruction of a binder, and loosening of fibers. Paper [8] experimentally proved the high strength of PCM based on organic reinforcing fibers such as Kevlar but which have fragility properties, which increases the risks of cracking, stratification, and thermal destruction. Typically, as shown in [9], at the input of the drill there are stratifications and rupture of PCM fibers, and, at output, there are additional stratifications and non-cutting of fibers. The cutting edge fragilely destroys the matrix (a binder) and cuts the reinforcing fibers. Work [10] proposes a methodology based on analytical modeling, which takes into consideration the properties of PCM with the subsequent optimization of the geometric shape of the cutting tool, a drill, but this is not confirmed by examples of implementation and practical introduction in production. It should be noted that if we are talking about connecting small thicknesses of PCM packages (up to 3 mm), then there is no need for drilling holes. Paper [11] shows the implementation of the connection of the package with a thickness of 1.5 mm and 2.4 mm without prior execution of holes in combined bags of aluminum alloys and carbon fiber by the pulsed setting of self-cut rivets with a special riveting tool. A special riveting tool can be a modern pneumatic pulse tool by the same authors [12]. Despite the actual practical significance of the hole-free technique of connecting packages made from PCM and combined packages, information on its use on thicker and other packages is absent and should be tackled in the future. Therefore, the industry continues to exploit the main trend in the search for new structural and technological solutions (STS) for AS made from PCM, which requires additional study of their machining modes (drilling, milling, sharpening, etc.). Work [13] experimentally investigated the influence of the geometry of the spiral drill and the parameters of the drilling process of the package of carbon fiber and aluminum alloys with a thickness of 3.6 mm. The determining parameters chosen for the study of this process were the feed speed, spindle speed, primary gap, front angle, rear angle, the angle of inclination of the screw groove, the angle of inclination of the transverse edge, and an angle at the top of the cutter. However, of the eight completed comprehensive experiments, only one with the best combination of drilling parameters, hole diameter accuracy, hole surface roughness was confirmed as adequate. From a practical point of view, such comprehensive research, in comparison with analytical modeling proposed in [10], is more reliable but expensive and requires special equipment. The authors of [14] compared the results of analytical modeling in ANSYS with field experiments to produce holes by drilling fiberglass. However, it should be noted that in the cited work the quality of the holes was estimated by establishing the dependences of the geometrical parameters of the holes and their location in samples on the resulting reduced strength of PCM along the hole. Despite the positive results reported in [14], they are insufficient to assess the quality of a hole according to such important parameters as the roughness and accuracy of the hole in AS made from PCM. According to the authors of [15], the proposed technique of electrical pulse drilling could solve the task of PCM machining (matrix cracking, stratification, and fiber breaks) and improve the accuracy and roughness of holes in AS made from PCM. This technique can be regarded as a new STS for drilling holes in PCM but there are no data on the non-cutting of fibers and stratification of PCM at the input and output of the hole. Obviously, the formation of uncut fibers and stratification of PCM is associated with its complex structure and depends on the variety of reinforcement schemes. In [16], this problem is solved using an example of drilling carbon fiber with a thickness of 8 mm using a drill with a new STS with the location of auxiliary cutting edges in parallel with the axis compared to the standard SECO SD290A-7.963. Owing to the new drill STS, high quality of the hole in PCM is ensured in terms of roughness and destruction along the hole. However, the relevant procedures and calculations are not given to confirm this STS; it, therefore, requires further research for various properties, reinforcement schemes, PCM thicknesses, etc. Thus, there are reasons to believe that the insufficient theoretical and practical certainty of the dependence of the parameters of the quality of the hole surface of a hole (accuracy and roughness) on the structure of PCM during drilling determines the need for comprehensive research in this area.

3. The aim and objectives of the study

The aim of our study is to ensure the specified quality, geometric accuracy, and roughness of a hole in AS made from PCM. This will make it possible to warrant high static strength, resource, reliability, and efficiency of assembling AS made from PCM.

To accomplish the aim, the following tasks have been set:

– to establish characteristic contact zones when drilling a hole in PCM, taking into consideration the kinematic scheme of contact of the drill with the PCM surface;

– to calculate the necessary efforts for the drilling process and roughness parameters when drilling PCM;

– to conduct experimental studies on shrinkage of the PCM hole in order to establish the characteristic zones.

4. The study materials and methods

4. 1. The study object and hypothesis

The object of our research is holes in aviation structures made of polymeric composite materials. The study is based on general hypotheses of machines and mechanisms theory.

The process of bladed circular machining of the inner surface of solid material with the removal of chips using a cutting tool, a drill, which executes rotational and translational movements relative to its axis, is called hole drilling.

The process of drilling and forming a hole in AS made from PCM is investigated by the kinematic method for determining the envelopes of a surface family.

The kinematic method for determining the envelopes in a family of surfaces involves the construction of a family of surfaces that are formed as a result of a certain movement of the predefined surface [17].

When the surface *D* moves and forms an envelope of the surface *I*, then the characteristic in a general form can be defined as a line at each point of which the vector of relative velocity is directed on the tangent to the surface *D* [18]. Analytically, this provision is recorded as follows:

$$\overline{N}\cdot\overline{V}=0. \tag{1}$$

That is, the scalar product of the normal vector $\overline{N}$ of the surface *D* and the vector $\overline{V}$ of the velocity of the relative movement of the surface *D* at the points of characteristic *E*, located on the surface *D*, should be zero. Consequently, the characteristic *E* depends not only on the shape and size of the surface *D* but also on the movements it executes. With different movements, the characteristic *E* can be determined based on the properties of partial movements. The movements of the surface of a part can be reduced to the instantaneous rectilinear-translational, rotating, or helical motion. Thus, if the arbitrary surface *D* executes translational motion, then the contact curve (characteristic *E*) is the geometric place of the points at this surface, for which the normal to the surface *D* is in the plane perpendicular to the axis of instantaneous translational motion.

4. 2. The study's subject

The subject of our study is the formation of geometric accuracy and roughness of drilling holes in aviation structures made of polymeric composite materials.

The formation of geometric accuracy and roughness of drilling holes in AS made from PCM is ensured by shaping the machining area of the part after removing the allowance from a workpiece. The allowance is removed in parts in the form of chips. The study into the formation of geometric accuracy and roughness of drilling holes in AS made from PCM is based on the construction of kinematic schemes for shaping the parts' machining areas.

The design of cutting tools assumes determining the original surfaces *I*, conjugated with the surface *D* of the part, and the transformation of the body bounded by the surface *I* into a working cutting tool. When determining the output surface and the corresponding cutting tools, it is necessary to consider various variants of the movements of the part's surface *D* relative to the tool [18].

The totality of the movements of the surface of the tool relative to the part is to be considered a kinematic scheme of shaping.

From the point of view of the process of shaping the machining area of a part, it does not matter what combinations of the movements of the workpiece and tool resulted in the relative movement on the machine. Thus, when drilling holes on the lathe and drilling machines, the shape of a machined workpiece is identical, although the helical movement of the drill relative to a workpiece in both cases is enabled by a combination of different movements of the tool and part.

By choosing different movements of the surface *D* relative to the tool when determining the source surface *I*, one can build various kinematic schemes of shaping. Rotational and translational movements of the drill, the speed of which is perpendicular to the axis of rotation, refer to the process of drilling of the second class, the first type of surface shaping scheme.

5. Results of studying the specified geometric accuracy and roughness of a hole in the structures made of composites

5. 1. Establishing characteristic contact zones when drilling a hole in a polymeric composite material

5. 1. 1. Analyzing the kinematics of bladed machining of holes

The process of chip formation with any blade treatment of the hole in PCM made of carbon fiber and fiberglass is largely different from the blade machining of holes in metals where mainly drain chips are formed [15]. To understand the complete pattern of chip formation during PCM blade machining, consider the kinematic scheme of PCM chip formation by a cutting wedge (Fig. 1).

The actual experience of cutting PCM confirms that the displacement of the deformed PCM material occurs at an angle of $\beta\approx45°$ [17]. In Fig. 1, the following wedge positions are marked: β – chip chipping angle; α – rear angle; γ – front angle; *r* is the radius of the cutting tool; *t* – the depth of cutting; OKMO – the contour of deformation of the PCM zone; h_w is the length of wear on the back edge; δ_o – the value of the elastic deformation of the composite (1...2) %.

When moving in the direction relative to the fiber at speed V, on the front surface of the cutting wedge, a deformation zone of the material in the OKMO contour is formed. Under the influence of cutting forces, dust chips are formed by chipping the PCM in the OKMO zone.

It should be noted that when working with a drill with wear on the back surface at $h_w>0.3$ mm (Fig. 3, *b*), stratifications, cracks, and chips of PCM appear directly in the thickness of the material under the wedge. This is especially true of drilling in the direction perpendicular to reinforcing fibers.

During PCM bladed machining, in the process of chip formation, there is a violation of the integrity of the surface layer, which significantly affects the accuracy and roughness, and, subsequently, the operational properties such as strength, resource, moisture absorption, etc.

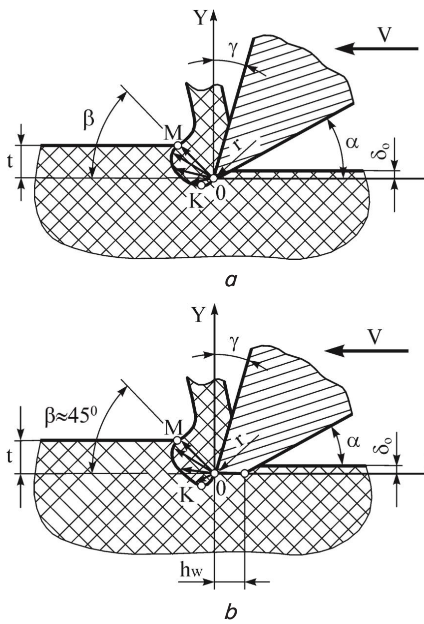


Fig. 1. The kinematic scheme of chip formation during the blade machining of a polymeric composite by a cutting wedge: *a* – chip formation with a non-worn cutter; *b* – chip formation with a worn cutter

An important factor in the process of PCM blade machining is the location of the tool cutting wedge relative to the orientation of the filler fibers and the location of the cutting wedge relative to the structure of the PCM material.

The kinematic scheme of action of cutting forces and the plane of displacement of chips during the deformation of PCM across the fibers are shown in Fig. 2.

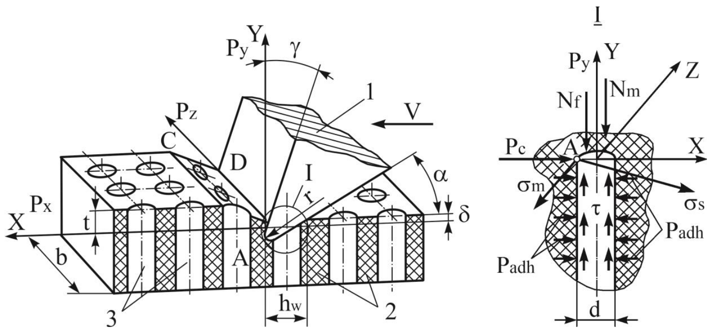


Fig. 2. The kinematic scheme of action of cutting forces and the plane of displacement of chips during the deformation of a polymeric composite across the fibers

In Fig. 2, the following positions are designated: 1 – cutting wedge; 2 – matrix; 3 – filler (fiber); V – cutting speed; b – blade width of the wedge; N_f, N_m are the normal forces in the fiber and matrix; σ_s, σ_m – stresses arising in the fiber and matrix; OKCD – chip shear area (S_3).

Depending on the compression force P_c, the friction forces P_x change, altering the wear intensity of the tool by the size h_3.

The cutting tool, wedge 1, with its rear surface (including h_w), under the pressure of the component of the cutting force P (the sum of forces P_x, P_y, P_z), contacts fibers 3 of matrix 2 and cuts them off. At the same time, the roughness of the machined surface forms.

5. 1. 2. Analyzing the kinematics of the process of drilling holes

The following analyzes the effect of the tool's kinematics on cutting forces, cutting wedge geometry, and hole roughness, given the fact that various deformation forces in PCM are perceived mainly by fibers. To simplify the analysis, the characteristic cutting zones A, B, C, D (Fig. 3) are indicated.

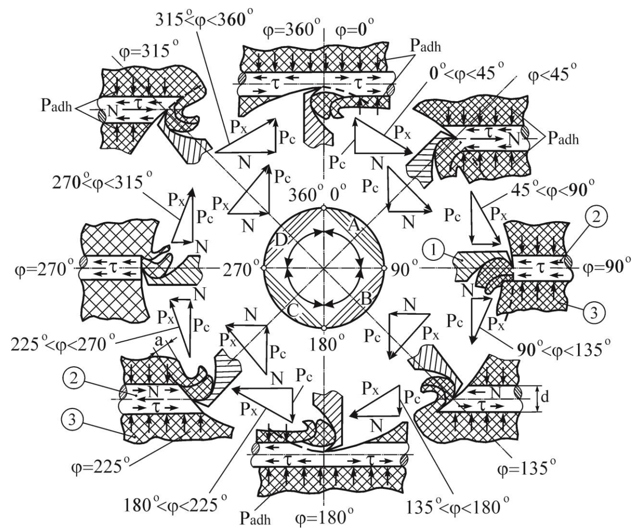


Fig. 3. Conditional scheme of cutting forces operating in a polymeric composite during drilling: P_x, P_y, N – external cutting forces; P_{adh}, τ – fiber adhesion force with the matrix

When rotating the drill, the cutting wedge is in contact with the composite fibers, while at points with angles of φ from 0° to 360° there is a change in stretching forces to compression forces, where φ is the angle of rotation of the drill. In the zones of angles A, B, C, D, the tool contacts fibers, with its rear surface, along the maximum ellipsoidal plane, that is, along the plane of the cut, which affects the roughness and increases the wear intensity of the cutting wedge. In the contact zones of the tool with the angles φ=90° and φ=270°, with the help of cutting efforts P_y, the fibers are shifted perpendicular to their location and the formation of cracks. When drilling holes at φ=0° and φ=180°, the layers of PCM that fall on the cutting edge, are subjected to local bending deformation, which is also the cause of cracking and stratification of the material around the hole. In general, cracking and stratification are observed more often with small axial forces and small thicknesses of an uncut layer of PCM. Works [17–19] describe the physics of microcrack occurrence due to cutting forces acting in the deformation zone of the surface layer of the material.

The size of the hole in PCM and the roughness of its surface are determined by the kinemics of movement in the machined material (Fig. 4). In the contact zone of the back surface of the cutting wedge with PCM, which has a structure with different strength characteristics, high contact pressure and temperature evolve. As a result, there are large tangent stresses that cause interlayer destruction (cracks) of PCM surface and the springing of PCM after cutting at Δ_0.

Properly selected PCM cutting forces allow the cutting wedge to contact the minimum area equal to the displacement area along the diameter of the fiber. At the same time, the accuracy of the specified sizes is ensured, roughness improves, compared to other cutting zones. If the contact area of the cutting wedge increases along the back edge, where $h_w > 0.3$ mm, the cutting forces are reduced due to an increase in friction force while the surface quality deteriorates. This does not ensure the accuracy of the specified hole size and roughness.

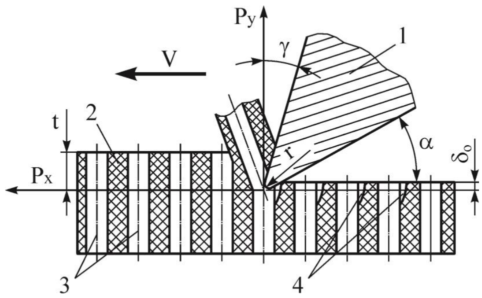


Fig. 4. Kinematic scheme of the formation of cracks in the surface layer of the composite: 1 — cutting wedge at speed V; 2 — matrix; 3 — fiber; 4 — the area of crack formation near the fibers

Fig. 5 shows a plot of the distribution of cutting forces P_x, N, P_y, acting on fibers. Within zones A (φ=0°...90°) and C (φ=180°...270°), compression forces act on the filler fibers when cutting. The cutting wedge, with its back surface, presses the fibers into the material matrix. According to this scheme of contact of the tool, cutting forces are reduced while surface quality indicators are improved, surface roughness decreases, machining accuracy increases. In zones B (φ=90...180°) and D (φ=270°...360°), under the influence of cutting forces, low quality of the machined surface is assumed. This is observed in reducing the actual executive dimensions of the hole and in the increased formation of cracks and roughness compared to the cutting zones A and C.

In the zones of angles φ close to φ=90° and 270°, normal forces N tend to zero while compressive forces increase to P_x. This change in cutting forces has a positive effect on the cutting process. In these zones, there is a transverse shift of the fibers, and the contact of the cutting wedge with the fiber on the back surface occurs over a minimum area, which reduces abrasive wear and contributes to increasing the stability of the tool.

Extracting filler fibers from the matrix may occur in zones B and D and is explained by a significant increase in cutting forces N over adhesion forces P_{adh} and tangential clutch forces t, that is, $N \gg P_{adh}$.

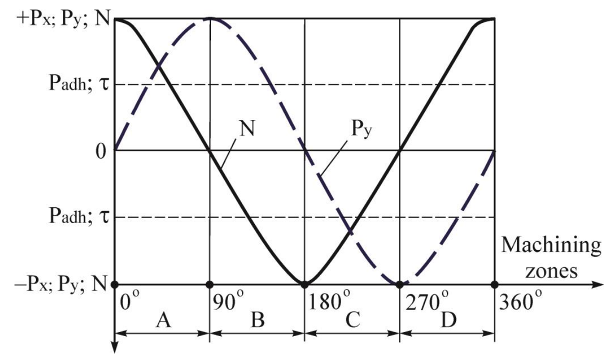


Fig. 5. Plot of the action of cutting forces P_x, N, P_c on fibers

5. 2. Calculating the required cutting forces and roughness height when drilling polymeric composite materials

5. 2. 1. Analyzing the classic types of drills used for drilling polymeric composite materials

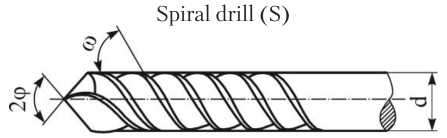
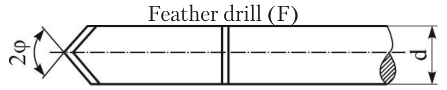
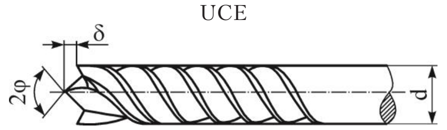
Below are the most common types of drills that are used to drill holes in AS made from PCM whose structural and geometric parameters are given in Table 1.

The simplest design is that of a feather drill. The main advantage of the feather drill (*F*) is the simplicity of the structure; the disadvantage is the poor removal of chips from the cutting area. The most common type is the spiral drill (*S*) differs from the feather drill in that the flat front surfaces of the blades are converted into screw surfaces, which simplifies the removal of chips when drilling. A spiral drill with the undercut cutting edge (UCE) does not have a cutting part in the center of the drill, which facilitates positioning above the center of the hole and ensures high surface purity for PCM. However, when blunting the UCE drill, stratification and detachment are more intense than for a traditional spiral drill with an angle at a top of 90°.

The process of drilling, according to the theory of cutting materials, is a general case of oblique-angular cutting. For the scheme of oblique-angular cutting, the velocity vector is not perpendicular to the cutting edge and forms some angle with it due to the kinematics of movement in the chipping zone. At the same time, the static angles of the drill point, relative to the machined surface of the material, change in the direction of reducing the angles γ, α. Figure 6 shows changes in static angles (γ_N, α_N are the angles on normal; γ_V, α_V – angles in the cutting plane of the cutting wedge) for the feather and spiral types of drills for glass and carbon fibers.

Table 1

Structural and geometric parameters of drills

Drill type	Grade	Structural and geometric parameter					Permissible wear size, mm
		d, mm	ɣ, °	α, °	2φ, °	β, °	
Spiral drill (S) 	P18	5	18	15	110	–	0,25
Feather drill (F) 	BK8	5	18	15	110	–	0,25
UCE 	P18	5	18	12	120	45	0,26

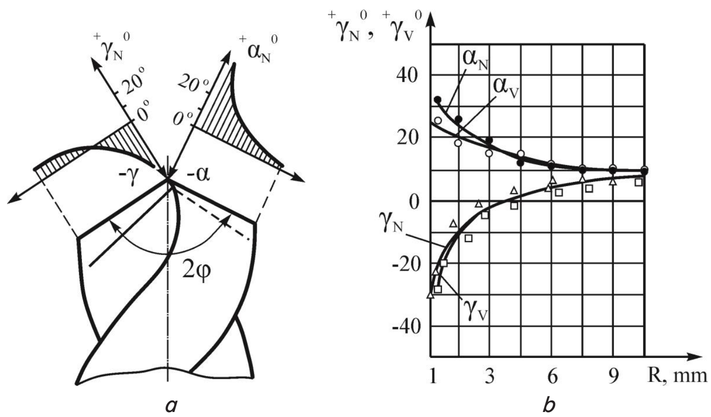


Fig. 6. The plot of change in the static angles of sharpening in the kinematics of rotation of the feather or spiral drills: *a* — depending on the radius of the drill *R*; *b* — along the cutting edge; Δ and ● — marking the values of angles along the normal to the cutting wedge; □ and ○ — marking the values of angles in the cutting plane of the cutting wedge

The plot of change in the static angles of sharpening in the kinematics of the spin of the drill demonstrates that the angle α is always positive compared to γ (Fig. 6). It should be noted that the main purpose of the angle α is to reduce the friction force that occurs when drilling not only PCM but also metal. The main function of the angle γ is to remove chips, so its values can be both positive and negative, and depend on the properties of the material. As the diameter of the hole increases, the angles α and γ decrease.

Experimental studies on drilling glass and carbon fibers show that the best indicators of the quality of holes in PCM are achieved by type *S* and *F* drills at angles α exceeding 10° [18]. Holes of small diameter (less than 10 mm) in PCM are produced by drills with a sharpening angle of 2φ (Fig. 6, *b*). A hole with a diameter of more than 10 mm should be pre-drilled by a drill with a diameter of 5...6 mm at appropriate angles α and γ (Fig. 6, *a*), and then gradually drill with drills of increased diameters to the predefined hole size. Taken together, the angles α and γ help perform the drill work – bladed machining of a PCM surface, forming the parameters of its quality, that is, the quality of the hole in the PCM. When choosing drilling modes, existing recommendations and empirical ratios of drill parameters recommended by manufacturers should be taken into consideration.

To ensure the predefined geometric accuracy of the hole, it is important to correctly assign tolerances to the geometry of the tool. While the accuracy of the manufacture of geometrical parameters does not significantly affect the accuracy of machining, the deviation of the angles of the working part of the tool must be assigned at ±1°...2°. For small angles (up to 3°), the deviation is ±30′. If the accuracy of the tool production affects the accuracy of the part and the duration of operation of the tool, then the tolerance is even lower. For example, the deviation at angles α and γ of tooth-cutting combs is ±10′ [17].

5. 2. 2. Calculation of the required cutting forces

The calculation of the required cutting forces is based on the assumption that the mechanical properties of PCM are low under a transverse load to fibers and when PCM moves along the fibers. The low mechanical properties of PCM across the fibers are explained by the insufficient strength of the connector and reinforcing fibers at the boundary of the component section.

Theoretically, the mechanical characteristics of PCM components in the direction of reinforcement are determined from the rule of mixtures:

$$\sigma_c = V\sigma_f - \left(1 - V_f\right)\sigma_m; \tag{2}$$

$$E_c = VE_f - \left(1 - V_f\right)E_m; \tag{3}$$

$$\rho_c = V\rho_f - \left(1 - V_f\right)\rho_m, \tag{4}$$

where V, V_f are the volumetric content of the connector and the volumetric fiber content; σ_s, E_f, ρ_f are the limiting stresses, elasticity module when stretching, and the density of fibers; σ_m, E_m, ρ_m are the limiting stresses, elasticity module at stretching, and the matrix density.

Each material has its optimal values for the quantity V_f, which are equal to 0.61...0.63 for fiberglass, and 0.63...0.67 for carbon fiber. The strength limit for the composite is defined as:

$$\left[\sigma\right] = V\sigma_f - \left(1 - V\right)\sigma_m. \tag{5}$$

In accordance with the kinematic scheme of the action of cutting forces (Fig. 3, 4), the stress in the fibers and the PCM matrix during drilling is:

$$\sigma_s = 4NS \bigg/ \frac{bt}{\sin\beta\pi d^2 i} = 4N\frac{S}{bt}\pi d^2 i \sin\beta, \tag{6}$$

$$\sigma_m = N \bigg/ \frac{bt}{\sin\beta\left(1 - \pi d^2 i\right)} = N\frac{\left(1 - \pi d^2 i\right)\sin\beta}{bt}, \tag{7}$$

where S – the area of chip displacement, mm^2; N – the forces acting along the fiber, N; i – the number of fibers within the shear area, pcs/mm^2; β – shaving angle, degree; d – the fiber diameter, mm; t – cutting depth, mm; b – the width of the cutting wedge, mm.

Based on (2) to (7), it is possible to calculate the forces anywhere in the cutting zone, taking into consideration the angle of rotation φ.

5. 2. 3. Determining the roughness of the hole in a polymeric composite material

During the simultaneous rotation and feed of the cutting wedge, on the machined surface of the material, roughness combs are formed. The following is the analyzed kinematics of the formation of roughness combs (Fig. 7).

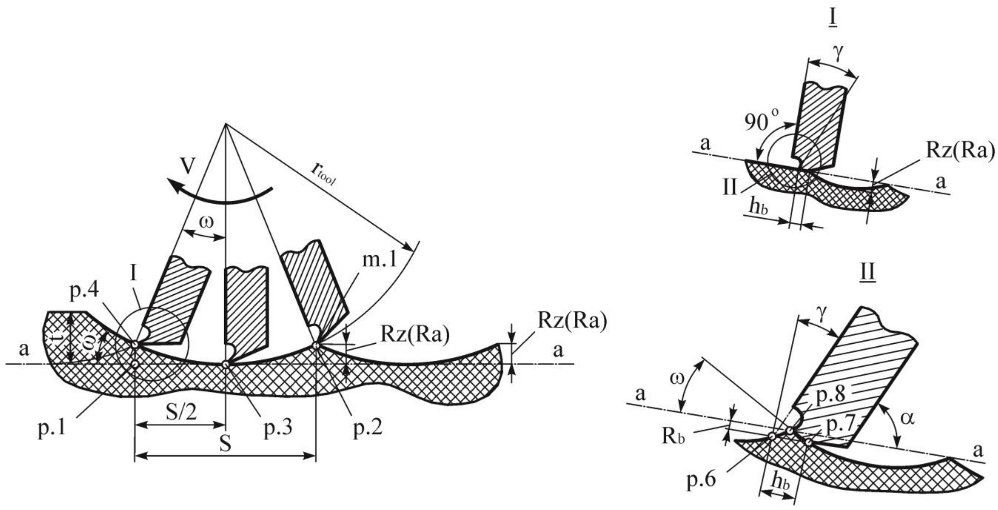


Fig. 7. The kinematic scheme of shaping the roughness R_z (R_a)

In Fig. 7, the following positions are designated: 1, 4 – points of the input and output of the cutting wedge of the tool; 1–2–3 and 3–4–5 – points of the triangle for calculating the values of theoretical roughness R_1 with forecasting for the total roughness R_z (R_a); 6–7–8 – points of the triangle regarding the calculation of the value of bearing ridges, R_b; h_b – the bearing/wear on the back edge of the cutting wedge, mm; a–a – cutting area (the cylindrical cutting surface conditionally deployed in the plane); ω is the angle between the radii at feeding $S/2$.

Taking into consideration the small values of angle ω and feed S, we assume the following: the line between points 3 and 4 is perpendicular at point 5 to the radius of the drill. At the same time, the allowed heights of roughness R_1, without taking into consideration the wear of the cutting wedge, are equal to:

$$R_1 = \frac{S}{2\text{tg}\omega}. \tag{8}$$

The roughness plane, limited by the geometric construction with points 6–8, is to be called a roughness comb. With a small error, we assume that the angle of inclination of line 7, 8 is equal to the angle ω (Fig. 9).

Taking into consideration the value of the wear of the cutting wedge on the front plane h_b and the kinematics of movement, the next in the previous cutting wedge, a decrease in the height of the roughness R_1 by the amount of bearing the roughness combs R_b is formed, which is equal to:

$$R_b = \frac{h_b}{2}\text{tg}\omega. \tag{9}$$

The total geometric height of roughness, under the accepted assumptions, when drilling is equal to:

$$R_Z = \frac{S}{2}\text{tg}\,\omega - \frac{h_b}{2}\text{tg}\,\omega + \delta = \frac{1}{2}\text{tg}\,\omega\left(S - h_b\right) + \delta_o, \tag{10}$$

where δ_o is the amount of shrinkage of PCM at drilling, mm. The amount of shrinkage of PCM Δ for fiberglass and carbon fibers is negligible, so in the calculations of roughness for the accuracy of the hole with a qualifier of 11–12, it can be neglected. For the holes of 7–8 qualifiers, it is desirable to take into consideration shrinkage, which is established experimentally.

5. 3. Analyzing the effect of shrinkage on the geometric accuracy of the hole in a polymeric composite material

The classic idea of drilling holes in PCM involves low feed speed and high cutting speed, which improve the quality of the hole surface, reducing the risks of stratification. However, at low feed speed and high speed of rotation of the drill, intense heating appears in the cutting zone, which provokes thermal destruction of the matrix and deterioration of drilling and shrinkage of PCM in the cutting zone. It is believed that the shrinkage factor for PCM is within 2...20 % [17, 18]. The shrinkage parameter for each type of PCM is different; its most reliable indicators are established experimentally. Fig. 8 shows a plot of the dependence of the shrinkage of holes with a diameter of 6 mm in carbon fiber on the drilling speed for three types of drills S, F, and UCE. The geometry of the holes was measured using the Faro Fusion Arm coordinate and measuring machine (USA).

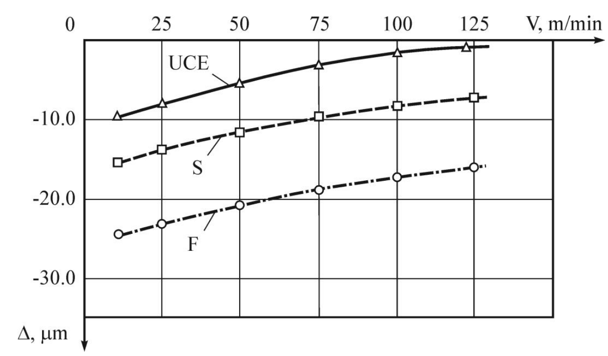


Fig. 8. Dependence plot of the shrinkage of holes Δ in carbon fiber on the drilling speed V [20]

Our analysis of the plotted data has made it possible to assert that:

– when drilling carbon fiber with UCE drills, holes with minimal shrinkage Δ are formed;

– with an increase in the cutting speed V to 100 m/min, a slight decrease in the shrinkage of holes occurs;

– when drilling with feather drills, a maximum shrinkage of holes is formed (up to 0.25...0.30 μm).

Fig. 9 shows a cyclogram of hole shrinkage in carbon fiber when using S, F and UCE drills according to the characteristic cutting zones A, B, C, D, where Δ is for UCE, □ – for S, ○ – for F.

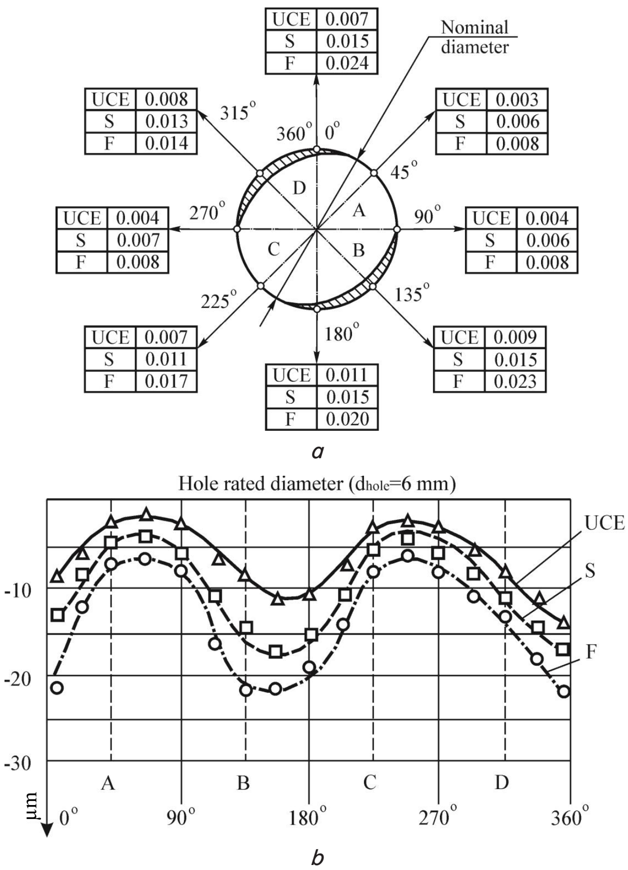


Fig. 9. Cyclograms of hole shrinkage in carbon fiber according to the characteristic cutting zones A, B, C, D: *a* – circular; *b* – expanded

The results of experimental studies on the shrinkage of holes with a diameter of 6 mm in AS made from carbon fiber showed their identity to the results of theoretical studies on the distribution of zones A, B, C, D (Fig. 3). The cyclogram in Fig. 9, *a* demonstrates that the distribution of shrinkage from 0° to 360° occurs accordingly to the distribution of cutting forces operating in PCM during drilling (Fig. 5). Minimal shrinkage is observed in the ranges from 0° to 90° and from 180° to 270°, and the maximum – from 90° to 180° and from 270° to 360°. Thus, within the drill operation zones from 0° to 90° and from 180° to 270°, the cutting forces are reduced, which exactly improves the indicators of shrinkage, surface quality, roughness, and geometric accuracy of the hole in PCM. In the zones from 90° to 180° and from 270° to 360° – on the contrary, cutting forces increase, which explains the low surface quality in these ranges. It should be noted that the tendency to shrink holes in carbon fiber in the characteristic cutting zones A, B, C, D is the same for all experimental drills F, S, and UCE.

Based on the results of experimental studies on the shrinkage of holes made of carbon fiber with a diameter of 6 mm, the following recommendations can be provided:

– the most effective type of drills among the studied F, S, and UCE to ensure the quality of the hole in PCM is UCE;

– to compensate for shrinkage when drilling a hole with types of drills F and S, the size of drills larger by 0.01...0.025 mm should be used than indicated in the drawing;

– to obtain holes without shrinkage, it is proposed to use drill sweeps that implement the drilling process with deployment. The rated sweep size should be selected at 0.01...0.03 mm larger than the rated size of the predefined hole.

6. Discussion of the study results to ensure the predefined geometric accuracy and roughness of the hole

The established characteristic contact zones of the drill bit and the surface of a hole in PCM, taking into consideration the kinematic scheme of contact of the drill bit and the PCM surface, allowed us to analyze and predict the deformation zone of the material. It has been found that the deformation zone for chip formation is in the OKMO zone (Fig. 3). Chips are formed by shaving the PCM in the OKMO zone under the wedge and not only at the input and output of the drill, as shown in work [9]. Establishing the OKMO deformation zone provides an understanding of the starting zone for stratification, cracks, and chips of PCM in the thickness of the material and in the perpendicular direction of the reinforcing fibers.

In accordance with the kinematic scheme of contact of the drill and the surface of PCM, our understanding of the kinematics of the tool's movement and the formation of cutting force, the geometry of the cutting edge, and the quality and roughness of a PCM hole is simplified. The kinematics of the movement of the drill in PCM, described by the characteristic cutting zones A, B, C, D (Fig. 5), complements the procedure proposed in [10] and could be used to refine the analytical model.

Indeed, Fig. 5 shows that in the zones of angles A, B, C, D, the tool contacts with its rear surface, over the maximum plane, the PCM fibers, which affects the roughness and increases the wear intensity of the cutting wedge. In the contact zones of the tool at angles $\varphi=90°$ and $\varphi=270°$ there is a shift of fibers perpendicular to their location and the formation of cracks. When drilling PCM at $\varphi=0°$ and $\varphi=180°$, the layers of composite material that fall on the cutting edge are subjected to local deformation for bending, which is the cause of cracking and stratification of the material around the hole. In general, cracking and stratification are observed more often with small axial forces and small thicknesses of an uncut layer of PCM. The extraction of filler fibers from the matrix may occur in zones B and D and is explained by a significant increase in the cutting forces N over the adhesion forces P_{adh} and the tangential clutch forces t, that is $N \gg P_{adh}$. This does not diverge from the data reported in [13] whose authors experimentally established the deformation zones of PCM when drilling carbon fiber with aluminum 3.6 mm thick. Such conclusions may be considered appropriate from a practical point of view because they allow for a reasonable approach to defining the drilling parameters, the accuracy of the diameter of the hole, and the roughness of its surface.

The peculiarity of our approach to calculating the required cutting forces and determining the quality and roughness of the hole in PCM is that it is based on:

– taking into consideration the shrinkage of holes in PCM, which, together with advancements from [14], will make it possible to evaluate the quality of holes not only by the parameters of roughness and geometric accuracy of the hole in the PCM but also by strength parameters;

– an integrated approach to the quality of the hole in PCM, which is based on the primary analysis of the kinematics of the tool's movement in PCM. This could be used to refine the results of electric pulse drilling [15], especially for uncut fibers and stratification of PCM at the input and exit of the hole;

– the use of classic types of drills such as F, S, and UCE and can be used for the standard SECO SD290A-7.963 drill bit and drill bits with the new operational STS [16].

It should be noted that the calculation of the required cutting forces presented in the current paper is carried out in accordance with the established kinematic scheme of the action of cutting forces (Fig. 1, 2) and does not take into consideration the wear of the drill. This will manifest itself, first of all, in an increase in friction forces during drilling and deterioration of the surface quality of the hole in PCM. The problem may be solved by further studies into the automatic adjustment of drilling parameters for AS made from PCM of different thicknesses, diameters, and compositions.

7. Conclusions

1. Our studies have established the features and characteristic contact zones when drilling a hole in PCM, taking into consideration the kinematic contact scheme of the drill and the surface of the PCM. It is established that within the drilling areas from 0° to 90° and from 180° to 270°, the cutting forces are reduced while the indicators of surface quality, roughness, and geometric accuracy of the hole in PCM are improved. In zones from 90° to 180° and from 270° to 360° – on the contrary, low quality of the machined surface is assumed. This is observed in reducing the actual executive dimensions of the hole and in the increased formation of cracks and roughness, compared to the cutting zones A and C.

2. The calculation of the required cutting forces and the calculation of the height of roughness of drilling holes in PCM have been proposed. The calculation of the required cutting forces takes into consideration the plane of chip displacement in accordance with the established zone of deformation of the material depending on the action of the wedge according to the kinematic cutting scheme. The calculation of the height of the roughness of drilling holes in PCM takes into consideration the area of bearing of the chips under the influence of the wedge in accordance with the kinematic cutting scheme.

3. The results of our experimental studies on the establishment of characteristic shrinkage zones in the drilling of PCM have confirmed the results of theoretical studies on the kinematic schemes of drill operation in PCM. The distribution of the quality, roughness, and geometric accuracy of the hole according to the characteristic rotation zones of the drill from 0° to 360° depends on both the drilling parameters and the PCM properties. When analyzing data, the minimum shrinkage of holes with a diameter of 6 mm in carbon fiber is observed when drilling with UCE drills; the maximum shrinkage of holes – when drilling with feather drills. The results of an increase in the cutting speed to 100 m/min showed a slight decrease in the shrinkage of holes in carbon fiber. This indicates the possibility of setting a range to increase the cutting speed with minimal risks of losing the surface quality of the PCM hole.

Acknowledgments (if any)

Special thanks to the Rector of the National Aerospace University named after M. E. Zhukovsky «Kharkiv Aviation Institute», Mykola Nechyporuk, and Vice-Rector for Scientific Work of the National Aerospace University named after M. E. Zhukovsky «Kharkiv Aviation Institute», Volodymyr Pavlikov, as well as General Director of the State Enterprise «Antonov», Sergiy Bychkov, for all possible support in the implementation of the research reported here.

References

1. Shyha, I., Huo, D. (Eds.) (2021). Advances in Machining of Composite Materials. Springer, 552. doi: https://doi.org/10.1007/978-3-030-71438-3
2. Bychkov, S. A, Kotsiuba, O. A. (2016). State and problems of usinf of new construction materials in domestic civil aircraft in modern conditions. Report 1. Approaches to the choice of metal construction materials of aircrafts. Aviatsionno-kosmicheskaya tekhnika i tekhnologiya, 5 (132), 4–14. Available at: http://nti.khai.edu:57772/csp/nauchportal/Arhiv/AKTT/2016/AKTT516/Bychkov.pdf
3. Andrieiev, O. V. (2020). Naukovi osnovy pidvyshchennia efektyvnosti stvorennia konstruktsiy transportnykh litakiv iz polimernykh kompozytsiynykh materialiv na etapakh zhyttievoho tsyklu vyrobu. Kyiv, 333. Available at: https://er.nau.edu.ua/handle/NAU/44706
4. Tjahjanti, P. H., Firdaus, R., Iswanto, Ahnan, M. F. (2020). Study of Crack Connections in Materials Composite Based on Polymer. IOP Conference Series: Materials Science and Engineering, 874 (1), 012026. doi: https://doi.org/10.1088/1757-899x/874/1/012026
5. Raskutin, A. E., Khrulkov, A. V., Girsh, R. I. (2016). Technological features of composite materials machining in manufacturing details of structures (review). Proceedings of VIAM, 9 (45). doi: https://doi.org/10.18577/2307-6046-2016-0-9-12-12
6. Globa, A. V., Bondarenko, A. S. (2009). Analysis of process of the aircraft materials drilling with three-wings drills in order to improve cutting part geometry. Visnyk NTUU «KPI». Pryladobuduvannia: zbirnyk naukovykh prats, 37, 92–97. Available at: https://ela.kpi.ua/handle/123456789/8835
7. Khavin, G. L. (2015). Obrazovanie defektov pri sverlenii sloistykh kompozitov i mekhanizm poyavleniya rasslaivaniya. Visnyk NTU «KhPI», 4 (1113), 96–100. Available at: http://repository.kpi.kharkov.ua/bitstream/KhPI-Press/15182/1/vestnik_HPI_2015_4_Khavin_Obrazovanie.pdf
8. Yang, X.-Q., Chen, X., Tan, D., Li, R., Gao, H. (2021). Evolution of frictional damage of PTFE/Kevlar fiber braided materials. Surface Technology, 50 (8), 282–294. doi: https://doi.org/10.16490/j.cnki.issn.1001-3660.2021.08.026
9. Patel, P., Chaudhary, V. (2021). Delamination evaluation in drilling of composite materials – A review. Materials Today: Proceedings. doi: https://doi.org/10.1016/j.matpr.2021.09.267
10. Rahmé, P., Landon, Y., Lachaud, F., Piquet, R., Lagarrigue, P. (2010). Analytical models of composite material drilling. The International Journal of Advanced Manufacturing Technology, 52 (5-8), 609–617. doi: https://doi.org/10.1007/s00170-010-2773-5

11. Vorobiov, I., Nechyporuk, N., Maiorova, K. (2018). Experimental and numerical investigations on impulse self-pierce riveting of lightweight aircraft aluminium and mixed structures. Proceedings of 22nd International Scientific Conference Transport Means 2018. Trakai, 121–128. Available at: https://transportmeans.ktu.edu/wp-content/uploads/sites/307/2018/02/Transport-means-I-dalis-2018-09-25.pdf
12. Vorobiov, I., Maiorova, K., Voronko, I., Boiko, M., Komisarov, O. (2022). Creation and Improvement Principles of the Pneumatic Manual Impulse Devices. Lecture Notes in Networks and Systems, 178–191. doi: https://doi.org/10.1007/978-3-030-94259-5_17
13. Hassan, M. H., Abdullah, J., Franz, G., Shen, C. Y., Mahmoodian, R. (2021). Effect of Twist Drill Geometry and Drilling Parameters on Hole Quality in Single-Shot Drilling of CFRP/Al7075-T6 Composite Stack. Journal of Composites Science, 5 (7), 189. doi: https://doi.org/10.3390/jcs5070189
14. Tesfaye Jule, L., Ramaswamy, K., Nagaprasad, N., Shanmugam, V., Vignesh, V. (2021). Design and analysis of serial drilled hole in composite material. Materials Today: Proceedings, 45, 5759–5763. doi: https://doi.org/10.1016/j.matpr.2021.02.587
15. Chevychelov, S. A., Snopkov, M. V., Bondartsev, I. V., Maslennikov, A. V. (2017). Diagram of fixture for vibration drilling of holes in composite materials. Proceedings of the Southwest State University, 21 (6), 76–84. doi: https://doi.org/10.21869/2223-1560-2017-21-6-76-84
16. Hrechuk, A., Globa, A., Devin, L. (2017). Increasing the quality of drilling holes in fiber reinforcement composite materials. Bulletin of Kyiv Polytechnic Institute. Series Instrument Making, 54 (2), 80–85. doi: https://doi.org/10.20535/1970.54(2).2017.119556
17. Hocheng, H. (2012). Machining technology for composite materials. Woodhead Publishing. doi: https://doi.org/10.1533/9780857095145
18. Ravska, N. S., Melnychuk, P. P., Mamliuk, O. V., Nikolaienko, T. P., Okhrimenko, O. A. (2013). Osnovy formoutvorennia poverkhon pry mekhanichniy obrobtsi. Kyiv, 215. Available at: http://repo.snau.edu.ua/bitstream/123456789/1799/1/Формування%20поверхні.pdf
19. Shorshorov, M Kh. (2021). Modelirovanie protsessov resursosberegayuschey obrabotki slitkovykh, poroshkovykh, nanostrukturnykh i kompozitsionnykh materialov. Moscow: Infra-Inzheneriya, 360.
20. Lupkin, B. V., Mamlyuk, O. V., Dranik, A. I., Kass, A. L. (2016). Influence of Technological Parameters of Drilling CM Strength. Otkrytye informatsionnye i komp'yuternye integrirovannye tekhnologii, 71, 125–135. Available at: http://nbuv.gov.ua/UJRN/vikt_2016_71_13