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FORMING A DEFECTIVE SURFACE LAYER WHEN CUTTING PARTS MADE FROM CARBON-CARBON AND CARBON-POLYMERIC COMPOSITES

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Представлені результати теоретико-експериментальних досліджень, спрямованих на встановлення механізмів формування дефектного шару на оброблюваних поверхнях з вуглецевих композиційних матеріалів, зокрема, карбон-карбонової та карбон-полімерної груп. Володіючи комплексом унікальних фізико-механічних властивостей, останні знаходять усе більше застосування в авіа- і космічній техніці. Однак, оскільки властивості матеріалу обумовлюються не тільки застосовуваними компонентами, але й процесами одержання виробів (укладанням армувальних волокон, орієнтацією джгутів), проведення механічних випробувань зразків-свідків є обов'язковим етапом виконуваних робіт.

На основі узагальнення статистичної та теоретико-аналітичної інформації розроблена модель виникнення та поширення тріщин у квазікрихкому матеріалі, зокрема, карбон-карбоновому та карбон-полімерному композитах, викликаних дією різального клина. Показано, що створювані напруження в поверхневому шарі обумовлюють інтенсивність росту тріщин, а напрямок поширення мікротріщин обумовлений прикладеним силовим навантаженням. Тому управлінням напрямку дії сили, а також використанням певних технічних засобів, у тому числі, гідроабразивного струменя, можна досягтися локалізації мікротріщин у малих об'ємах на поверхні формованої крайки.

Установлені закономірності формування дефектного шару при механічній обробці (включаючи гідроабразивне різання) дозволили виявити шляхи підвищення якості зразка та досягти зниження товщини шару до 0,05 мм. Отримані залежності параметрів зони деструкції від виникаючих при різанні напружень дозволили одержати раціональну послідовність переходів обробки, при якій дефектний поверхневий шар найменший.

Отримані результати дають можливість суттєво підвищити точність механічних випробувань вуглецевих композиційних матеріалів, знизивши дисперсію вимірів контрольованих параметрів на 30–40 %.

Результати мають реальне виробниче впровадження, і становлять інтерес для подальших досліджень, спрямованих на гібридизацію процесів, а також розробку технологій, що базуються на основі функціонально-орієнтованого підходу.

Ключові слова: механічне різання, гідроабразивне різання, вуглецевмісний композиційний матеріал, дефектний шар

1. Introduction

Wide use of composite materials based on carbon-polymer fibers is predetermined by the high durability of goods, their light weight, the capability to perceive different kinds of force loads. Carbon-carbon materials possess in addition the capability to maintain mechanical properties at high temperatures.

Typically, the workpieces for products made from carbon-carbon composites are obtained by laying the wire strands, threads or fabrics onto the appropriate models followed by the saturation with pyrocarbon under conditions of high temperatures [1]. Parts made of the carbon-polymeric materials are obtained by using prepregs with laying onto the model and subsequent impregnation with components of polyester resins. This makes it possible at the stage of forming a material to assign the main axes of stiffness and strength, thereby achieving the desired level of anisotropy of properties of the structural elements and the finished product in general.

Even though the shape of a workpiece may be close to the shape of the finished part in the process of formation, there is a necessity for the finishing machining along the surfaces of joints, openings, grooves, elements of supports. In general, all of them are curvilinear.

At the same time, the final shape formation of an article does not rule out the machining of the most critical surfaces, however, the heterogeneous structure of a material leads to the emergence of surface defects forming a defective (destructive) layer.

When fabricating critical parts, as well as in the preparation of samples for mechanical tests, the existence of such a layer is inacceptable. Therefore, the description of the phenomena accompanying the machining, as well as the establishment of methods and techniques to prevent degradation in surface layers make it possible to set rational approaches to ensuring an adequate level of quality. Established regularities could form a basis for developing an engineering procedure for predicting the level of quality of edges to be obtained and for determining appropriate modes of conducting the machining, as well as a sequence of technological transitions.

2. Literature review and problem statement

Paper [2] shows that the fibrous composite materials (especially polymeric) have low machinability, parts made from them can be mechanically cut only with specialized tools. In addition, materials are susceptible to delamination, destruction, damage to the top and bottom edges, as well as to the emergence of a number of other defects, which may lead to that the finished product is discarded.

Better machining (with the minimal number of defects) is possible only when specialized tools. When drilling [3], the issues related to the cutting modes optimization, ensuring machining within the critical temperature of the material, have not been sufficiently studied. At milling [4], there remains unresolved the problem of chip formation and subsequent overheating of the tool. Abrasive machining [5] requires further study into related phenomena in the form of surface defects. Thus, even under these conditions, the emergence of various defects is quite likely.

Paper [6] shows the possibility of using the inkjet machining methods for cutting the parts made from composite materials. It is also noted that the heterogeneous structure of a material and the anisotropy of their properties require additional measures to prevent the destruction of machined materials and reduce the likelihood of defects.

Authors of [7] give a comparison table of the effectiveness of various methods of treating the workpieces made from composite materials based on glass and carbon fibers; however, conditions for obtaining high-quality surfaces are not described.

A study into mechanical properties of carbon composites [8] revealed the dependence of articles quality on the processes for their obtaining; however, the issues related to the impact of a force scheme acting on a material during machining remained unsolved.

Publication [9] is of interest; it reveals the issues related to the use of another class of superhard materials with nanocomposite coatings for the machining of new constructional materials and alloys. However, the authors did not specify the possibility of their use for cutting the carbon-containing composites.

Insufficient knowledge about the issues of machining of carbon-carbon composite materials became a prerequisite for undertaking a comprehensive study, with its relevance emphasized by the prospects and uniqueness of a given type of the material.

3. The aim and objectives of the study

The aim of this work is to develop the techniques for reducing the thickness of a defective layer based on the establishment of patterns in the formation of a defective layer at the machined surfaces at different technologies for cutting the samples made from carbon composites. The machining was performed by blade and diamond abrasive tools employing a jet-abrasive method.

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

– to define analytical correlations that relate the physical-mechanical properties of machined materials, modes of mechanical or jet-abrasive action to the thickness of the destructive layer, which forms at the machined surface;

– to determine whether the cutting modes, as well as the parameters of the applied tool, in particular its graininess and the grade of a super-hard material, influence the machining performance, as well as the thickness of the defective surface layer. This should be taken into consideration when treating samples for mechanical tests.

4. Research methods and equipment used

To conduct experimental study, we used standard and specialized laboratory equipment for mechanical and jet-laser machining.

The jet-abrasive contour cutting was performed at the laser-jet complex LSK-400-5 (ChP «Roden», Ukraine) with a 5-coordinate control system. The complex enables machining by the hydroabrasive flow with a diameter of 1.02 mm, flowing from a calibration tube with a mass flow rate of abrasive particles of 0.4–0.6 kg/min. We used as an abrasive garnet sand with a fraction of 50/75 μm. Thie contour feed speed was 300–800 mm/min. The diamond-abrasive cutting was carried out by the cutting wheel 1A1 150 AS6 100/80 on galvanic sheaf with a cutting speed of 50 m/s. Drilling the openings was carried out at the machine, model Proxxon MF70 (PROXXON GmbH, Germany), using drills of tubular type with the diamond powder AS6 100/80 AU on galvanic sheaf with a cutting speed of 10 m/s.

We cut the parts using the renovator Bosch PMF 250 CES (Bosch Power Tools, Germany) applying a specialized tool for reciprocating machining, the working surface of which is covered with a working layer of the diamond powder AS6 40/28 on galvanic sheaf.

State of the surface of the machined surfaces of parts was controlled by using the raster electron microscope REM-106-I and the optical digital microscope Omni_scan (OOO «NPP Akadempribor», Ukraine).

The influence of a technological medium (water) in the machining zone on the state of the surface layer of parts was estimated based on the results of mechanical tensile tests. In this case, we compared samples obtained by the mechanical and hydroabrasive cutting, both immediately following the machining and after their complete drying in a drying chamber at the air temperature of 60–75 °C and air flow rate 150 m^3/h.

Mechanical properties of the composites were evaluated using the universal testing machine UME-10TM (PAO «Tochpribor», Ukraine).

As a reference, we used samples obtained in line with the technologies that almost completely eliminate the formation of a defective layer by preliminary laying the samples-witnesses with subsequent polymerization for carbon-polymeric composites or sintering for carbon-carbon materials.

When applying a load, samples are destroyed when reaching the value of breaking force P_p, at which $\sigma_e>[\sigma]$. In this case, stresses:

$$\sigma_e = \frac{P_p}{b \cdot h},$$

emerge over area f in samples without a defective layer, in samples after machining –

$$\sigma'_e = \frac{P'_p}{(b-h_d)\cdot h},$$

where h_d is the depth of a defective layer.

Thickness of the defective layer:

$$h_d = \frac{b}{2}\left[1-\frac{P'_p}{P_p}\right]. \quad (1)$$

Similar considerations were accepted when comparing the mechanical characteristics of dry and wetted samples.

5. A problem on predicting the thickness of a defective layer and the solution to it

The heterogeneous structure of the examined materials, spatial interlacing of fibers with the formation of cavities and zones with a lack of the matrix, exert a significant impact both on the quality of the surface layer and the strength parameters, controlled by mechanical tests.

An analysis of micro photographs of the machining zone has shown that defects (Fig. 1) of the surface layer of parts made of carbon-carbon composites can be categorized in the following way:

– defects in the elastic recovery of the matrix fibers, as a result of which a controlled size is maintained, and the fibers are above the surface;

– defects of disruption of adhesion at the surface zone, resulting in a decrease in the active cross section of a sample by the magnitude of destruction;

– defects of the cohesion irregularity in the surface layer, at which the resulting micro- and macro cracks develop deep into the material and could actively grow at cyclic loading.

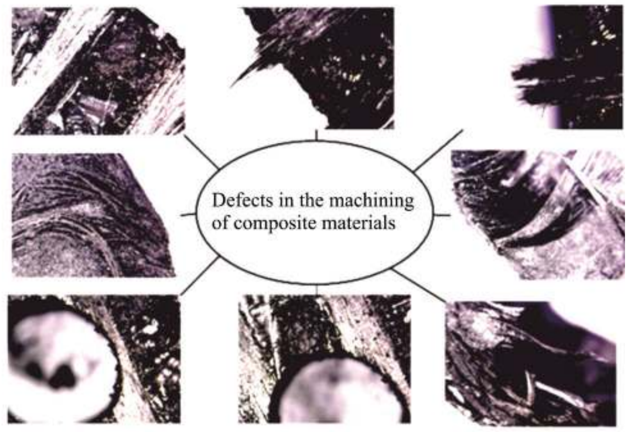


Fig. 1. Defects in the machining of composite materials

The emergence of various defects is determined by peculiarities of the thermobaric action on a workpiece surface layer by the instrument that is used. Thus, there is a certain connection between defects that occur in the surface layer of parts as a result of machining and the conditions for its execution, which is consistent with results obtained in [10].

We shall consider the basic mechanisms of defect formation when cutting parts made from carbon-carbon composites using different methods.

The basic mechanism for the formation of new surfaces at blade machining is linked to the chip formation process and is due to the phenomena of the emergence and development of micro defects, leading to the occurrence of cracks in the surface layer of a machined part at the macro level. Paper [11] noted that the stressed state at the top of the crack that appeared under the action of the tool along a hypothetical cutting surface ensures the development and propagation of cracks in the direction of the velocity vector of the main motion. The theory of Griffiths for elastic bodies, which under condition of isotropy could include the examined composites, makes it possible to expect a deviation of the crack from the initial direction at $K_{II}\neq 0$ (displacement) at a certain angle $\chi=-\chi_c$. This angle coincides with the direction of action of maximum strength P.

An increase in pressure causes a certain increase in the rate of progression of the crack, simultaneously reducing the path to the point of its bifurcation. In reinforced composites, there is a critical speed of crack propagation, which does not depend on the supplied energy. This phenomenon is due to the absorption and accumulation of micro defects, localized in the direction of roughly $\chi=\pi/3$, where there are the maximum tensile stresses. Therefore, the applied external force, at which there would be an active crack formation, should not exceed the resistance to cracking. In practice, this condition is difficult to satisfy because a periodic change in the cutting force is predetermined by both the cutting modes and the structure of a material, although paper [11] shows that the process of branching can be localized by regulating the type of load and energy-force parameters of loading.

A study into cutting patterns using a blade tool for the reinforced non-metallic materials, conducted by the author of paper [12] demonstrates, in particular, that the heterogeneity of a material structure leads to a redistribution of the regions where microcracks accumulate. When a cutting wedge moves along the direction of reinforcement, the high concentration, interaction, and coalescence of cracks lead to the formation of macro cracks. Macro cracks can be located at a distance from a cutting wedge, or be in contact with it, being positioned at an angle of 15–20° relative to the principal motion vector. When a cutting wedge moves at an angle of 90° to the direction of reinforcement, they concentrate in the polymer matrix and at the interface «fiber–matrix». A crack in this case develops at an angle of 40–60°. The structure of the transversely reinforced plastic material inhibits the development of a main crack and guides it along the fiber. It is at this site that the defects associated with chemical polymerization and residue from reaction products emerge, thereby weakening the strength of the composite.

Motion of the cutting tool causes fiber deformation, leading to a redistribution of loads in the cutting zone. Paper [10] noted that the machining of the transversely reinforced plastic material proceeds with a large delamination of fibers and the matrix, disruption of the surface structure and a significant decline in the quality of the machined surface layer of the product.

The periodic origination, development and merging of cracks lead to the separation of a material's particles, which predetermines the cyclical nature of the process of blade machining. At such a machining, cutting force first rises to the maximum value (at the origination of a crack grid), and then rapidly declines (when the main crack appears and a chip element peels off).

Thus, the mechanical cutting of composites from the carbon-carbon group using a blade tool is accompanied by the formation of a defective surface layer, which, as experience shows, can reach 0.9–4.5 mm [13].

At micro cutting using a tool with abrasive grains (for example, *cutting wheel*), crack formation proceeds in line with a similar scheme. In this case, four main types of cracks form: radial C_R, median C_M, lateral C_L, and conical C_K.

Despite certain differences in the mechanism of crack formation, their sequence will be as follows. Initially, there appear the median cracks at the border between the deformation zones under and around a single grain. When a load is removed (as a result of chipping or grain tear), those cracks reach the surface similar to the radial ones. When the load increases, or completely removed, under the influence of residual stresses the lateral cracks appear. Conical cracks may occur at the significant feed magnitudes, when a single grain is embedded into the machined surface using an impact method.

Paper [13] shows that the fragments of a material are peeled off mainly due to the formation of lateral cracks. The thickness of the defective layer in this case does not exceed 0.1–0.4 mm. Applying the tool with a reciprocating action leads to the fact that, owing to the limited motion speed of abrasive grains, as well as small (not larger than 3–4 mm) runs, the machined surface demonstrates lower quality. To improve the quality, the concentration of diamond in a tool should be as high as possible while the machining process should not be accompanied by significant force loads. In this case, it is necessary to take into consideration that the removal of a material when using the tool of a reciprocating action is significantly less than that when employing an abrasive wheel.

When *drilling the samples of materials using a spiral drill,* the force action changes, with the resultant cutting force also being changed; the crack formation zone consequently covers a certain volume of the material, greatly exceeding the zone of direct contact «part – tool».

Due to the imperfection of structure of actual composite materials, as well as the difference in the physical and mechanical properties of their components, cracking resistance depends on various manifestations of crack formation – the emergence of shear cracks or tear cracks. If we take into consideration that the direction of a crack propagation always contributes to its opening, the task on assessing the likely direction of a crack propagation then comes down to establishing the expected curve of the force load on a machining zone from the tool. The curve depends on the process scheme and conditions for its implementation.

When *drilling materials using tubular drills*, a certain microrelief appears on the machined surface, whose parameters define the height of micro irregularities R_a. Directly below it, there is the fissured layer δ, much more extensive than the first one. The density and size of cracks decrease when moving deep into a part. Both layers represent its defective surface layerWhen considering the mechanism of crack formation, one may note that the basic quality parameters of the surface layer depend on the length of cracks: magnitude R_a is defined by the size of median crack C_M while the depth of defective layer δ is defined by the size of conical cracks C_K.

Below the fissured layer, there is a micro plastic layer that surrounds each crack and extends to a distance of *t*. Its thickness is 1–2 μm, which is confirmed by data from [13].

The same paper also established that a surface roughness is related to the overall depth of the defective layer through a linear law:

$$\delta = a \cdot R_a + b, \tag{2}$$

where *a, b* are constant coefficients.

A similar dependence is observed for crack formation: there is a correlation between the size of conical and median cracks that define d and R_a. It was established that these coefficients depend on the grain size of diamond powder and properties of the machined material.

The most dangerous defect when drilling polymeric composites is considered to be the delamination between the adjacent layers of reinforcement along their direction.

The main cause for the emergence of delamination is a high value of the acting axial force whose magnitude is mainly defined by the tool feed. A significant role is also taken by the wrong choice of cutting tools and the degree of its wear. There are several known techniques to reduce the delamination, such as reducing the feed or drilling into a subplate. A layer-to-layer destruction (delamination) that occurs when drilling composites is the main defect that reduces the integrity of the product, the bending and fatigue strength of a composite.

Numerous experimental observations have shown that the delamination is evident around the opening at the input and output of the tool from a part and is related to the magnitude of the axial force. This phenomenon is more characteristic of the drilling using spiral drills rather than the tubular ones.

The emergence of layer-to-layer cracks at the input is due to the contact interaction between a transverse cutting edge of the tool and a workpiece surface. As a result, the thin layer of a composite starts to peel off, is separated from the neighboring one with the formation of a delamination zone around the input region of the opening. At a time when the drill is at the output of the opening, the number of layers of composite, located in front of the drill, reduces, resulting in a decrease in the overall hardness of a material. The result is the delamination of last layers and the destruction of last fibers in a material.

Many studies addressed the qualitative and quantitative characteristics of composites delamination [10, 14]; however, there are no dependences for carbon-carbon materials of the magnitude of delamination on thermobaric load during machining.

We shall analyze the stressed-deformed state of cutting zone at drilling. A tubular drill (Fig. 2) is a pipe with external radius r_z and internal radius r_{bn}, located perpendicularly to the machined surface.

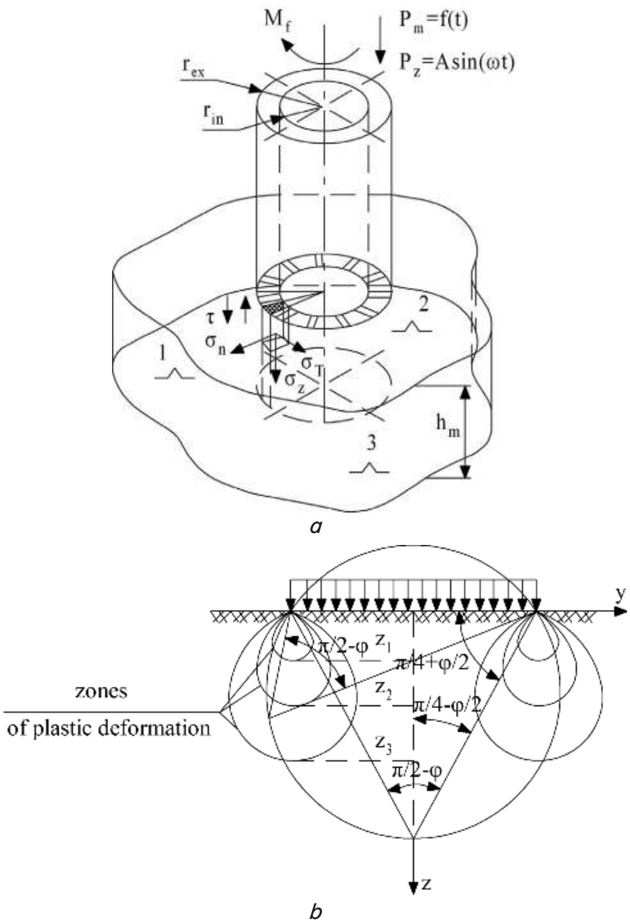


Fig. 2. Tubular drill:
a — action; *b* — stressed-deformed state in a cutting zone

At a force impact of the tool on the part, stresses σ_r, σ_z, σ_t and τ emerge in the corresponding microvolumes of a body with thickness h_{ob}. Components of displacements $U(t)$ and $H(t)$ at a specific point at surface [14], which accepts an almost perpendicular load, can be recorded:

$$U(t) = -\frac{(1-2\mu)}{G}\frac{P_z(t)}{\left(D_{\max}-D_{\min}\right)^2}r,\ r > \frac{D_{\max}}{2},$$

$$H(t) = -\frac{(1-2\mu)}{G}P_z(t)\frac{2}{\pi(D_{\max}-D_{\min})}, \quad (3)$$

where G, μ is the shear modulus and the Poisson's coefficient of the machined material, respectively; ε is the volumetric deformation;

$$\Delta = \frac{d^2}{dr^2} + \frac{d}{r\partial r} + \frac{d^2}{\partial z^2}$$

is the Laplace operator.

If we take into consideration that the corresponding components of stresses and deformations are derived from:

$$\varepsilon = \varepsilon_r + \varepsilon_t + \varepsilon_z = \frac{\partial U}{\partial r} + \frac{U}{r_m}\frac{\partial \mathrm{H}}{\partial z},$$

$$\varepsilon = \frac{1-2\mu}{2(1-\mu)G}\left(\sigma_r+\sigma_t+\sigma_z\right) = \frac{1-2\mu}{E}\left(\sigma_r+\sigma_t+\sigma_z\right), \quad (4)$$

the delamination of a material is then possible in the region where U and H reach a critical value, and, therefore, at load P_z a condition for the delamination takes the form:

$$\sigma_z \geq [\sigma_a], \sigma_r, \sigma_t \geq [\sigma_k]. \quad (5)$$

Paper [15] shows that despite the patterns in the method, jet-abrasive machining is a serious alternative to the mechanical cutting of parts made from composite materials.

At *jet-abrasive cutting*, there occurs the active destruction of a material by both a jet of fluid and the abrasive particles, causing the impact quasi-fragile micro destruction with the formation of finely-dispersed sludge. This phenomenon is observed when cutting the parts made from carbon-carbon materials in which relative elongation is approaching zero.

However, the non-dense structure of such materials, especially at spatial reinforcement, requires addressing the issue of the absence of damage by the flow, which, as already pointed in [16], is not a rigid indenter.

To analyze the interaction between a two-phase flow of small diameter and an obstacle – a heterogeneous machined part – we shall employ the energy concept, according to which energy E_Σ, given to the flow, turns into a work of destruction A_p and a change in the surface state A_c, as well as is used to change the motion direction of flow H, excluding the losses at various stages E_n, resulting in the development of a jet erosion funnel and in the formation of a destructive surface layer. In this case, a cutting groove forms as a result of a series of successive positions of the jet, at which the destruction of a material was complete throughout the entire thickness of workpiece h. General equation of energy balance for the case of jet-abrasive cutting takes the form:

$$E_\Xi = A_p + A_c + H + E_n. \quad (6)$$

Based on considerations [16], and with respect to the research results, kinetic energy of the jet is:

$$E_\Xi = \frac{M_{ij}V_{ij}^2}{2} - E_c - H, \quad (7)$$

where M_{ij} is the distribution of the working medium masses over the area of jet contact, kg; V_{ij} is the distribution of motion speeds of the working medium in cross-section, m/s; E_n are the energy losses in a jet, J.

A deviation of the jet stream incident to the corner deflector, which may be a bundle of fibers in composites with a 3-D structure, can be determined from dependence:

$$\varepsilon = \arctan\frac{a_1 - a_2\sqrt{\frac{v}{v_o\xi_{\max}}}}{\frac{y_d}{\xi_{\max}} - a_2\tan a\sqrt{\frac{v}{v_o\xi_{\max}}} - a_1\tan\varepsilon_d}, \quad (8)$$

where the constants are:

$$a_1=\frac{\varepsilon_d\cos\varepsilon_d}{\pi+\varepsilon_d};\;\; a_2=\frac{\pi+-0.6\varepsilon_d}{\pi+2\varepsilon_d}\frac{\sin\varepsilon_d}{\sqrt{(1-\varepsilon_d/\pi)/2}};$$

ε_d is the angle of an envelope, which is defined by the location of fiber in the matrix and depends on the resistance to the destruction of a material; v is the kinetic viscosity of liquid; v_o is the jet velocity; ξ is a coordinate, measured along the front (Fig. 3).

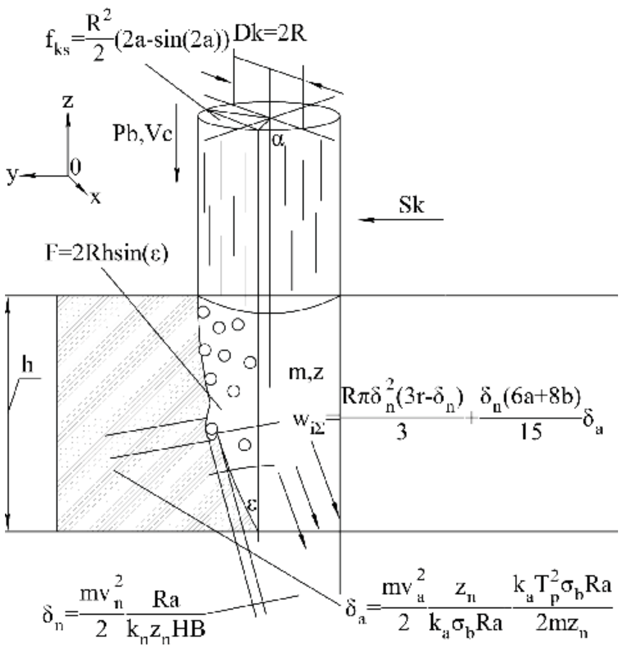


Fig. 3. Deviation of the jet when flowing over the front of a cutting zone

By assuming the absence of a large curvature of the front of a cutting groove (that is, the existence of an instantaneous value of the inclination angle of the front of a cutting groove) and the linearity of pressure distribution in cross-section of section CA, the force of pressure will be derived from:

$$P_z=\int_0^{\xi_{\max}} p\frac{l}{3}\cos\varepsilon_d \,d\xi, \quad (9)$$

for the case of $l=AC$, it will equal:

$$P_z=\frac{\rho v_0^2 y_0\xi_{\max}\varepsilon_d(3\pi-\varepsilon_d)\cos\varepsilon_d}{6\pi(\pi+\varepsilon_d)}.$$

The angle of deviation for the point of equal pulse in the direction parallel to the plane of jet flowing is derived from:

$$\varepsilon_i=\arctan\frac{P_{iz}}{J_{ix}};\;\; P_{iz}=k_z y_i z_i P_z.$$

Given that the pulse of the i-th point is $J_{ix}=J_0/n$, and the coefficient is:

$$k_z=\frac{1}{\sum_{i=1}^{n/2} y_i z_i},$$

the deviation angle of the determined i-th point is:

$$\varepsilon_i=\arctan\left[\frac{y_0\xi_{\max}\varepsilon_d(3\pi-\varepsilon_d)\cos\varepsilon_d}{6\pi(\pi+\varepsilon_d)}\cdot\frac{n y_i z_i}{\sum_{i=1}^{n/2} y_i z_i}\right]. \quad (10)$$

Then the offset of the i-th point of equal pulse in two directions – y and z is:

$$\Delta y_i = x\tan\varepsilon_0;\;\; \Delta z_i = x\tan\varepsilon_i. \quad (11)$$

At the time of flowing against the obstacle (a workpiece), the load on the machined surface would be derived from:

$$F_g=\rho A_1V_1^2 - C_f\rho z V_1^2\sqrt{A_c}, \quad (12)$$

where ρ is the density; A_1 is the amount of fluid between the cut of the nozzle and the machined surface; V_1 is the initial jet velocity; z is the depth of the formed ledge; A_c is the area of the cut-out; C_f is the coefficient of total resistance to friction at the surface.

Exceeding the critical value by force F_g can lead to the violation of condition (5) and the emergence of surface defects.

Action of the jet when flowing over an obstacle over time:

$$t_d=\frac{2r_cKv_c}{C^2}$$

will be derived from:

$$p=0.5\rho u_r^2+\rho Q u_t, \quad (13)$$

where u_r is velocity of fluid flowing from the nozzle of diameter $d=2r_c$, $u_t=\sqrt{2p_c/K_c\rho}$; K is a correction factor defined by the shape of the jet, $K=1–4$, C is the speed of propagation of impact wave in liquid, roughly equal to the speed of sound in a fluid; K_c is the compression ratio; ρ is the density of liquid; Q is the fluid flow rate.

At the same time, it was established by earlier studies [16] that the effect of particles of the abrasive, depending on the incidence angle ε, erodes the material, derived from:

$$\delta_n=\frac{m\left(0.335R\left(\frac{X}{X_c}\right)\left[1-\sqrt{\frac{\sigma_c}{2P_1}}\frac{X}{X_c}\right]^{\frac{4}{3}}\frac{2p_bf_k}{f_k\sqrt{2p_b\rho}+Q_m}\right)^2\sin\varepsilon}{2}\frac{R_a}{k_nz_nHB};$$

$$\delta_a=\frac{m\left(0.335R\left(\frac{X}{X_c}\right)\left[1-\sqrt{\frac{\sigma_c}{2P_1}}\frac{X}{X_c}\right]^{\frac{4}{3}}\frac{2p_bf_k}{f_k\sqrt{2p_b\rho}+Q_m}\right)^2\cos\varepsilon}{2}\frac{z_n}{k_a\sigma_bR_a}-\frac{k_aT_p^2\sigma_bR_a}{2mz_n}, \quad (14)$$

where p_b is the pressure before the jet nozzle, σ_b is the tensile strength of the material; k is the compression ratio; r is the radius of the active part of the jet; r_c is the nozzle cutoff radius; v_c is the velocity of the jet flowing from the nozzle attachment; f_k is the area of jet contact, $f_k=\pi d_c^2/4$; M_a is the mass consumption of the abrasive. Accepting that for a ball segment the volume is:

$$w_1=\frac{\pi\delta_n^2(3R-\delta_n)}{3},$$

where R is the radius of an abrasive particle, and for a cylindrical section:

$$w_2 = \frac{\delta_n(6a+8b)}{15}\delta_a,$$

the total amount of the removed material is:

$$w_{i\Sigma} = w_1 + w_2 = \frac{\pi\delta_n^2(3r-\delta_n)}{3} + \frac{\delta_n(6a+8b)}{15}\delta_a. \quad (15)$$

The width of the groove is:

$$\delta_b = 2\sqrt{\delta_n(2R-\delta_n)}. \quad (16)$$

When analyzing the formation of a destructive layer from the positions of linear mechanics of destruction, it becomes obvious that the depth of destruction is directly linked to both the properties of the machined material, its structure, and the nature of the mechanical loading of its individual components.

It is known that the stress intensity factor k, responsible for the release of energy of elastic deformations:

$$G = \frac{1-v^2}{E}A(V)k^2,$$

is related to the geometrical parameters of a crack and acting stresses σ in the following way:

$$k = \sigma\sqrt{\pi a}, \quad (17)$$

where a is half the length of the crack.

For the estimation diagram (Fig. 4, *a*), the micro stresses at the base of a crack are defined by dependence:

$$\sigma = \sigma_k + \left(\frac{b-l}{b}\right)\frac{3M_0}{2b^2}\cos\omega t, \quad (18)$$

where M_0 is the momentum acting on the surface microprojection.

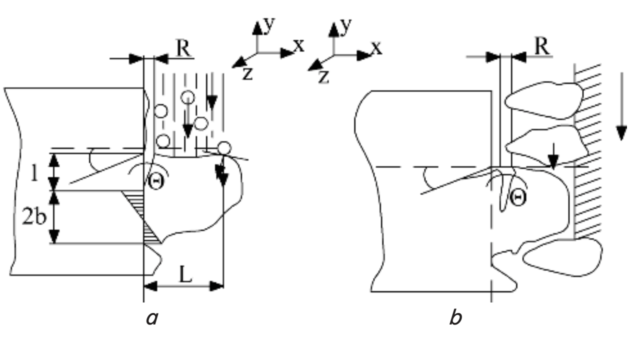


Fig. 4. Abrasive particles interaction with a surface layer of the part: *a* — at hydroabrasive cutting; *b* — when machined with a diamond circle

When an abrasive jet flow acts on the surface microprojections, crack growth velocity is proportional to $\sqrt{\omega\eta}$, where η is the kinematic viscosity of the fluid; ω is the frequency of load fluctuations, $\omega = 2\pi F$. The disjoining action of fluid molecules is evident in that the latter seek to maximally penetrate the crack and prevent closing its sides.

A momentum of external forces applied to a crack is derived from:

$$M_f = \frac{1}{2}\left[M_0\cos\omega t - \frac{(b-l)^3}{b^3}M_0\cos\omega t\right] = \frac{3l}{2b}M_0\cos\omega t, \quad (19)$$

where l, b are the geometrical parameters of a microprojection.

A pressure of the jet stream causing the disjoining effect is determined:

$$p = \frac{6\eta l^3}{h^3}\frac{d\Theta}{dt}\log\frac{x}{l} + p_c, \quad (20)$$

where p_c is the pressure of fluid outflow,

$$p_c = (0.5+\varepsilon)\cdot 10^{-6}\rho v^2;$$

h is the width of a crack; x is the distance from the base of the crack; h is the kinematic viscosity of liquid; $d\Theta/dt$ is the angular velocity of motion of the crack sides.

Bending momentum M_e, predetermined by an incident fluid flow, will equal:

$$M_e = \int_{b-e}^{b} py\,dy = \left[(0.5+\varepsilon)\cdot 10^{-6}\rho v^2\right]\left(\frac{l^2}{2} - bl\right) - \frac{6\eta l^4}{h^3}\left(b - \frac{3}{4}l\right)\frac{d\Theta}{dt}. \quad (21)$$

Given that at the base of the crack, when it opens, the stress increases at the expense of the momentum:

$$M_i = \int_{e^*} \sigma(h,y)y\,dy,$$

based on [16]:

$$M_f + M_e = \frac{3l}{2b}M_0 f(t). \quad (22)$$

Assuming the width of crack opening h is proportional to the momentum of external forces, with respect to:

$$M_0 f(t) = M_0\left(\frac{h}{h_0}\right)$$

and $l d\Theta = dh$, we obtain:

$$M_0 = \frac{2}{3}\frac{b}{l}\frac{\frac{6\eta l^3}{h^3}\left(b - \frac{3}{4}l\right)\frac{dh}{dt} - \left[(0.5+\varepsilon)\cdot 10^{-6}\rho v^2\right]\left(\frac{l^2}{2} - bl\right)}{\cos\omega t - \frac{h}{h_0}}, \quad (23)$$

where h is the width of the crack; η is the kinematic viscosity of liquid; dh/dt is the opening speed of a crack, which is determined by the physical and mechanical properties of a material and width $2b$, which indirectly defines the density of micro defects in the body of a workpiece.

Condition for the destruction of a microprojection is $\sigma \le [\sigma_a], \sigma \le [\sigma_k]$. Otherwise, a defective layer will grow (according to (5)).

For mechanical cutting (micro cutting) when treating with the tool of diameter D_I, to which momentum M_{kr} is applied:

$$M_0=\frac{2}{3}\frac{b}{l}\frac{R_r}{\cos\omega t-\dfrac{h}{h_0}}=\frac{2}{3}\frac{b}{l}\frac{M_{kr}}{\left(\cos\omega t-\dfrac{h}{h_0}\right)D_I}. \quad (24)$$

It is possible to determine the thickness of a destruction zone by assigning the number of loading cycles N, depending on the number of acts of interaction between a surface point and a cutting wedge or a diamond grain. To this end, we shall take into consideration that the simplified equation of crack development under cyclic loading is described by dependence:

$$\frac{da}{dN}=\left(\frac{\Delta k}{\bar{c}}\right)^n.$$

The integration of the latter makes it possible to link a number of loading cycles N to the relative size of the crack a_0/a_c in the form:

$$\frac{a_0}{a_c}=\sqrt[n/2-1]{1-\frac{CN}{K}}.$$

Therefore,

$$C=a_0^{n/2-1}\left(\frac{\sigma}{\rho}\right)^n\left(\frac{\rho}{\bar{c}}\right)^n,\quad K=\frac{1}{\sqrt{\pi}(n/2-1)},$$

a_0 is the initial length of the crack; a_c is its current size (critical until a moment of branching); ρ is the density of a material; n, $\bar{c}$ are material's constants; s are the micro stresses derived, for example, from (12).

Both at mechanical cutting using a diamond-containing tool and when treating materials with a hydroabrasive stream, the micro chips formation mechanism is similar. From the point of view of forming a destructive layer caused by the emerging stresses due to a cyclic action, the number of acts of contact interaction at hydroabrasive cutting is determined from:

$$N=\frac{Q_m}{\xi(N)m}t=\frac{Q_m d_c}{\xi(N)ms_k}, \quad (25)$$

where s_k is the contour feed speed, Q_m is the abrasive mass consumption, m is the mean mass of an abrasive particle, and a crack length is:

$$a_c=\frac{a_0}{\sqrt[n/2-1]{1-\dfrac{CQ_m d_c}{\xi(N)ms_k K}}}. \quad (26)$$

In this case, the thickness of a defective layer is:

$$h_d=\frac{D_0-D_a}{2}+\frac{a_0}{\sqrt[n/2-1]{1-\dfrac{2.182C_pC\sqrt{D_0^2/2-D_a^2/2}}{s_rK\left(\dfrac{\rho}{p_b}\right)^{0,5}}}}-x_c, \quad (27)$$

where x_c is the thickness of a layer of matrix.

To cut the carbon materials using a mechanical diamond-containing tool, the number of interaction acts over the time of contact between the tool and a machined surface t is $N=2\pi r_I nW$, and a crack length reaches:

$$a_c=\frac{a_0}{\sqrt[n/2-1]{1-\dfrac{2C\pi r_I nW}{K}}}, \quad (28)$$

where r_I is the radius of the tool; n is the rotation of its frequency (frequency of double runs); W is the number of abrasive grains per unit length of the periphery.

As there is no follow-up action of the tool on a machining zone, the growth of cracks is practically not limited by anything. The cracks will grow until their coalescence causes the chipping of a surface fragment.

The obtained correlations link the physical-mechanical properties of the machined material, the modes of mechanical or jet-abrasive impact, to the thickness of a defective layer, which forms on the machined part. It is easy to note that the thickness of destruction for all types of machining is determined primarily by the stresses that occur at cutting.

We shall consider the machined workpiece as solid half-space whose physical and mechanical properties at each point in the general case are different and can be determined based on experimental research. We shall apply to the surface of the workpiece an orthogonal grid at step $\Delta x\Delta y$ and assign a marker A_{ij} to each node. A perpendicular axis will be represented at each point of node A_{ij}. We shall determine the physical-mechanical properties of the machined material at nodes and into depth at step Δz.

Select the thin section Δx, which is between the two planes that pass through nodes A_{ij} и A_i+1_j. We consider the physical-mechanical properties of separate material fractions within the selected thin layer to be unchanged. They are derived as the arithmetic mean of the properties, determined at points A_{ij} and A_i+1_j, and can also be determined in the neighboring thin layers $A_i-1_j-A_{ij}$ and $A_i+1_j-(A_i+2_j)$. Such an assumption allows us to reduce the task on the volumetric formation of a cutting groove to the areal problem on the development of a cutting groove profile in a particular cross section. In this case, the machined composite is represented as an orthotropic material in which there is a consistent change in fractions with the deterministic properties.

We assume that the composite basically is a two-phase material (matrix and filler), each of the phases in which interacts with the other along the boundaries of contact. Therefore, it is necessary to take into consideration the existence of a transitional site, formed due to the adhesion of phases and characterized by a set of own physical-mechanical properties.

Such an approach ensures the identification of material properties at nodes z_{ij} as $\sigma_{ij}=\sigma_{0ij}+\sigma''_{ij}$, where σ_{0ij} is determined based on the deterministic sequence of transition from one component of the composite to the other. And σ''_{ij} accounts for a possible difference in properties at the fixed nodes, located at the same level z_{ij}.

A criterion for the macro destruction in a cutting zone will be the simultaneous implementation of the mechanisms for cutting the fibers using a cutting wedge and a grid of cracks in all those adjacent to the examined node: V_{ijk}: $V_{ijk}+1$, $V_{ij}+1k$, $V_{ij}-1k$, $V_{ijk}-1$. Take into consideration that in the case when the requirement is met, a node refers to the contour of the resulting opening. Otherwise, one can argue about forming a destructive layer. The case of the existence of three nodes is considered as a possible motion of the main crack, for which one calculates the load due to the action of a tool.

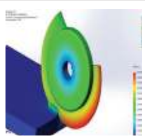
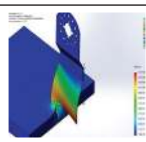
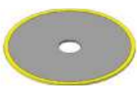
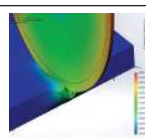
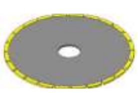
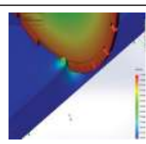
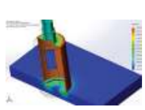
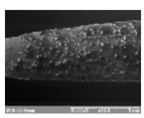
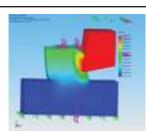
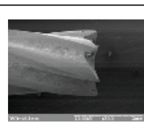
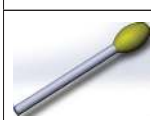
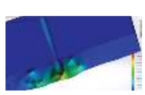
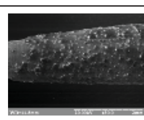
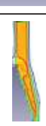
Int his case, the redistribution of loads is performed similarly to the case considered above.

6. Results obtained during formation of a defective layer at various machining methods

For the machining methods under consideration, we determined maximum stresses and stress distribution diagrams based on the cut cross section in workpieces made from carbon-containing composite materials. Results of the visual study and the stressed state of the surface layer of samples are summarized in Table 1.

Table 1

States of the tool cutting edges and the cut quality

Tool model	Stresses in a machining zone	State of the tool after machining	State of the machined surface
			
			
			
			
			
			
			–
Jet (puncture)		–	
Jet (cut)		–	

Drilling and micro milling make it possible to obtain minimum destruction of the surface layer while the hydroabrasive stitching of openings leads to the predicted destruction of a material at a considerable distance from the point of load application.

A change in the parameters for the zone of destruction (Fig. 5), determined by calculation and measured at field samples (shown as separate points in the diagram), reveals the following. The «non-rigidity» of a hydroabrasive jet leads to that the force scheme of interaction is constantly changing (interaction time τ in the absence of a working feed is accepted from [14]). Thus, the flow eventually washes out the machined sample, which requires minimizing the time of the jet in a stationary state.

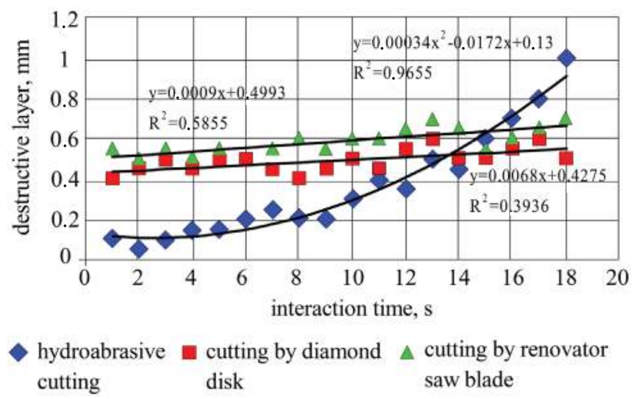


Fig. 5. Width of destruction zone (h) depending on time (τ) the tool is in the cutting zone

When machining the materials with diamond disks or electric submersible blades, there is no any significant change in the width of the destruction zone.

The research results allow us to propose fairly simple regression dependences of width of the destruction zone on a function of maximum stresses in the cutting zone $\delta = f(\sigma_{max})$. That made it possible to build and compare diagrams for an increase in the width of the destruction zone (Fig. 6), formed at different machining methods of carbon composites.

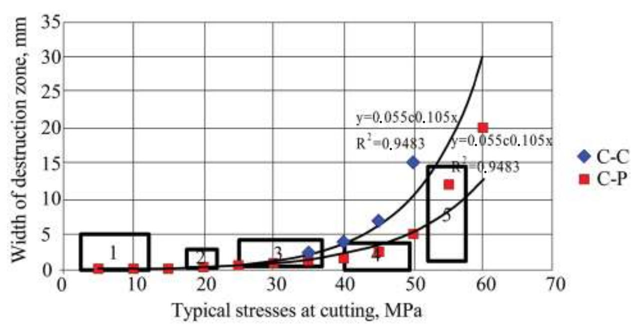


Fig. 6. Influence of stress (σ) in the cutting zone at different machining methods on width of the destruction zone (h): 1 – hydroabrasive cutting; 2 – grinding; 3 – drilling; 4 – milling; 5 – hydroabrasive stitching

7. Discussion of results obtained in the course of simulation and full-scale experiments on determining the thickness of a destructive layer

We have conducted both model experiments using the established regularities in the development of micro cracks in the surface layer (as the basic mechanism for the formation of a destruction zone) and a field study. Based in them, we substantiated not only the knowledge of the mechanism of development of a defective layer at machining, but also revealed some inaccuracies and simplifications when formulating mathematical notations.

Thus, it was noticed that the adequacy of the results obtained was maximal only at short-term machining. Subsequently, the thickness of a destruction zone gradually grew, larger – for the abrasive machining using tool with an associated abrasive (Fig. 7), less – for the hydroabrasive cutting.

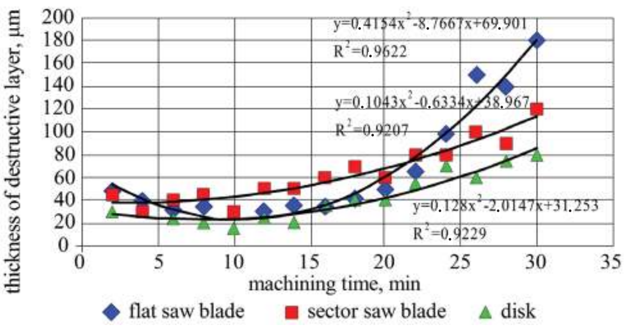


Fig. 7. Magnitude of destruction zone (h) depending on time of tool operation (τ_1) with the maximum permissible load (cutting speed is 70 m/s)

It was also found that in the process of operating a cutting tool with a diamond-containing layer, particularly galvanically-based, there occurs the chipping of grains due to the loss of adhesion with the base. Fig. 8 shows the dependence of the loss of grains at the renovator saw blade in a function of the frequency of double runs of the working body.

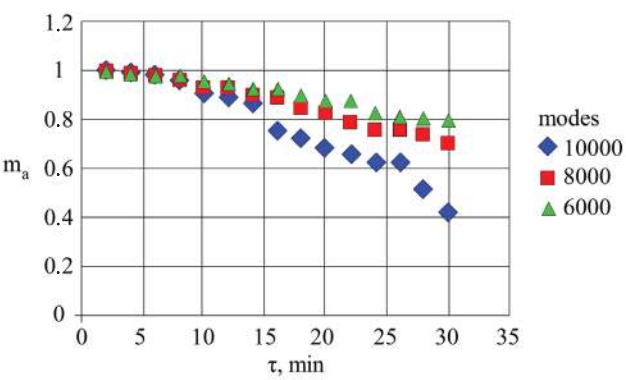


Fig. 8. Decrease in the mass share m_a of diamond grains in a working layer when using a saw blade of renovator (at maximum blade load of 150 N)

Reducing the number of cutting micro edges leads to a change in the thickness of a destruction layer. Our study has shown that simultaneously with a decrease in the number of grains at the surface of a tool, the thickness of a destruction layer first decreases, and then increases slightly with the simultaneous growth of cutting forces.

This phenomenon can be explained by that at a constant feed speed the cutting properties of the tool are reduced, with a simultaneous decrease in the cyclic impact at the cutting surface behind the zone of active destruction. Cracks start to branch out actively until stresses in the cutting zone do not exceed the adhesion or cohesion strength of a composite at the place of defects.

For the hydroabrasive cutting, a change in the thickness of a destructive zone is connected primarily to an increase in the diameter of a calibration channel; in this case, pressure on the end of the hydro cutting front also increases and, according to (12), there is an increase in the cyclic stresses. Thus, we have proven a direct impact of the averaged stresses in the zone where abrasive particles influence the thickness of a defective layer.

That made it possible to establish the limits for the expected values of the thickness of a defective layer at the surface, shown in Fig. 6 in the form of the respective rectangles. Therefore, the rational choice of conditions and modes of machining enables the reduction in the thickness of a destructive layer to 0.05 mm. At mechanical tensile tests of samples with a cross section of 6.0×6.0 mm, this makes it possible to decrease the variance of measurements of the controlled parameters by 30–40 %.

The formation of a complex of properties of the finished product (a sample for mechanical tests) in the form of set $\boldsymbol{F_i}(l, b, h, r, \delta...)$ is possible by the implementation of a certain totality of technological influences $\boldsymbol{M_j}$, peculiar to a particular method of machining. Each technological influence can be represented as a totality of sets of tool properties T_j, dynamic properties of the machined system W_j, a technique of force impact P_j, for which $(T_j, W_j, P_j)\in \boldsymbol{M_j}$, which allows us, for a workpiece with properties S_i, to represent the output quality parameters represented in the following form:

$$F_i(l,b,h,r,\delta...)=M_j\cdot S_i. \qquad (29)$$

Based on [13], it is possible to record a condition for ensuring the output parameters of machining in the form:

$$F_i(l,b,h,r,\delta...)=T_j\cdot S_i\cap W_j\cdot S_i\cap P_j, \qquad (30)$$

that produces a totality of variants for the machining transitions, the best among which can be select based on a specific criterion.

In this case, the main condition for obtaining the desired result is to limit the destruction layer thickness at the level of 2 % of the measurement base.

The study conducted into the state of a surface layer at various methods of machining with subsequent testing the samples in accordance with recommendations from [17] allowed us to derive dependences that link the conditions for machining to the thickness of a destruction layer for the carbon-carbon and carbon-polymeric materials.

As an example, we shall consider the case of fabricating a prototype of dimensions $b\times l\times h$ from a cubic workpiece of dimensions $B\times L\times H$; in this case, the prototype has curved sections with radii r_i.

Denote: R_1 – milling; R_2 – machining using an abrasive wheel; R_3 – machining with a reciprocating movement of the tool (renovator); R_4 – drilling; R_5 – hydroabrasive cutting. The following technological operations are possible: (R_2)–(R_1); (R_2)–(R_5); (R_2)–(R_4)–(R_5).

When optimizing the process based on the criterion for the minimization of machining time to obtain the preset quality level, we received variant (R_2)–(R_4)–(R_5), whose scheme is shown in Fig. 9. This sequence of operations allows the fullest use of all advantages of the hydroabrasive cutting (a significant reduction of machining time) and makes it possible to avoid the destruction of a material at the time of the jet puncture.

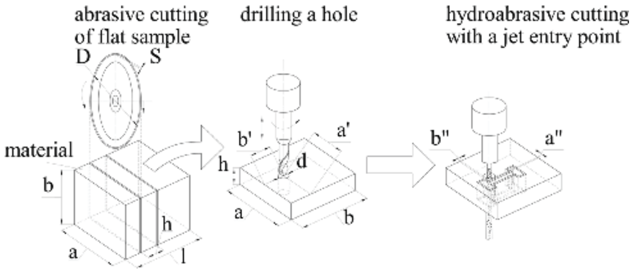


Fig. 9. Sequence of the preparation of a sample made from a carbon workpiece

Cutting modes, as well as parameters of the applied tool, directly define not only the machining efficiency, but also the thickness of a defective surface layer, which must be taken into consideration when machining parts made from carbon-carbon composites. During machining, there is a wear of tools: changes in angles at the cutting edge, chipping of abrasive grains. All this leads to that the parameters of a surface layer alter even under stable cutting modes.

Machining with an unbound abrasive in the flow significantly extends the technological possibilities of the method. Varying the fractional composition of an abrasive suspension, by the jet outflow velocity, by the flow rate, and by the speed of contour feed, reduces the defective layer and improves stability when obtaining the part's surface parameters. At the same time, it is of interest to further develop a given study to include a wider range of superhard materials (in particular, abrasive tools made from cubic boron nitride). Their application might be more efficient in some cases.

The results obtained could form a basis for the further development of the functional approach to creating hybrid machining processes for new constructional materials.

8. Conclusions

1. The result of the performed complex of theoretical and experimental research is the established analytical correlations that relate the physical-mechanical properties of machined materials, the modes of mechanical or jet-abrasive exposure, to the thickness of a destructive layer that forms at the machining surface. We show the possibility to predict parameters for a defective layer based on the predicted stresses in a cutting zone induced by the high-frequency contact interaction between the particles of an abrasive and the machined surface.

2. The established regularities in the formation of a defective layer at machining (including the hydroabrasive cutting) have made it possible to identify ways to improve the quality of a sample and to reduce the layer thickness to 0.05 mm. The derived dependences of the destruction zone parameters on the stresses that occur at cutting allowed us to obtain the rational sequence of machining transitions, at which the defective surface layer is the smallest.

3. The results obtained provide a possibility to significantly increase the accuracy of mechanical tests of carbon composite materials, thereby reducing the variance in the measurements of controlled parameters by 30–40 %.

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DEVELOPMENT OF THE GEARLESS ELECTRIC DRIVE FOR THE ELEVATOR LIFTING MECHANISM

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Розглянуто можливість застосування, вдосконаленого тихохідного електричного двигуна біїндукторного типу з безобмотковим ротором. Подібний двигун виконується з ротором торцевого типу і статором, що не мають загального ярма. Ротор являє собою кілька феромагнітних полюсів, закріплених на немагнітному диску. Сформовано основні проектні дані біїндукторних двигунів для ряду швидкостей руху ліфтової кабіни. Надані рекомендації щодо вибору відповідності швидкостей ліфтових лебідок і діаметрів канатоведучих шківів. Проведено синтез системи управління ліфтового електроприводу.

Пропонується використання мікропроцесорної системи підлеглого управління з використання релейного регулятора струму, ПІ-регулятора швидкості та П-регулятора положення. За результатами дослідження показано, що надається можливість точного відтворення заданої траєкторії руху кабіни і точної зупинки, яка виконується на певному поверсі без додаткових операцій підходу до заданої точки. Рух виконується згідно з розрахованою траєкторією з обмеженням заданої швидкості на рівні номінальної, прискорення – до 1 м/с^2 та ривка – до 3 м/с^3. Ці параметри повністю відповідають умовам комфортного переміщення пасажирів. Різниця між експериментальними даними та результатами моделювання не перевищують 7 % в статичних і 15 % – в динамічних режимах. Зазначені основні переваги запропонованого безредукторного ліфтового електроприводу. Зокрема, визначено, що запропонований електропривод, за рахунок конструктивних особливостей тихохідного двигуна, має масу, габарити і інерційність, значно менші, ніж у традиційного у базовому варіанті, при подібних інших параметрах

Ключові слова: ліфтова лебідка, безредукторний електропривод, біїндукторний двигун, безколекторний двигун, механізм підйому

1. Introduction

The elevator industry is a powerful component of the global technology and economy, which by its significance reflects one of the most important features of modern civilization. The main task of all passenger elevators is providing transportation in the vertical plane in the buildings and structures for different purposes. Elevators not only facilitate everyday physical movement of people, but quite often are the only means of such movement. In large cities, the total daily volume of transportations in passenger elevators exceeds the volume that is carried out by all kinds of public transport [1]. At the turn of the last two centuries, the elevator building, like virtually all areas of technology, saw a quality jump, thanks to the achievements of mechanics, electromechanics, power- and microelectronics, and mecha-