UDC 629.73.002
DOI: 10.15587/1729-4061.2023.279618

FORMATION OF THE QUALITY OF HOLES OBTAINED BY DRILLING IN AVIATION STRUCTURES MADE FROM POLYMER COMPOSITE MATERIALS

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The subject of this study is the quality indicators (geometric accuracy, roughness, cylindricity and taperness) of holes obtained by drilling in aircraft structures (AS) made of polymeric composite materials (PCM). The quality indicators of holes in AS made from PCM were studied by using kinematic schemes across and along the direction of drilling. A kinematic scheme of formation of the predicted surface roughness of the hole in AS made from PCM has been built. The calculation of the predicted roughness of PCM holes taking into account the geometry of the drill and drilling modes has been proposed. Experimental studies have been implemented to establish the parameters of predicted roughness, geometric accuracy, taperness, as well as deviations from cylindricity. The methods used were the method of expert assessments and experimental studies of quality indicators of PCM openings. The following results were obtained: the roughness in full-scale experiments turned out to be lower than the theoretical calculated values with a difference of not more than 10...15 %. It was found that roughness, taperness, deviations from geometric precision and cylindricity differ in characteristic rotation zones of the drill from 0° to 360° and depend on the drilling parameters and PCM properties. It was found that the deviation from the hole cylindricity is affected by the shrinkage of the material. The appearance of ovality in the holes of prototypes was established. The results of experimental studies of measurements of hole diameters to establish deviations from cylindricity, geometric accuracy, and taperness met the production requirements for the accuracy of their manufacture. For geometric precision and deviation from cylindricity, the results ranged from 7 to 12 IT grades, and for taperness, from 0.083 to 0.28 % per a hole in AS made from PCM and 9–10 IT grades

Keywords: polymeric composite materials, hole drilling, hole roughness, geometric precision

Received date 14.03.2023
Accepted date 17.05.2023
Published date 30.06.2023

How to Cite: *Lupkin, B., Andrieiev, O., Maiorova, K., Antonyuk, V., Vysloukh, S. (2023). Formation of the quality of holes obtained by drilling in aviation structures made from polymer composite materials. Eastern-European Journal of Enterprise Technologies, 3 (1 (123)), 59–67. doi: https://doi.org/10.15587/1729-4061.2023.279618*

1. Introduction

The production of modern aircraft structures (AS) is impossible without the use of polymeric composite materials (PCM), which successfully replace metal due to their advantages in properties. PCM have high specific strength, which provides reliability and low wear rate with the extension of the life of AS [1]. It should be noted that when using PCM, an increase in service life by 2–5 times, a reduction in the mass of the structure and material consumption of the structure by 30–50 %, as well as a reduction in the labor intensity of production by 20–40 %, is achieved [2]. However, the scope of PCM application is limited by the complexity of their machining and the need to comply with special requirements for labor protection [3]. Given this, the quality of PCM processed surface is significantly affected by the performance of composites machining.

One of the mass processes of PCM machining in the manufacture of AS is the drilling of holes, the accuracy requirements for which range from 7–8 to 11–12 IT grades with a surface roughness parameter Rz in the range from 20 μm to 60 μm. However, incorrectly selected drilling modes and geometric parameters of the cutting tool (drill) contribute to the formation of microcracks, chips, and delamination during the drilling process. Such damage, in turn, affects the parameters of geometric accuracy, roughness, as well as cylindricity (taper) along the surface of the hole. Scientific experience on this problem contains very contradictory information regarding the technology of drilling holes in AS made from PCM. For example, with incorrectly selected geometric parameters of drills and work with a drill with wear, delamination, cracks, or chipped PCM may appear on the back surface, especially in the direction perpendicular to the reinforcing fibers. Too high a drill feed contributes to

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the pulling of fibers, which increases the roughness of the hole surface. At high drilling speeds, the temperature in the cutting zone increases and loosening, destruction of PCM or vice versa can be formed – local melting of the composite.

Therefore, an integrated approach in the study of the formation of quality parameters of holes in AS made from PCM, obtained by drilling, renders relevance to our research.

2. Literature review and problem statement

An important role in ensuring the geometric accuracy and physical and mechanical properties of PCM belongs to shaping, machining, and assembly operations [4]. According to [5], the greatest number of defects in AS made from PCM occurs precisely during the mechanical treatment of the composite. Among such defects are cracking of the binder, delamination, pulling out of fibers, non-cutting of fibers, thermal destruction of the binder, and loosening of the fibers. There are successful studies of PCM compounds in combined packages of carbon fiber with aluminum by holeless method [6] with a special pulse tool [7]. The only drawback of such connections is the inability to transfer high operating loads. Therefore, drilling of PCM packages, as demonstrated in [8], is still one of the most widely used methods for obtaining holes for the connection of AS from carbon fiber. Thus, in article [9], the high strength properties of PCM from reinforcing fibers of the Kevlar type were experimentally proved. However, this revealed zones of thermal destruction and delamination. As shown in [10], delamination usually appears at the inlet and outlet of the drill and depends on the selected cutting modes. Continuation of work [10] is the results reported in [11], which takes into account the geometry of the drill. According to work [12], important is the material of the tool, which must be selected for each PCM. The only drawback is the high cost of such work, requiring preliminary full-scale experiments, measurements, and control. An alternative is provided in [13], which presents an approach for determining the quality of the hole, based on the analysis of a digital image to measure the experimental parameters of the geometry of the hole and measure different indices of detachment and chipping. A number of subsequent works show that the stratification of PCM is significantly influenced by drilling modes. Thus, in [14], numerical methods investigated the effect of feed and speed on cutting forces for different drills. It has been established that double cone drills require less cutting force than standard spiral drills. However, the use of such complex cone drills should be economically feasible and in practice they are usually used for mixed PCM packages with aluminum layers. Thus, in [15], it is proved that to obtain a satisfactory quality of the opening (11–12 IT grades) of fiberglass and carbon panels, it is enough to use standard drills. If it is necessary to make holes with high surface quality (7–8 IT grades), drilling parameters play a special role. Thus, in [16], full-scale experiments on mixed bags of carbon fiber CFRP, titanium and aluminum Ti-6Al-4V proved that burr formation and average surface roughness of the hole depend on the feed rate. It was noted that smaller detachments of PCM are in mixed bags, but the service life of the tool is much shorter due to rapid wear along the rear edge. The solution can be the correct geometry of the drill (the angles of the top φ and the inclination of the helical groove ω). Work [17] offers a digital procedure that establishes the influence of cutting modes and parameters, as well as the geometry of the drill, on the quality of the hole surface by taking into account the area of damage. The adequacy of finite element modeling has been proven by full-scale experiments. This approach can be used to predict future defects in advance, depending on the parameters of the drill and drilling. However, for each specific PCM, the methodology is subject to adjustment and requires a full-scale experiment, which increases the complexity and cost of work.

It should be noted that full-scale experiments are always expensive and require highly qualified performers with preliminary planning of the experiment, so science is often satisfied with SEM results. According to this principle, there are enough experiments. Thus, in [18], a procedure based on analytical modeling is proposed, which takes into account the properties of PCM with subsequent optimization of the geometric shape of the cutting tool – drill. In [19], on the basis of previously built mathematical models of a PCM hole, an algorithm is proposed that calculates the value of diametrical roughness in different parts of the cutting zone in accordance with the structural-geometric parameters of the drill. Despite the significance of results reported in [18, 19], their reliability is in doubt without confirmation by a full-scale experiment on witness samples or testing of AS. The solution is provided by work [20], where the data of analytical modeling of SEM are compared with full-scale experiments of drilling holes in fiberglass, which confirms the adequacy of the theoretical statement of problems. However, despite the positive results in [20], they are not sufficient to determine the quality parameters of a PCM opening: geometric precision, roughness, taperness, and cylindricity. It is obvious that scientific research is impossible without full-scale experiments, which will confirm or refute the selected process models. Therefore, there is reason to believe that insufficient theoretical and practical certainty about the quality parameters of a PCM hole depending on the type of cutting tool (drill) and drilling parameters necessitates research to ensure the specified parameters of the holes.

3. The aim and objectives of the study

The purpose of this study is to ensure the specified quality parameters (geometric accuracy, roughness, taperness, and cylindricity) of holes in AS made form PCM. This will make it possible to guarantee high reliability and low wear rate of the drill, as well as lengthening the service life of AS made from PCM.

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

– to construct a kinematic scheme for the formation of the predicted roughness *Rz* of the surface of an AS hole made from PCM by analyzing the kinematic scheme of contact between the cutting wedge of the drill and the filler;

– to conduct experimental studies of roughness *Rz*, geometric precision, taperness, and cylindricity of the surface of a PCM hole.

4. The study materials and methods

4. 1. The study object

The object of our research is the process of drilling holes in AS made from PCM.

The study is based on the general principles of the theory of machines and mechanisms. The process of drilling and hole formation in AS made from PCM are investigated by the kinematic method for determining the envelopes of a family of surfaces. The kinematic method for determining the envelopes of a family of surfaces is the construction of a family of surfaces that are formed as a result of a certain movement of the predefined surface [1, 21].

4. 2. The study subject

The subject of our study is the formation of geometric accuracy, roughness, cylindricity, and taperness of holes by drilling in PCM.

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

From the point of view of the shaping process of the machining zone of a part, there is no difference what combination of movements of the workpiece and tool obtained relative motion on the machine. Thus, when drilling holes on lathes and drilling machines, the shape of the machined surface of the part is identical while the helical movement of the drill relative to the workpiece in both cases is ensured by a combination of different movements of the tool and part.

The formation of geometric accuracy and roughness of holes by drilling in PCM is ensured by shaping the machining zone of the part by removing the allowance from the workpiece. The allowance is removed in parts in the form of chips.

The study of shaping geometric precision, roughness, taperness, and cylindricity of holes in PCM is based on the construction of a kinematic scheme of shaping of drilling zones along the surface of the hole. This scheme is constructed in accordance with the adopted kinematic scheme of interaction of the cutting edges of the drill with the fibers of the PCM filler across the drilling [22]. Fig. 1 shows the kinematic scheme of interaction of the components of cutting forces *Px*, *Py*, normal cutting force *N*, and adhesion force P_{adh} between the fibers and the matrix. In this case, the angle of rotation of the drill (orientation of the cutting wedge) was determined clockwise. The study of the kinematics of PCM drilling was performed by determining the influence of the angle of rotation of the drill on the cutting forces, taking into account the fact that the forces are perceived mainly by the filler fibers in the characteristic areas of the hole *A*, *B*, *C*, *D*. During the rotation of the drill, the cutting wedge at the points of contact with the monofilament of the filler at angles φ=0° (360°) and φ=180° cyclically changes the cutting forces from tensile to compressed.

In sections of the hole with the location of the cutting wedge to the filler fibers close to angles φ=0° (360°) and φ=180°, the tool is in contact with the rear surface along the maximum plane with the filler fibers (along the ellipsoid). In this case, the process of «planning» occurs, which affects the roughness, especially for a material with an uneven arrangement of fibers and increases the intensity of wear of the cutting wedge. In these sections of the hole, the tensile forces of cutting in the filler fibers change to compressive. This scheme of cutting forces leads to the destruction of the surface layers of the composite, on which stratification, cracks, chips, and stretching of fibers occur.

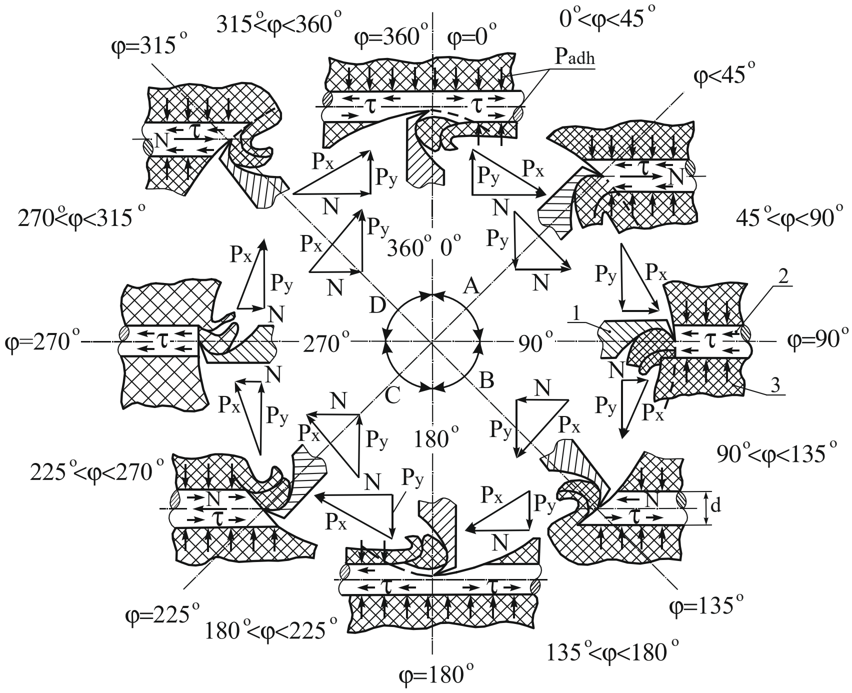

Fig. 1. Kinematic scheme of interaction of the cutting edges of the drill with the fibers of the composite filler in the cutting zones *A*, *B*, *C*, *D*: 1 — cutting wedge; 2 — fiber; 3 — matrix; *Px*, *Ru*, *N* — external cutting forces, MPa; P_{adh}, τ — adhesion and adhesion forces between the fiber and the matrix, MPa; *d* — fiber diameter, mm; *V* — cutting wedge speed, m/min [22]

In areas of φ angles close to 90° and 270°, the compressive forces *Py* increase; in these zones, a «clean» displacement of fibers perpendicular to their location is carried out. This pattern of force change has a positive effect on the cutting process due to a decrease in effort when removing the allowance. In these areas of the hole, the drill is in contact with the minimum plane of the filler, which is equal to the shear area of the fiber diameter. This contact of the tool with the filler helps improve the accuracy of the holes and the quality of the surface compared to other parts of the hole.

Within sections *A* and *C* (φ=0°...90° and φ=180°...270°), a cutting wedge with the back surface presses the fibers into the matrix while external compressive forces act on the filler fibers. According to this tool contact scheme, the components of the cutting force are reduced due to the fact that the fracture forces during compression are less than during stretching.

In sections *B* and *D* within the angles from φ=90° to 180° and from 270° to 360°, we obtain a decrease in the quality of the hole surface.

Under the influence of an increase in cutting forces and temperature, due to deformation, the actual dimensions of the hole decrease and, at the same time, the size of cracks and the amount of roughness increase compared to cutting zones *A* and *C*.

The accepted assumptions for sections *B* and *D* were based on an increase in the normal cutting forces *N* acting along the fibers. When tensile, normal cutting forces *N* have the highest values compared to adhesion and tangential forces ($N \geq P_{adh}$).

In the zones of angles φ from 90° to 180° and φ from 270° to 360°, the normal force N coincides with the force component Px and acts on the displacement of the fiber. Due to the thermal factor of deformation that occurs in the contact zone, the filler fibers are «pulled» from the matrix. In this case, there are large tangential stresses that can cause the destruction of the bonds between the fiber and the matrix, create cracks in the micro depth δ and detachment of fibers in the matrix.

5. Results of studies into the quality of the hole surface in the polymer composite material

5. 1. Kinematic scheme of formation of predicted roughness *Rz* of hole surface in polymer composite material

The kinematic scheme of interaction of the cutting edges of the drill with the fibers of the PCM filler is analyzed below in order to establish the parameters of formation of the predicted roughness Rz along the surface of a hole in AS made from PCM (Fig. 2).

It should be noted that the drilling process represents a sequential (generating) cutting scheme with two main rectilinear edges of the intake part of the drill. One is placed at an angle of φ to the axis of the drill. The other two, auxiliary side spiral edges of the drill, are placed at an angle ω to the axis. Therefore, in order to change the load on the active part of the main and auxiliary cutting edges of the drill, the length of the active part of the cutting edges can be changed by selecting the angles φ and ω.

In order to determine the predicted surface roughness Rz, which is formed in the process of PCM drilling, we conditionally draw in the hole in the direction of the axes X and Z the cutting frontal plane H (Fig. 2, *a*). In the process of drilling, the first main rectilinear cutting edge of the drill AO, rotating, forms a cutting line AA_1 on the plane KMM_1K_1 of the intersecting plane H (Fig. 2, *b*).

The second main cutting edge BO and the auxiliary spiral edge BD with the formative vertex B, rotating moving to point B_1, together with the edge B_1D_1 and with the first cut line AA_1 form the roughness value Rz (FE). From the geometric construction of the triangle AB_1E we determine the maximum value of the predicted roughness Rz of height FE. To do this, the triangle AB_1E is divided into two triangles AFE and AB_1E and the roughness values are found, provided that its base is half the feed, that is, $S/2 = AF + FB_1$, then:

$$b_{1(AF)} = \frac{FE}{\text{tg}\varphi}, \quad (1)$$

$$b_{1(FB)} = \frac{FE}{\text{tg}\omega}, \quad (2)$$

where FE is the value of the predicted roughness Rz.

Then the predicted roughness Rz is defined as:

$$R_Z = \frac{S}{2\left(\frac{1}{\text{tg}\varphi} + \frac{1}{\text{tg}\omega}\right)}, \quad (3)$$

where S – drill feed, mm/rev; φ – angle of the edge of the intake part of the drill, degrees; ω – angle of the lateral spiral part of the drill, degrees.

5. 2. Results of experimental studies on geometric precision, taperness, cylindricity, and surface roughness of the hole

In order to optimize the cutting modes (speed V and feed S), experimental studies were carried out when drilling carbon fiber CMU-P-0.1-A on a conjunction 5-211-BN with a thickness of 6 mm. The experiments were carried out on the 1K62 machine, on which carbon fiber samples were fixed in a chisel holder, and the investigated drills made from VK8 with a diameter of 5 mm were fixed in the spindle of the machine.

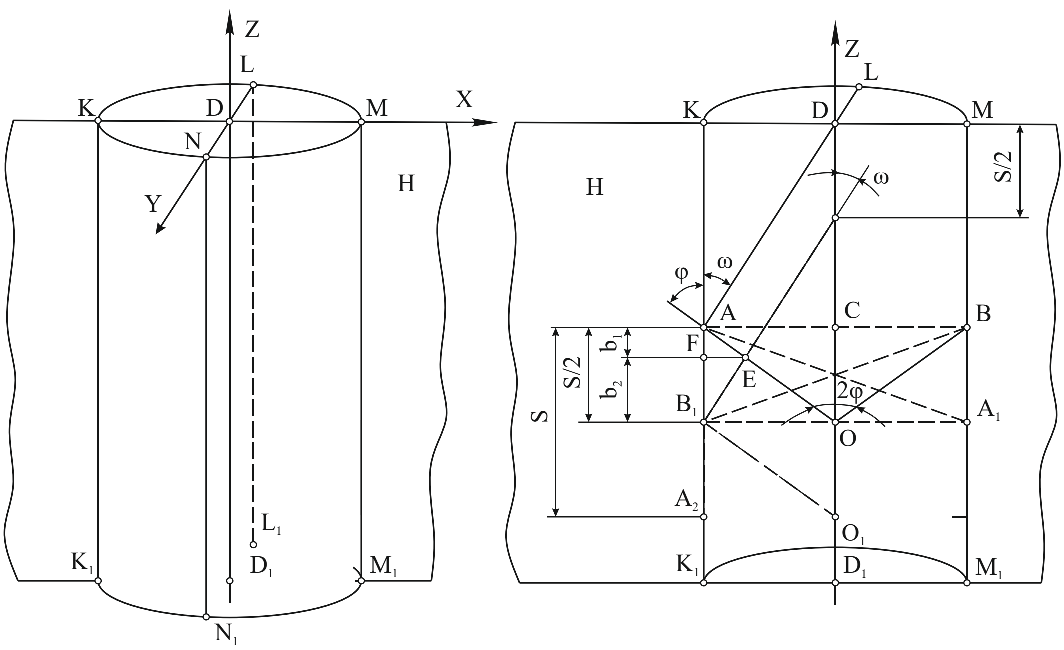

Fig. 2. Kinematic scheme of the formation of hole roughness when drilling a composite: *a* – when crossing the plane *H*; *b* – taking into account the parameters of the cutting edges of the drill

Cutting modes varied within:

– cutting speed V from 45 to 90 m/min,

– feed S from 0.025 to 0.15 mm/rev,

– wear of the cutting edge on the back face h_w no more than 0.3 mm.

The roughness along the surface of the hole was measured on the PM-7 profilometer.

The experimental indicators for drilling holes with a diameter of 5 mm on carbon fiber samples CMU-P-0.1-A for different types of drills were compared: with manual and automatic feed – BK8, and only with automatic feed – Guhring-732; Guhring-704.

Fig. 3 schematically shows the scheme of measurements of the diameters of the carbon fiber hole, where d_{real} is the real (actual) diameter of the hole in PCM; d_{in} – diameter at the drill inlet; d_{out} – diameters at the outlet of the drill.

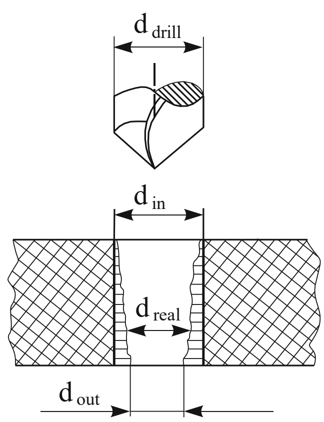

Fig. 3. Scheme of measurements of diameters along the hole, at the inlet and outlet of the drill in the hole of carbon fiber KMU-P-0,1-A

Taperness is calculated from the following formula [23]:

$$C = \frac{d_{in} - d_{out}}{h} 100\,\%, \qquad (4)$$

where h is the thickness of the carbon fiber prototype, which is equal to 6 mm.

Table 1 gives the diameters of the holes at the inlet d_{in} and the outlet d_{out} of the drill with diameter d_{drill} in order to establish deviations from cylindricity and taperness.

The results of measurements of deviations from the cylindrical shape of the hole, as well as taperness for different drills, allow us to draw the following conclusions. The size of the hole in the PCM, the roughness and hole cylindricity are determined not only by the geometry of the selected drills but also by the kinematics of movement in the machined material according to the accepted drilling modes (Fig. 2).

For all experimental drills, the same trend is observed: the diameter at the inlet of the drill d_{in} is more important than the diameter of the drill d_{drill} and vice versa, the diameter at the outlet of the drill d_{out} has smaller values than the diameter of the drill d_{drill}. This is explained by the fact that in the contact zone of the rear surface of the cutting wedge of the drill and PCM, a high contact pressure and temperature develop, as a result of which shrinkage of the material appears [22]. The taperness of the hole is formed by obtaining the real diameter d_{real} by deviating the predefined diameter size from that actually obtained along the hole, as well as at the inlet and outlet of the drill. According to Table 1, we have RMS deviations of diameters, i.e., taperness from 0.083 to 0.28 %, which satisfies the IT grades of 9–10 per PCM hole.

Deviations of geometric accuracy and cylindricity by measurements of hole diameters showed results that met production requirements ranging from 7 to 12 IT grades. Analysis of deviations depending on the hole cylindricity showed the appearance of ovality of the hole as a deviation from the roundness. The ovality in this case is denoted as the real profile of a cylindrical surface in cross-section with an oval-shaped figure, the largest and smallest diameters of which lie in mutually perpendicular directions [24]. Fig. 4 shows a cyclogram of the deviation from the hole cylindricity in PCM (according to RMS measurements of diameters along the hole surface) in accordance with the cutting zones *A*, *B*, *C*, *D*.

The results of experimental studies of drilling holes with a diameter of 5 mm in samples of carbon fiber KMU-P-0.1-A showed their identity to the results of theoretical studies on the distribution of zones *A*, *B*, *C*, *D* (Fig. 1). From the cyclogram (Fig. 4) it can be seen that the distribution of shrinkage from 0° to 360° occurs according to the distribution of cutting forces acting in the PCM during drilling (Fig. 1). Minimum deviations are observed in the ranges from φ angles 0° to 90° and from 180° to 270°, and maximum deviations from 90° to 180° and from 270° to 360°. Thus, within the drill operation zones from 0° to 90° and from 180° to 270°, cutting forces are reduced, which improves the geometric accuracy, roughness, cylindricity, and taperness along a hole in the PCM. In zones of angles φ from 90° to 180° and from 270° to 360° – on the contrary, cutting forces increase, which explains the low quality of the surface in these ranges. It should be noted that the trend for the experimental parameters of holes in carbon fiber according to the characteristic cutting zones *A*, *B*, *C*, *D* is the same for all experimental drills – spiral VK8, Guhring-704, and Guhring-732.

Deviations from cylindricity and taperness along the hole can be explained by the appearance of shrinkage of carbon fiber CMU-P-0.1-A. For Guring-732 drills, these deviations are associated with the appearance of stratifications and uncut fibers, and for the Guring-704 type – with a decrease in chips, delamination, and uncut fibers both at the inlet and outlet of the drill.

Table 1

Measurements of hole diameters when drilling carbon fiber CMU P-0.1-A; thickness, 6 mm

No. of entry	Type of drill	Drill angles, degree		Drill diameter d_{drill} before drilling, mm	Feed type		Measurements of hole diameters, mm			Taperness of hole C, %
		2φ	ω		manual	automatic	d_{in}	d_{out}	d_{in}–d_{out}	
1	Spiral BK8	120	25	4.689	+	–	4.700	4.683	0.017	0.28
				4.989	–	+	4.990	4.980	0.010	0.16
2	Guhring-704	85	20	4.993	–	+	4.998	4.982	0.016	0.26
3	Guhring-732	118	25	4.990	–	+	4.992	4.987	0.005	0.083

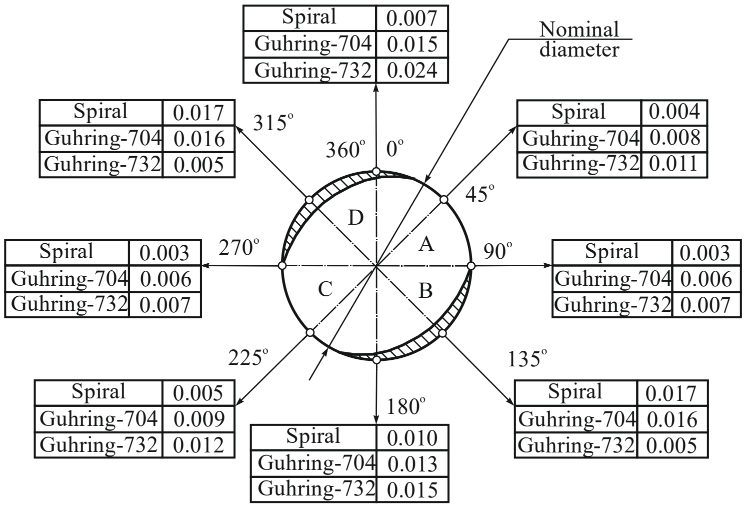

Fig. 4. Cyclogram of deviation from the hole cylindricity of the composite (according to RMS measurements of diameters along the hole surface)

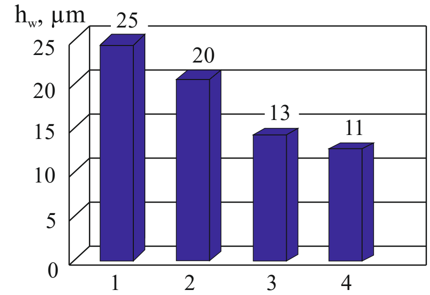

Fig. 5. Diagram comparing the intensity of wear h_w of drills when drilling plastic CMU-P-0,1-A: 1 – spiral VK8 with manual feed; 2 – spiral VK8 with automatic feed; 3 – Guhring-732; 4 – Guhring-704

Fig. 6 shows plots comparing the obtained data on the predicted roughness *Rz* by full-scale experiments with theoretical calculations under accepted cutting conditions (V=50 m/min, S=0.1 mm/rev).

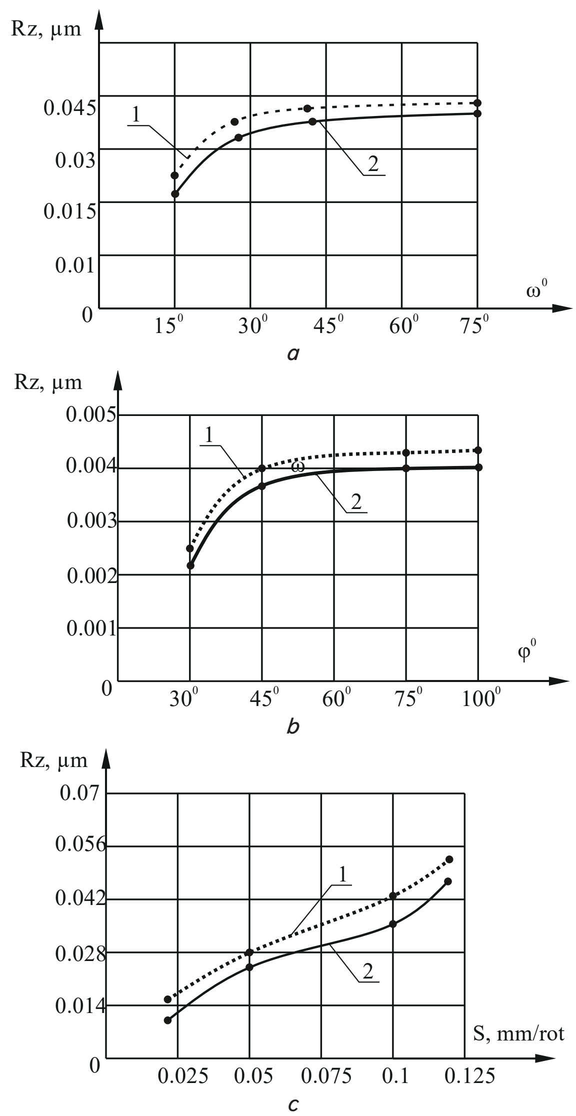

Fig. 6. Plots that compare the predicted roughness *Rz* when drilling carbon fiber CMU-P-0,1-A: 1 – theoretical calculations; 2 – field experiments; *a* – φ=60°; *b* – ω=25°; *c* – ω=25°, φ=60°

To assess the adequacy of the experimental data obtained, experimental drills were additionally monitored according to the tool wear parameter along the rear edge, h_w. The experience of blade processing of PCM shows that the wear parameter of the tool, h_w, should be no more than 0.3 mm since its value directly affects the cutting forces in the contact zone of the cutting wedge of the drill [22]. With increasing tool wear parameter along the rear edge (h_w>0.3 mm), the friction forces of the tool increase, which in turn reduces the cutting forces. The latter leads to a decrease in geometric accuracy and an increase in roughness along the hole, as well as at the inlet and outlet of the drill.

Fig. 5 shows comparative measurements of the values of the wear intensity along the rear edge h_w for experimental drills per meter of the cutting path. The wear intensity was established when processing carbon fiber CMU-P-0.1-A according to cutting modes at speed V=40 m/min. and feed S=0.1 mm/rev. Measurements of wear along the rear edge of the drill h_w confirm the fulfillment of experimental conditions, namely: h_w no more than 0.3 mm.

However, it should be noted that the best stability properties (lower wear intensity) and quality parameters among all experimental drills belong to the Guring-704 type drill with automatic feed.

Based on the results of experimental studies of drills and drilling holes with a diameter of 5 mm in carbon fiber, the following recommendations can be provided:

– all experimental drills, spiral VK8, Guhring-704, and Guhring-732, showed sufficient efficiency in ensuring geometric accuracy, roughness, cylindricity and taperness, but preference should be given to the Guhring-704 drill with automatic feed;

– for drills of spiral type VK8, with increasing speed and feed, the drilling process is associated with an increase in chips both at the inlet and outlet of the drill, while at the inlet the magnitude of delamination and uncut fibers decreases. To reduce such defects in order to ensure 8–12 IT grades when using the VK8 helical drill, automatic feeding should be used;

– to obtain holes without shrinkage and geometric accuracy of 7–8 IT grades, it is proposed to use drills that implement the process of drilling with deployment. The nominal size of the sweep should be selected 0.01...0.025 mm larger than the nominal size of the given hole.

Analysis of the results of full-scale experiments allows us to draw the following conclusions. The obtained results of drilling carbon fiber holes showed that the roughness primarily depends on feed S (Fig. 6, *c*) and drill sharpening angles φ and ω (Fig. 6, *a, b*). Experimental roughness measurements made it possible to establish that it is lower than the theoretical calculated values. This is due to the additional destruction of the fragile PCM fibers due to the reverse course of the drill (exit from the hole).

The reverse stroke of the drill in the calculated formulas of the predicted roughness Rz (1) to (3) was not taken into account, which confirms the adequacy of theoretical roughness calculations, which are within the error range of 10...15 %. The accuracy of the results can be increased by taking into account material shrinkage and tool backstroke.

However, the obtained formula for predicting the surface roughness of the hole when drilling PCM, taking into account the geometry of the tool and cutting modes, can be used for approximate and preliminary calculations. Such roughness can be obtained for any type of drill.

6. Discussion of results of investigating the quality of a carbon fiber hole

The study of mechanical processing of carbon fiber CMU-P-0.1-A is due to its wide demand for use in the production of various parts and structures, which is confirmed by work [8]. It was established that the quality of the surface of the carbon fiber hole depends on its physical and mechanical properties, drill geometry, and cutting modes. In accordance with the kinematic scheme of interaction of the cutting edges of the drill with the fibers of the PCM filler (Fig. 1), parameters for the formation of the predicted roughness Rz along the surface of a hole in AS made from PCM were established (Fig. 2). The formulas of predicted roughness Rz (1) to (3) combine cutting modes and geometry of the tool, which complements works [10, 11] and can be used for pre-selection of the drill and cutting modes of high-strength carbon PCM the type of Kevlar.

Our experimental results from the study of carbon fiber holes showed that the roughness primarily depends on feed S (Fig. 5, *c*) and the angles of sharpening the drill φ and ω (Fig. 5, *a, b*). This can be used to refine the mathematical model reported in [17], which will increase the accuracy of obtaining results for any RCM.

The peculiarity of the proposed approach to the calculations of the predicted hole roughness in PCM is that it is based on:

– an integrated approach to the quality of the hole in the PCM, which is based on a preliminary analysis of the kinematics of tool movement along the thickness of the PCM. This can be used to refine the methodology based on analytical modeling [18] in order to optimize the geometric shape of the cutting tool – drills;

– taking into account the cylindricity and taperness of holes in PCM, which, together with the findings from [19], will allow us to evaluate the quality of the holes in accordance with the structural-geometric parameters of the drill.

Such conclusions may be considered appropriate from a practical point of view since they provide a reasonable approach to determining the specific quality parameters of a PCM hole. This does not contradict work [22] but, conversely, constitutes the scientific novelty of the study where the kinematic scheme of drilling holes was developed by establishing contact of the cutting wedge of the drill with the filler along the PCM hole. Moreover, from a theoretical point of view, it is possible to determine the predicted roughness, which is a certain advantage of this study. However, it is impossible not to note that the determination of the predicted roughness does not allow determining the taperness, cylindricity, and deviations from the geometry of the hole. Such uncertainty imposes certain limitations on a comprehensive assessment of the quality of the hole surface, which can be interpreted as a drawback of this study. The inability to remove this restriction in the framework of this study gives rise to a potentially interesting direction for further research. In particular, it can be focused on establishing new dependences and formulas that can predict taperness, cylindricity, and deviations from the geometry of the hole. Theoretical results of forecasting the parameters of the hole will make it possible to avoid additional full-scale or numerical experiments, measurements and control, which will reduce labor intensity and time. This means that the practical significance of our results is in their use for devising production technology and assembly of any parts from PCM.

However, the appearance of these defects directly depends on the size of tool wear along the rear edge h_w. Increasing the parameter h_w entails an increase in friction forces during drilling and an increase in roughness, taperness, and deviations from the cylindricity and geometry of a PCM hole. There is a solution to this problem by operational control over drill geometry or pre-established measurements of wear intensity values along the rear edge for experimental drills when processing PCM according to selected cutting modes. It should be noted that the calculations of the predicted roughness reported in this paper do not take into account tool wear along the rear edge h_w, so the reliability of the results is ensured if the condition for h_w no more than 0.3 mm is met.

Obviously, the improvement of theoretical positions and their confirmation experimentally in the formation of quality parameters of holes in AS made from PCM obtained by drilling is an urgent task in the future. Therefore, further studies can focus on an integrated approach, taking into account tool wear along the rear edge, its reverse, and the appearance of shrinkage in a RCM hole, as well as in automatic regulation of drilling modes.

7. Conclusions

1. A kinematic scheme of formation of the predicted surface roughness of the hole in PCM by analyzing the kinematic scheme of contact of the cutting wedge of the drill with the filler along the hole is proposed. According to this kinematic scheme, the influence of cutting modes and drill geometry on the roughness parameters along the surface of the hole made from PCM was established.

2. In the course of data analysis, the roughness in full-scale experiments turned out to be lower than the theoretical calculated values. This is due to the existence of the reverse stroke of the drill (exit from the hole), which further destroys the fragile fibers of PCM. The reverse stroke of the drill was not taken into account in the calculations of the predicted roughness, but the error was no more than 10...15 %, which confirms the adequacy of the accepted theoretical calculations. The error can be reduced by taking into account the shrinkage of the material and the reverse of the tool. Therefore, the proposed formula for predicting the surface roughness of the hole when drilling PCM, taking into account the

geometry of the tool and cutting modes, can be used for approximate and preliminary calculations for any type of drill.

3. The results of experimental studies on the formation of the quality parameters of the hole in the PCM by drilling confirmed the results of theoretical studies according to the accepted kinematic schemes of the drill operation in PCM along and across the hole. The roughness distribution, taperness formation, deviations from geometric precision, and cylindricity by characteristic rotation zones of the drill within angles from 0° to 360° depend on the drilling parameters and on the properties of the PCM. It has been established that shrinkage has an effect on the formation of a deviation from the cylindrical hole of the PCM (the appearance of ovality). The results of measurements of hole diameters to establish deviations from cylindricity and geometric accuracy satisfied production requirements. For the PCM hole, accuracy ranging from 7 to 12 IT grades and taperness from 0.083 to 0.28 % were achieved, i.e., 9–10 IT grades.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

Funding

The study was conducted without financial support.

Data availability

All data are available in the main text of the manuscript.

Acknowledgments

Special thanks to the head of the workshop for the production of parts from composite materials of the State Enterprise «Antonov», Oleksandr Kass; the leading engineer for the production of composite materials of the State Enterprise «Antonov», Volodymyr Nytka; the head of the aviation aircraft production department of the Kyiv Aviation Vocational College, Sergey Tolstoy, for all possible support in the implementation of the research reported here.

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