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RESEARCH OF THE PROCESS OF DRILLING HOLES IN PARTS MADE OF POLYMER CARBON PLASTIC

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Abstract. *The article presents analytical models for evaluating the process of drilling holes in parts made of fibrous composite materials by drilling, which is accompanied by unusual defects that are not typical for metal cutting, such as delamination, chips, hairiness, composite chipping, thermal destruction and uncut fibers around the drilled hole, as they affect the service life of composite details. The influence of processing conditions and modes (feed, spindle speed and drill tip angle) of carbon fiber on the drilling quality parameters (delamination coefficient and roughness of the machined surface) and axial cutting force is established. The delamination coefficient (K_{sr}) in composite materials was taken into account, for which the critical axial force was determined, the excess of which leads to delamination of the hole surface, by an indirect method - by measuring the axial force. Measurement of the axial force and determination of its parameters were performed using an experimental setup. The machining modes during experimental studies varied within the following limits: the number of revolutions n - from 1250 to 4000 rpm and the feed S - from 50 to 800 mm/min. Drilling was performed on a vertical milling machine with a CNC SMG-300 with a maximum spindle speed of 5000 rpm. carbide drills with a diameter of 5 mm SANDVIK class ISO K20. Analytical dependencies were constructed using modern methods of multivariate statistical analysis - by the method of group consideration of arguments for calculating the quality parameters of holes in composite materials from cutting modes: the number of revolutions of the drill n, the feed S and the angle φ at the tip of the drill. An optimization problem of nonlinear programming was solved where the material removal rate was chosen as the optimality criterion. The value of the optimal mode for drilling holes in carbon fiber with a carbide drill VK8 with a diameter of 5 mm with an angle at the edge $2\varphi = 100°$ ($V = 2.83$ m/min, $S = 406.26$ mm/min) was established, which ensures maximum hole processing performance. The results of the study are the practical importance for mechanical engineering and the aviation industry, as they allow to increase the stability and productivity of technological processes for manufacturing products from composite materials.*

Keywords: *Composite materials; drilling; carbon fiber plastics; quality parameters; delamination; roughness; experimental researches; experimental setup; axial cutting force; modeling; optimization.*

1. Introduction

Fibrous polymer composite materials, such as carbon fiber and fiberglass, are widely used in various branches of modern instrument and mechanical engineering, in particular in the aircraft industry [1, 2], due to their unique physical and mechanical properties.

Composite materials are characterized by high strength, stiffness, corrosion resistance, low coefficient of thermal expansion, improved fatigue performance during operation, electrical insulation properties and anisotropy, which allows you to control the properties of the final product by changing the number of fibers, their orientation and the type of layer arrangement. Polymer composite materials with carbon fibers and a flexible epoxy resin matrix have become particularly widespread [3].

2. Problem statement

Despite the high physical and mechanical performance of multilayer composite materials, their use in various industries, especially in aircraft construction, requires taking into account the peculiarities of drilling polymer composite materials, which is accompanied by the occurrence of specific geometric defects, including uncut fibers, delamination, hairiness, chipping of the composite, shrinkage of the material, as well as thermal destruction and high roughness of the machined surface.

Therefore, an urgent task is to study the process of processing composite materials by modeling the quality parameters of the process of drilling holes in details made from polymer composite materials for its optimization.

3. Literature review

For critical structures made from composite materials, drilling is used, which is accompanied by unusual defects inherent in metal cutting, such as delamination, chips and uncut fibers around the drilled hole. The presence of such defects leads to the formation of gaps between parts, as a result of which the connections of structures are weakened, which is unacceptable for the general requirements of mechanical engineering [4]. This is due to such characteristics of the material as heterogeneity, anisotropy, the presence of highly abrasive reinforced fibers, the combination of hard abrasive fibers with a soft matrix [5].

The widespread use of composite materials in obtaining holes for fasteners requires ensuring high-quality holes for connections between details and increasing the efficiency of the drilling process, which is possible by determining the optimal cutting modes [6].

The machinability of composite materials can be analyzed using: axial cutting force, torque, roughness of the machined surface, delamination of the hole, the degree of uncut fibers and tool wearing out [7].

These parameters are influenced by cutting modes (feed and speed), properties of the workpiece material and tool material. Intensification of these modes leads to an increase in cutting force and increased tool wearing out. In the process of drilling composite materials, axial force can lead to delamination and interlayer cracking at the exit of the hole, where the low thickness of the layered material provides less resistance to tool penetration [8]. At the same time, a higher cutting speed allows for better hole quality.

Surface roughness is one of the main characteristics in the drilling process of composite materials, which is used to analyze the quality of the machined surface by studying the microroughness of the detail's surface, which is most often estimated by the parameters R_a and R_z [7, 8].

4. Materials and Methods

To implement the tasks of researching the quality of machined hole surfaces in polymer composite materials, drilling efficiency indicators were considered, since they affect the service life of composite details. During the drilling of polymer composite materials, various defects can be formed, such as delamination, damage to the surface layer, high roughness of the machined surface, dimensional error and deviation from roundness [9].

Delamination is the most common defect during drilling of composite materials. This quality parameter is divided into delamination at the entrance of the cutting tool into the material and delamination at the exit from it. There are many ways to assess the quality of the hole for fiber-reinforced polymers, including delamination and uncut fibers. One of the methods for non-destructive assessment of the drilled holes quality is the analysis of the hole exit in carbon fiber plastics, which is a simple measured variable that reflects the quality of the hole. [10].

The most common characteristic of the delamination parameter when drilling composite materials is the delamination coefficient (K_{sr}), proposed by Chen [11], the value of which is determined by the formula:

$$K_{sr} = \frac{D_{max}}{D}$$

where $D_{\max}$ is the maximum diameter of the hole with the damaged area; D is the nominal diameter of the hole. To analyze delamination in composite materials, Ho-Cheng used a fracture mechanics approach [12]. To do this, they determine the critical axial force P_{caf}, exceeding which leads to delamination of the hole surface.

This parameter relates delamination to the properties of the composite material according to the following formula:

$$P_{caf} = \pi \sqrt{\frac{8G_{Ic}E_1h^3}{3(1-\upsilon_{12}^2)}}$$

where G_{Ic} is the interlayer fracture toughness, J/m^2; E_1 is the modulus of elasticity, N/m^2; h - the thickness of the uncut layer of the workpiece, mm; υ_{12} - Poisson's ratio. Compared to other fibrous polymer composite materials, carbon fiber composites are most prone to delamination, which is accompanied by an excess of the critical axial force, although their interlaminar fracture toughness is lower (Table 1). This is due to the fact that these materials have a higher elastic modulus [13].

Table 1 – Critical axial force for carbon fiber composites, fiberglass composites and hybrid composites at a layer thickness of h = 0.5 mm.

Material	G_{Ic}, J/m^2	E_1, GPa	υ_{12}	P_{caf}, N
Carbon fiber	290	150	0,25	391
Fiberglass	568	25	0,18	220
Hybrid material	299	52,5	0,20	231

To obtain mathematical dependencies of the parameters of the quality of processing holes in composite materials, corresponding experimental researches were conducted.

5. Experiments

In the experimental researches, carbon fiber composite with a carbon fiber content of 50% with an orientation of 0/90° was used as the processing material [14]. The matrix material was epoxy resin LY564 and hardener HY 564 manufactured by Huntsman Co. The total thickness of the composite material was 8±0.1 mm and contained 32 layers with a thickness of 0.25 mm. The carbon fiber composite was manufactured using the transfer molding technology (RTM). The workpiece was a sheet of material 160 mm × 160 mm × 8 mm, which was cut into bars 20 mm wide for further processing. In the experimental researches, carbon fiber composite with a carbon fiber content of 50% with an orientation of 0/90° was used as the processing material.

The total thickness of the composite material was 8±0.1 mm and contained 32 layers with a thickness of 0.25 mm.

The holes were drilled on a vertical milling machine with a CNC SMG-300 with a maximum spindle speed of 5000 rpm. As a cutting tool, carbide drills with a diameter of 5 mm SANDVIK class ISO K20 were used.

The angles at the apex 2φ of the drills were 60º, 100º and 140º, they were formed by the grinding operation.

To measure the axial force signal, the workpiece was mounted on a four-component piezoelectric dynamometer Kistler 9272, which in turn was fixed on the machine table. The experimental data were transmitted via an RS-232C data interface using three Kistler 5070A amplifiers and processed on a PC using the corresponding DynoWare software from Kistler. The surface roughness of the machined holes, according to the parameter R_a, was measured using a Perthometer M2. The base length value was 0.8 mm..

The value of the delamination coefficient was determined by photographing the drilled hole using a microscope with a 500-fold magnification, on which a camera was installed.

The maximum diameter of the hole was calculated by processing images using the LabView v. 6 system.

The study of the process of drilling holes with measurement of axial force and determination of its parameters was performed using an experimental machine. The general scheme of the experimental machine for studying the process of drilling carbon fiber parts is shown in Figure 1

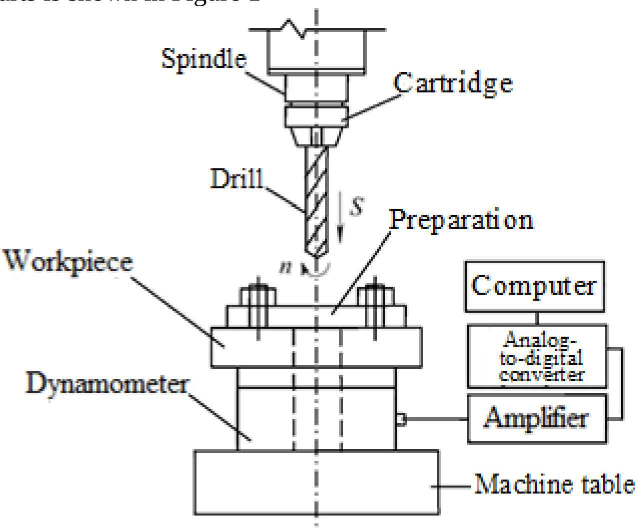

Figure 1 – Scheme of the experimental machine for studying the drilling process of carbon fiber parts

The purpose of experimental research on the drilling process of carbon fiber parts is to study the influence of processing conditions and modes (feed, spindle speed and drill tip angle) on the parameters of carbon fiber drilling quality (layering coefficient and roughness of the machined surface) and axial cutting force. The processing modes during the research varied within the following limits: speed *n* – from 1250 to 4000 rpm and feed *S* – from 50 to 800 mm/min.

6. Results

Processing of the results of experimental studies to obtain the corresponding mathematical models was performed using modern effective methods of multivariate statistical analysis [15].

Using the GMDH Shell DS software, which implements the advantages of group argument accounting methods (MGAA), mathematical dependences of quality parameters on the number of revolutions of the drill *n*, feed *S* and sharpening angle *φ* at the tip of the drill were obtained [16].

When obtaining the mathematical dependence of the axial force $P = f(n, S, \varphi)$ on the number of rotations, feed and angle at the tip of the drill, 25% of the initial data were used as a test sample to assess its accuracy.

As a result, the following dependence was obtained with a coefficient of determination $R^2 = 0.994$ on the test sample:

$$P = 0{,}37403531 \cdot S + 0{,}80636969 \cdot \varphi - 0{,}042552536 \cdot n + \\ +2{,}5174804 \cdot 10^{-3} \cdot S \cdot \varphi - 1{,}1838289 \cdot 10^{-4} \cdot S \cdot n \\ - 2{,}8640392 \cdot 10^{-4} \cdot \varphi \cdot n - \\ -6{,}6437653 \cdot 10^{-7} \cdot S \cdot \varphi^2 + 1{,}5512999 \cdot 10^{-8} \cdot S \cdot n^2 + \\ +3{,}7530623 \cdot 10^{-8} \cdot \varphi \cdot n^2 + 7{,}5583524 \cdot 10^{-8} \cdot \varphi^2 \cdot n - \\ -1{,}983767 \cdot 10^{-4} \cdot \varphi^2 + 5{,}5761222 \cdot 10^{-6} \cdot n^2 - 9{,}9045321 \\ \cdot 10^{-12} \cdot \varphi^2 \cdot n^2 - \\ -2{,}7554812 \cdot 10^{-14} \cdot S \cdot \varphi^2 \cdot n^2 - 7{,}9678736 \cdot 10^{-7} \cdot S \cdot \varphi \cdot n \\ + \\ +1{,}0441172 \cdot 10^{-10} \cdot S \cdot \varphi \cdot n^2 + 2{,}1027644 \cdot 10^{-10} \cdot S \cdot \varphi^2 \cdot n \\ + 99{,}778598$$

Since it is practically impossible to measure the value of the delamination coefficient during the machining process, it is proposed to determine this parameter by an indirect method - by measuring the axial force. For this purpose, the dependence $K_{del}=f(P)$ was obtained, which allows determining the value of the delamination of the hole in the processed material by the value of the axial cutting force.

A similar approach is also proposed to be performed to determine the roughness of the hole surface.

To obtain an analytical dependence of the delamination coefficient, a 5th order polynomial regression was used based on the results of experimental studies:

$$K_{del} = 1{,}58379455006 \cdot 10^{-12}P^5 - 1{,}7774707523 \cdot 10^{-9}P^4 + \\ +7{,}0153442442 \cdot 10^{-7}P^3 - 1{,}17101594923852 \cdot 10^{-4}P^2 + \\ +8{,}83914402978316 \cdot 10^{-3}P + 0{,}788058618989498$$

The quality of the obtained dependence $K_{del}=f(P)$ is confirmed by the accuracy parameters: average absolute error – 0.0351; average square error – 0.003; average relative error – 2.8941%; coefficient of determination R^2 – 0,9296.

To control the roughness parameter of the machined surface by the value of the axial cutting force, based on the results of experimental studies, a mathematical model of the dependence of roughness on the axial force $Ra = f(P)$ was obtained,

By the SPSS Statistics software, the curves of graphical dependences were compared using the regression module to obtain an analytical dependence that best describes the statistical data [17]. It was determined that the power form of the regression equation most accurately approximates this dependence best describes

$$Ra = 0{,}0898P^{0{,}5064}$$

statistical data with the following accuracy parameters: average absolute error – 0,2031; average square error – 0.069; average relative error – 15.6206%; coefficient of determination R^2 – 0,7419.

The developed mathematical dependencies of the quality parameters of the hole surfaces (delamination and roughness) are convenient to use for predicting these parameters when drilling holes in carbon fiber parts and as a constraint in the general mathematical model of the drilling process when solving the optimization problem. At the same time, these mathematical dependencies are adequate for the following processing modes: the number of rotations n - from 1250 to 4000 rpm and the feed S - from 50 to 800 mm/min.

Optimization of the conditions and modes of processing of composite materials involves solving various technological, structural, economic and organizational problems. For this, the following optimality criteria are used: the criterion of minimum cost; the criterion of maximum efficiency (productivity), which ensures the minimization of the time spent on mechanical processing; criteria of quality and accuracy of processing, etc.

As an example of solving the optimizing problem the drilling process in carbon fiber parts, which provides the necessary parameters of the quality of the holes, the maximum productivity N of this process was chosen as the criterion.

Therefore, the task of solving the optimization problem of nonlinear programming, which is built on a model where the material removal rate is chosen as the optimality criterion [17].

$$max \quad N = \frac{(m_w - m_p)}{\rho \cdot t}, \quad t = \frac{l \cdot n}{S} \quad \rightarrow \quad max \quad N = \frac{(m_w - m_p)S}{\rho \cdot t},$$

where m_w – mass of the workpiece, kg;

m_p – weight of the part, kg;

ρ – material density, kg/mm^3;

t – processing time, min.

l – cutting path when drilling one hole, mm;

n – number of holes;

S – drill feed, mm/min.

In this case, a set of restrictions is set on the parameters of the quality of the hole surfaces and the capabilities of the equipment used:

$$P=f(n,S,\varphi)\leq 138;$$

$$K_{sr}=f_1(n,S,\varphi)\leq 1,1;$$

$$R_a=f_2(n,S,\varphi)\leq 1,6;$$

$$50\leq S\leq 800;$$

$$1250\leq n\leq 4000$$

Thus, as a result of experimental research and solving the problem of optimizing the process of drilling holes in carbon fiber with a VK8 carbide drill with a diameter of 5 mm and an angle at the apex of 2φ = 100°, the value of the optimal drilling mode (V = 62.83 m/min, S = 406.26 mm/min) was obtained, which ensures maximum hole processing performance.

7. Discussion

According to the results of experimental researches, it was found that the roughness of the machined surface of the holes increases with increasing feed and decreases with increasing drill speed. In addition, by comparing the obtained models, it can be concluded that the angle at the tip of the tool does not have a clearly defined effect on the R_a parameter.

The studies have shown that the values of the axial force and the delamination coefficient can be minimized at high spindle speeds and reduced feed values.

Modern production is focused not only on the quality of the finished product, but also on its manufacture with the lowest possible costs in the shortest possible time and in accordance with the specified quality indicators.

With adequate mathematical models of the parameters of the drilling process in carbon fiber parts, it is possible to determine the influence of cutting modes and conditions on the stability of the cutting process and establish optimal values of modes that provide the necessary dynamic properties.

It has been established that increasing the thickness of the material layer leads to an increase in the critical value of the axial force, which accordingly requires an increase in the values of the optimal cutting modes. The use of fiberglass or hybrid composite material as the processed material reduces the feed value and the number of revolutions of the drill, which negatively affects the productivity of the process.

Conclusions

Based on the results of the research and modeling of the parameters of the drilling process in carbon fiber parts, the following conclusions can be made.

1. As a result of the analysis of the drilling process in carbon fiber parts, it was established that the criterion parameters of the quality of the process are the delamination coefficient and the roughness of the machined surfaces, which can be determined by the magnitude of the axial cutting force.

2. A scheme of the machine for conducting experimental reserches is proposed, which allows obtaining the necessary information for creating mathematical models of quality parameters when drilling holes.

3. As a result of processing the experimental research data, mathematical dependences of the axial force, delamination coefficient and roughness of the treated surface on the cutting modes and conditions were obtained, which allow forming a mathematical model of the drilling process in carbon fiber.

4. The developed mathematical model of the process of drilling holes in carbon fiber parts makes it possible to solve the problem of optimizing cutting modes, which ensures obtaining the specified quality parameters of the resulting surfaces with the highest productivity.

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Віктор Антонюк, Сергій Вислоух, Оксана Волошко, Київ, Україна

ДОСЛІДЖЕННЯ ПРОЦЕСУ СВЕРДЛІННЯ ОТВОРІВ В ДЕТАЛЯХ З ПОЛІМЕРНОГО ВУГЛЕПЛАСТИКУ

Анотація. *В статті представлені аналітичні моделі для оцінки процесу свердління отворів в деталях з волокнистих композиційних матеріалів свердлінням, що супроводжується незвичайними дефектами, які невластиві різанню металу, такі як розшарування, сколи, ворсистість, викришування композиту, термічна деструкція та нерозрізані волокна навколо просвердленого отвору, оскільки вони впливають на термін експлуатації композитних деталей. Встановлено вплив умов та режимів оброблення (подачі, кількості обертів шпинделя та кута при вершині свердла) вуглепластику на параметри якості свердління (коефіцієнт розшарування та шорсткість обробленої поверхні) та осьову силу різання. Враховано коефіцієнт розшарування (Ksr) в композиційних матеріалах, для чого визначали критичну осьову силу, перевищення якої призводить до розшарування поверхні отвору, непрямим методом – шляхом вимірювання осьової сили. Вимірювання осьової сили та визначення її параметрів виконували за допомогою експериментальної установки. Режими оброблення при проведенні експериментальних досліджень варіювались в межах: кількість обертів n – від 1250 до 4000 об/хв та подача S – від 50 до 800 мм/хв. Свердління виконували на вертикально-фрезерному верстаті з ЧПК SMG-300 з максимальною частотою обертання шпинделя 5000 об/хв. твердосплавними свердла діаметром 5 мм SANDVIK класу ISO K20. Побудовані аналітичні залежності з використанням сучасних методів багатовимірного статистичного аналізу – методом групового врахування аргументів для розрахунку параметрів якості отворів композиційних матеріалів від режимів різання: числа обертів свердла n, подачі S та кута φ при вершині свердла. Розв'язана оптимізаційна задача нелінійного програмування де критерієм оптимальності вибрана швидкість знімання матеріалу. Встановлено значення оптимального режиму свердління отворів у вуглепластику твердосплавним свердлом ВК8 діаметром 5 мм з кутом при вершині 2φ = 100° (V = 2,83 м/хв , S = 406,26 мм/хв), який забезпечує максимальну продуктивність оброблення отворів. Результати дослідження мають практичне значення для машинобудування та авіаційної промисловості, оскільки дозволяють підвищити стабільність та продуктивність технологічних процесів виготовлення виробів з композиційних матеріалів.*

Ключові слова: *композиційні матеріали; свердління; вуглепластики; параметри якості; розшарування; шорсткість; експериментальні дослідження; експериментальна установка; осьова сила різання; моделювання; оптимізація.*