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Formation of surface layer quality under abrasive treatment of polymer-composite materials

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Introduction. The study results of the abrasive processing of parts made of polymer-composite materials are presented. The features of processing polymer composites and the technology of preforming through waterjet cutting are described. The stages of preparation of a part made of polymer-composite material for the "glueing" operation are investigated.

Materials and Methods. Dependences for determining the surface roughness under waterjet cutting of polymer-composite material are considered. Research is carried out to achieve the required surface roughness under adhesive bonding of workpieces. The dependence is given that describes the roughness that is required for a reliable adhesive bond.

Results. The theoretical and experimental studies of the waterjet cutting process are resulted. Their implementation technique, the tool and equipment used are described. The results of theoretical and experimental studies are compared. Their high convergence is established. The results of experimental studies on the preparation of parts made of polymer-composite materials for glueing are shown. The abrasive tools and processing modes are selected.

Discussions and Conclusions. The process design procedure of abrasive treatment of workpieces from polymer-composite materials is proposed.

Keywords: treatment of polymer composites, waterjet cutting, treatment by petal wheels, surface roughness.

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Introduction. Increase in labor productivity in modern engineering production is possible through the use of new technologies and materials. For the manufacture of machine parts, polymer composite materials (PCM) are increasingly used. This is a composition of two or more materials, a base and a binder. Compared to metal products, products made of polymer composites have better physical and mechanical properties and, as a rule, weigh much less. The anisotropic structure of the polymer composite material allows the workload to be distributed throughout the product structure, which increases its performance properties. PCM is formed in a certain way. The base layers are laid in directions mutually opposite to each other. And the binder plays the role of filler, that is, it provides immobility and filling the space between the base layers. A special layer, formed by a hardened binder, is created on the surface of the polymer composite.

This layer may not match the ideal surface shape. Its adhesion properties provide:

— substances that are on the workpiece surface and contain a hardener,

— chemical reaction products occurring during curing.

The anti-adhesive layer of the polymer composite should be removed through mechanical treatment. This provides optimum surface roughness of the machined part. Mechanical processing of PCM has a number of features:

— delamination occurs,

— fibers close to the processing site loosen,

— a large amount of heat is generated during cutting,

— burns are formed,

— the material is destroyed.-.

In this case, it is not always possible to use lubricating coolants since their effect causes delamination, swelling, and the PCM loses the required physical and mechanical properties. This is due to the fact that polymer composites absorb moisture abundantly. The use of fluid in PCM processing requires further study.

At the majority of enterprises where parts are made from polymer composites, the technological process consists of cutting a sheet and further machining the workpiece. Polymer-composite parts are often glued together, which requires careful preparation of the surface layer. Within the framework of this work, the formation of surface quality under waterjet cutting of PCM, as well as during preparation of the surface for further bonding is studied.

Materials and Methods. In modern mechanical engineering, cutting of materials through water-jet cutting is on rise. Its advantages are as follows: a wide variety of processed materials, high productivity, good quality of the cut surface and the ability to obtain profiled surfaces. When using this method, significant internal stresses do not arise due to the low-temperature nature of the process.

In addition, waterjet cutting is characterized by a small allowance and high cutting accuracy. This is in contrast to edge cutting and fixed-abrasive machining. The process of cutting a material with water jet is rather complicated, underexplored. Its result is influenced by many technological factors: jet velocity, jet travel speed along the part, characteristics of the abrasive powder, distance from the jet to the surface to be treated, as well as physical and mechanical properties of the processed polymer composite materials. Some difficulties arise when designing cutting technology. They are primarily associated with the selection of optimal cutting conditions: it is necessary to provide the given workpiece surface quality under the lowest processing costs. The use of waterjet cutting for PCM processing also requires a study of the effect of water on the state of the cut surface. Preliminary investigations have allowed establishing the power of the energy of a supersonic jet of water with an abrasive. It is so great that when it interacts with the surface to be treated, destruction is comparable in intensity to damage from a hard abrasive tool. Under cutting, water does not deviate from the motion trajectory, the effect on the workpiece material is minimal, i.e. water is not absorbed [1–4].

As you know, under deep cutting of materials (including polymer composites) in the contact zone of the abrasive jet and the cut material, two clearly traceable zones appear:

— with low surface roughness (smooth cut zone),

— with higher roughness (wavy cut zone) [1, 2].

Their occurrence is due to the fact that, upon contact of the jet with the lower part of the cut, the angle of attack of the embedded particles grows. A significant number of them do not participate in an effective collision and are reflected from the material. In this case, new interacting particles encounter an obstacle, are reflected and cause blocking of particles entering the treatment zone. The result is a wavy cut zone with high surface roughness. In the upper part of the cut, there is nothing to prevent particles from collision; therefore, a smoother surface with lower roughness is formed. Under present-day conditions, when designing technological processes for waterjet cutting, it is difficult to determine not only the surface roughness of various cutting zones, but also the dimensions of the smooth and wavy cutting zones. The forecast of obtaining the required roughness at the stage of technology design will provide determining the feasibility of finishing and the required allowances in this case.

Theoretical studies of the formation of the roughness profile of various cutting zones of the PCM clearly show regularities that describe the abrasive particle - workpiece surface interaction process. It has been established that the cut surface roughness depends on the process parameters of the treatment. The cut layer of the material is conventionally divided into two cutting zones: wavy and smooth. The mechanism of the formation of these zones is described. The range of penetration depths of particles is specified [1–2]:

$$h_{\max} = DK_L \sin\alpha \sqrt{\frac{2P_{дин}\rho_ч}{3c\rho_{см}k_s\sigma_s}}\,, \tag{1}$$

where $\rho_ч$ is particle material density; k_s is the coefficient that considers the effect of the workpiece surface roughness on the real contact area; K is the volume concentration of particles in the process fluid; $P_{дин}$ is dynamic pressure of the mixture; $\rho_{см}$ is the density of the working mixture of liquid and particles; σ_s is the yield point of the workpiece material; D is the particle diameter; K_L is the coefficient of energy losses to overcome the distance from the jet to the workpiece surface; c is the bearing capacity factor of the contact surface; α is the impact angle of an abrasive particle with a processed surface.

Let us describe the flow of abrasive particles as an event stream corresponding to the Poisson distribution: the particles of the medium perform microcutting in a fixed time interval, which does not depend either on its origin or on possible realizations of previous or subsequent similar acts. The parameter λ in Poisson's law is the intensity of the flow of events. Let us assume for waterjet cutting that λ is the number of possible interactions per unit time on the square of the abrasive particles packing. Then, $\sqrt{\lambda}$ particles will pass through each side of the packing square $2R$, and $\frac{L_{ед}}{2R}$ particles will pass through the unit length. With this in view, a formula has been proposed that provides the determination of the arithmetic mean deviation of the profile of the steady-state surface roughness under the waterjet cutting of PCM [1, 2]:

$$Ra = 13.01 K_\alpha^{Ra} \cdot R \sqrt{K_L \cdot \sin\alpha \cdot \sqrt{\frac{P_{дин} \cdot \rho_ч}{\lambda \cdot c \cdot \rho_{см} \cdot k_S \cdot \sigma_S}}}\,, \tag{2}$$

where K_α^{Ra} is the coefficient considering the abrasive particles – workpiece surface impact angle; R is the average radius of particles.

The number of effective interactions λ functionally depends on the amount of feed, the pressure of the abrasive jet, and the depth of roughness measurement $\lambda = f(S, Q, h)$. A theoretical description of the value λ is difficult. Therefore, λ has been determined on the basis of experimental studies, which made it possible to propose a set of regression dependences.

The experiments were carried out on the basis of the Rostvertol, Russian Helicopters JSC. A *Flow* 5-axis waterjet cutting machine was used. Garnet was used as an abrasive medium. The samples were made of VPS-7 fiberglass reinforced with titanium foil (OT4-0-0.1 × 220 marking). This fiberglass is used at Rostvertol for full-scale parts of Mi-28 helicopter.

Surface roughness was measured using a *Surtronic* 25 digital profilometer from *Taylor Hobson*. The effect of water on PCM cutting was investigated on a *NETZSCH* DSC 200 F3 *Maia* differential scanning calorimeter. The results were processed by the method of mathematical statistics in the *MathCad* program.

Research Results. The cut surface roughness grows with the jet rate increase. At the same time, the relative height of the wavy cut zone increases. The intervals of surface roughness values and processing modes required for waterjet cutting of PCM with specified properties are determined. When studying the influence of the jet feed, its speed was varied in the range from 5 to 480 mm/min. The material is characterized by a layered structure and anisotropy. In this regard, the cut surface roughness was measured in two directions: perpendicular to the feed and along it.

The experimental results analysis of the waterjet cutting process allows obtaining models of the cut surface formation:

— one-factor that describes the change in roughness across the cut section;

— two-factor – for calculating the change in roughness along the cut section and varying the depth of roughness measurement (4) based on the regression analysis:

$$Ra = 3{,}538 \cdot 10^{-6} + 4{,}721 \cdot 10^{-6} \cdot S, \tag{3}$$

$$
\begin{aligned}
Ra = {} & 2.706\cdot10^{-13}\cdot S\cdot h - 3.157\cdot10^{-10}\cdot h + 1.886\cdot10^{-8}\cdot h^2 - \\
& -3.062\cdot10^{-7}\cdot h - 1.301\cdot10^{-10}\cdot S\cdot h + 1.469\cdot10^{-12}\cdot S^2\cdot h + \\
& +4.288\cdot10^{-6} + 1.324\cdot10^{-8}\cdot S - 5.142\cdot10^{-11}\cdot S^2 + 7.308\cdot10^{-14}\cdot S^3.
\end{aligned} \tag{4}
$$

The effect of water on the thermophysical properties of a polymer composite under the waterjet cutting has been studied. The investigation was carried out by the method of differential scanning calorimetry. As a result, the possibility of using this processing technique for cutting parts from PCM was established.

The cut surface roughness was determined using a theoretical model (2) and was compared with the results obtained experimentally. It is found that the discrepancy does not exceed 15%. This indicates that the resulting set of theoretical models can be used in the technological design of processing parts from PCM.

At many machine-building enterprises, manual processing with coated abrasive is used to prepare the surface for gluing (GOST 13344-79, GOST 5009-82 and GOST 10054-82). As a rule, the sample is sanded to gloss remove, which cleans a thin layer of binder from the part and does not damage the fibers. At the same time, the manual labor content is very high, and the costs for it are high. The coated abrasive wears out quickly and has to be replaced. In addition, the quality of sanding depends directly on the qualifications of the employee, his ability to create a certain pressing force and remove the surface layer without destroying the fibers of the composite [4–8]. It is required to reduce the labor content of the operation in question, to eliminate hand work while maintaining the quality of processing. In this regard, two approaches to solving the problem have been proposed. The first one is based on a comprehensive study of the processes of providing the roughness specified for PCM parts. It is assumed that the resulting roughness will provide adhesion strength without having to be limited by the minimum possible roughness. You can select a tool for mechanizing the processing of PCM parts. Such studies were carried out at Rostvertol with full-scale parts made of polymer-composite materials. The processing with grinding elastic tools, which provides mechanizing the process, was considered. The grains move in the direction of the normal component of the cutting force reducing the intensity of the heat flux and increasing the tool life [7]. A feature of this process is the absence of microcracks typical for processing with a hard grinding tool [8]. In addition, lack of the required rigidity is characteristic of many PCM parts: casings, shells, caps, etc. For their processing, it is much more reasonable to use an elastic grinding tool. Due to its elastic properties, such a tool (in contrast to a tool on a rigid base) quenches vibrations and oscillations, and also absorbs shocks under processing [4–8]. The hygroscopicity of polymer composite materials makes it difficult or does not allow the use of a coolant during processing. A flexible abrasive tool is well suited for such cases. It provides high quality grinding without cooling and without wetting the workpiece surface.

The formation of the surface quality of a PCM part intended for further bonding is theoretically investigated.

When calculating the surface roughness parameters, the technique developed by Prof. A.V. Korolev [9] was applied. It is used to describe the formation of a roughness profile when machining with a rigidly bound abrasive:

$$
Ra = 0.9\sqrt{\frac{t_c\cdot v_S\cdot l_{ф}^3\cdot L_{ед}}{60\cdot v_K\cdot L_K}}, \tag{5}
$$

where t_c is the thickness of the material layer removed in one pass; v_s is the feed rate; $l_ф$ is the actual distance between the contact grains; $L_{ед}$ is the width of the treated area; $v_к$ is the wheel speed; $L_к$ is the total length of the petals.

To check the adequacy of the dependence obtained, a set of experiments was carried out to prepare polymer-composite parts for further bonding. Specimens made of VPS-7 fiberglass, having a significant area (80 × 200 mm), were processed by flexible abrasive flap wheels from *Klingspor* (MM 630 model with dissected lamellae, Fig. 1).

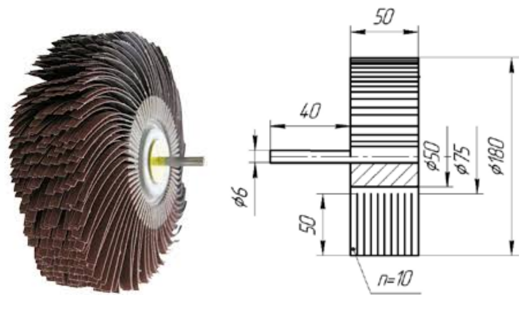

Fig. 1. Scheme of abrasive flap disc from *Klingspor* (MM 630 model): diameter is 180 mm, width is 50 mm, abrasive material is electrocorundum, binding material is synthetic resin

The sanding pads are fixed on a mandrel with a diameter of 6 mm and are cut in the radial direction into ten equal segments, which, in turn, are wrapped in the same direction. The length of such a segment is 50 mm. The tool has high elasticity and can be made of abrasive materials of various grain sizes.

The stability of the processing modes is achieved by the constancy of the centrifugal and elastic forces created by the sanding cloth petals. The quality of the surface layer of the processed parts is significantly affected by the feed rate and the specific pressure of the petals. Also of great importance is the dynamic radius of the wheel $r_Д$, the distance from its axis to the contact surface of the petal with the workpiece [7, 9].

The grinding wheel selected in this way was fixed in the spindle of the vertical mill. The wheel rotation speed was 450–1400 rpm, the feed was 100–800 mm/min. The dynamic radius was chosen from the sizes: 55 mm, 60 mm, 65 mm, which created a different contact area of the petals with the workpiece surface. The samples were fixed on the machine in a special device.

The experiments have proven the possibility of obtaining a uniform matte surface, devoid of gloss, using flexible petal discs. After processing, the integrity of the fibers was not compromised. The surface roughness of the samples was measured on a *Tailor Hobson* profilometer. For the above modes, the arithmetic mean value of the roughness Ra = 1.22 μm was obtained (Fig. 2).

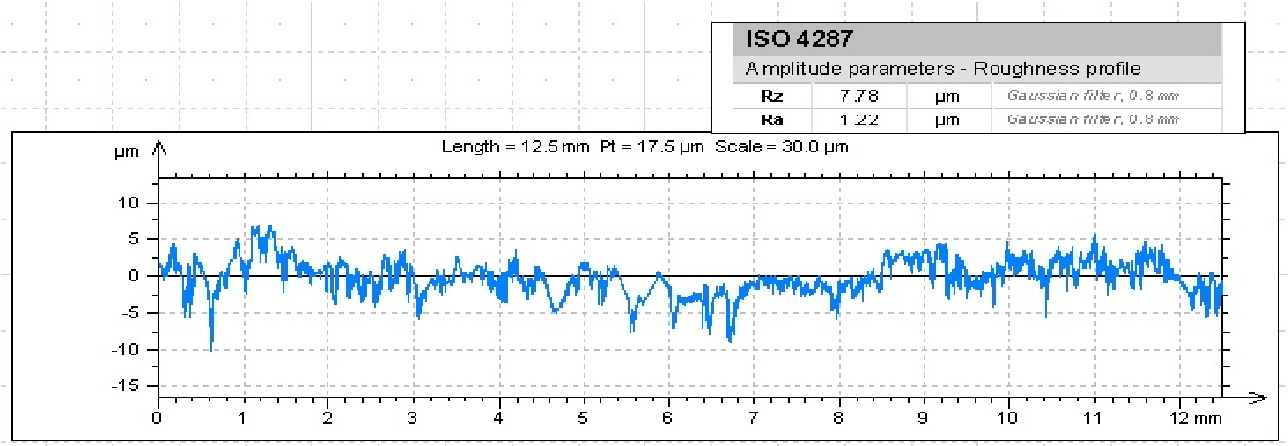

Fig. 2. Profilogram of the sample surface processed by the flap wheel: rotation speed is 1400 rpm, feed is 315 mm/min, and dynamic radius of the circle ($r_Д$) is 55 mm

As a result of the experiments on processing PCM samples with flexible petal wheels, a uniform matte surface devoid of gloss was obtained. In this case, the integrity of the fibers is not compromised. The finished surface was examined, and the roughness was measured on a *Tailor Hobson* profilometer. The roughness Ra = 1.22 μm was obtained under the selected processing modes, which is shown on the profilogram (Fig. 2).

Statistical processing of the experimental data has shown their high convergence with the results of theoretical calculations.

Discussion and Conclusion. The issues of design and optimization of the PCM waterjet cutting processes and preparation of their surface for gluing are considered. A technique has been developed that takes into account the specified roughness of the cut surface and the surface to be glued and provides the minimum cost of the product [1, 2, 10–13]. The cut surface roughness e is calculated from the formula (2). Taking into account the initial processing parameters ($P_{дин}$, R, $\rho_ч$, h, L, S, Q), the number of effective collisions λ is calculated. Then the roughness value Ra is determined. Variants of technological processes, in which the condition $Ra \le Ra_{зад}$ is not met, are eliminated, and the cost of the cut is calculated. The combination of processing parameters is considered optimal, at which the cost of the cut will be minimal.

Designing the preparation of a PCM part for gluing starts with a technological assessment of the part design and the glued joint in which this part is involved. For each type of adhesive and of adhesive bond to be made, the developer should indicate the required roughness class of the surface to be bonded. Taking this into account, the technologist chooses the grain size of the grinding tool and processing modes. The resulting PCM part surface should be homogeneous and uniformly processed over the entire bonding surface. The machining quality describes the arithmetic mean deviation of the roughness profile *Ra*. Measurements of this parameter are carried out using a probe-type profilometer. At this, a correct assignment of processing modes and an adequate tool selection provide the required surface roughness.

The part, whose surface is being prepared for gluing, should be cleaned and free from residues of crimping materials (separating materials, vacuum bag materials, sealants, etc.). Technological allowances that are not needed in subsequent operations are removed. The sanded surface is visually checked for runs, pebbles and other defects to be removed.

The roughness, which will provide the required strength of the adhesive bond, is determined. Depending on it, the grain size of the abrasive wheel is selected. To process thin-walled products with insufficient rigidity when preparing their surfaces for bonding, it is recommended to use grinding wheels of 240, 220, 180 and 150 grit according to FEPA (Federation of the European Producers of Abrasives).

To process PCM parts with a thickish surface epoxy layer (0.01 mm or more), the grain size 40, 80, 100, 120 (according to FEPA) is suitable. For sanding runs, pebbles, gradients, etc., with simultaneous preparation of the surface for bonding, it is recommended to use flap discs with grain size 80, 100, 120 (according to FEPA). The productivity of this process is increased (when compared to the use of wheels with smaller grit).

Processing modes are selected. Based on the surface area to be sanded, the number of tool passes is calculated. Separately, it should be mentioned about the odd-shaped parts with surfaces located at an angle, with spherical radii and curved sections of structural components. They are processed first and only then you move on to flat areas. Parts with curved surfaces can be treated on high-end machine tools and software-controlled installations. In this case, the tool moves in accordance with the control program, and its path follows the theoretical contour of the part.

Table 1 gives recommendations on the selection of processing modes for parts made of fiberglass, which will be glued further on. The equipment is flap discs from *Klingspor*. The grinding process parameters that provide the required roughness are as follows: wheel rotation speed *n* (rpm), feed *S* (mm/min) and $r_{\text{Д}}$ (mm).

Table 1

Recommendations for selection of cutting conditions for final abrasive processing of PCM parts

Required roughness	Material grain size		*Rc**, mm	*S*, mm/min	*n*, rpm
	of petal wheel, recommended by FEPA	of abrasive according to GOST 3647-80			
4.5–5.0	P40	40	55	200–350	1400–1600
4.2–4.5	P80	20	55	200–350	1400–1600
3.7–4.2	P100	16	55	200–350	1400–1600
3.0–3.7	P120	12	50	200–400	1100–1400
2.6–3.0	P150	10	50	200–400	1100–1400
1.6–2.5	P180	8	50	200–400	1100–1400
1.2–1.6	P220	6	48	200–350	1100–1200
1.0–1.2	P240	5; M63	48	350–500	1100–1200
0.6–1.0	P320	5; M50	46	350–500	1100–1200
**Rc* is specified for petal wheels of the model considered in this study.					

After finishing the treatment, the workpiece surface is cleaned of sanding products using a clean cotton cloth or a sweep brush with soft bristles. In this case, fiberglass dust should not rise into the air.

Visual inspection will reveal untreated areas (gloss on the surface), as well as exposure and destruction of polymer composite fibers.

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Claimed contributorship

M. A. Tamarkin: academic advising; formulation of the research objectives and tasks; correction of the conclusions. E. E. Tishchenko: analysis of the research results; text preparation; formulation of conclusions. A. V. Verchenko: formulation of the basic research concept; conducting experiments. V. M. Troitsky: experimentation and computational analysis; the text revision.

All authors have read and approved the final manuscript.