Surface quality formation at polymer composite details' abrasive processing

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Abstract. The article presents the results of studies of the process of abrasive processing of parts made of polymer composite materials. Special features of processing of polymer composites, technology of production of preform by hydroabrasive cutting are described. Studies have been carried out and stages of preparation of a part made of polymer composite material for "gluing" operation have been described. Dependencies for determination of surface roughness during hydroabrasive cutting of polymer composite material are given. Studies have been carried out to achieve the necessary surface roughness when gluing blanks. A curvature is given describing the surface roughness, which is necessary to achieve a reliable adhesive connection. Results of theoretical and experimental studies of hydroabrasive cutting process are presented. Technique of the execution, applied tools and equipment are described. The results of theoretical and experimental studies were compared. Their high convergence has been established. The results of experimental studies on preparation of parts from polymer composite materials for gluing are presented. Abrasive tool, processing modes are selected. Design method for abrasive processing of parts made of polymer composite materials is proposed.

1. Introduction

Modern machine-building production in a market economy could be developed by increasing labor productivity and using new technologies and materials. In this regard, polymer composite materials (PCM) are increasingly used for the manufacture of machine parts. They consist of a composition of two or more materials: a reinforcing base and a binder. Products made of polymer composites compared to metallic ones have better physical and mechanical properties, while, as a rule, they weigh much less. The anisotropic structure of the polymer composite material allows the distribution of the payload throughout the whole part, which improves its operational properties. Generally, the base layers are laid in mutually opposite directions, and the binder provides immobility and fills the space between the layers. The surface of the PCM part after molding appears to be an upper layer of composite consisting of a cured binder, has macro- and micro-deviations from the ideal surface. On the surface of the part there may be substances used as separation layers during molding, as well as products of chemical reactions of binder curing, which can give the surface anti-adhesion properties.

To remove the anti-adhesion layer and create optimal surface roughness, the part must be subjected to machining. Mechanical processing of PCM has a number of features: delaminations are formed, fibers near the treatment site are wetted, a large amount of heat is generated during cutting, which causes burns and destruction of the material. At the same time, the use of lubricating and cooling liquids is limited, since their effect causes delamination, swelling and loss of physical and mechanical
properties due to the fact that the material absorbs moisture abundantly. The use of liquid in the processing of PCM requires further study.

In most enterprises where polymer composites are manufactured, the process of their machining consists of cutting the sheet and further machining the workpiece. Often, polymer-composite parts are glued, for which careful preparation of the surface layer is required. In this article, we conducted studies of surface quality formation during hydroabrasive cutting of PCM, as well as in preparing its surface for further gluing.

2. Materials and methods

One of the most modern and promising technologies for cutting blanks from polymer composite materials is hydroabrasive cutting. Wide ranges of processed material thicknesses, high productivity, obtaining high quality cutting surface, the possibility of processing of complex geometry blanks make this method of processing the most popular in modern production conditions. The absence of thermal effect on the material, low cutting force, erosive nature of the destruction does not contribute to the development of internal stresses in the cutting zone. In addition, unlike blade treatment and machining with a bonded abrasive, hydroabrasive cutting is characterized by low allowance and high cutting accuracy. The process of hydroabrasive cutting is complex and poorly studied, its result is influenced by a variety of technological parameters, such as the pressure of the cutting jet, the supply of the nozzle, grain, hardness, abrasive consumption, the distance from the nozzle to the treated surface, and the physical and mechanical characteristics of the processed polymer composite. The difficulty of designing the cutting process is in choosing optimal cutting modes in which the specified quality of the surface layer of the part will be ensured at the lowest cost. The use of hydroabrasive cutting for the processing of PCM also requires the investigation of the effect of water on the state of the cutting surface. Preliminary studies have found that a supersonic jet of water with an abrasive has so much energy that its interaction can be considered as the effect of a solid abrasive tool. During cutting, the water does not deviate from the trajectory, and the impact on the billet material is minimal, i.e. the absorption of water does not occur [1-4].

As is known, when cutting materials to a greater depth, including polymer composite materials, two clearly traceable zones arise in the contact zone of the abrasive jet and the cut material: a zone with low surface roughness (smooth cutting zone) and a zone with higher roughness (wavy cutting zone) [1,2]. Their appearance is due to the fact that when the jet penetrates to the bottom of the cut, the angle of attack of the insertion of particles increases. A larger number of particles, without causing useful collisions, are reflected from the material, new particles encountering obstruction are reflected and block the particles entering the cutting zone. As a result, a wavy cut zone with high surface roughness is formed. At the same time, nothing prevents the impact of particles in the upper part of the cut, so a smoother surface with less roughness is formed. The manufacturing technologist faces the difficulty of determining not only the surface roughness of both zones, but also the size of the smooth and wavy cutting zone. Predicting surface roughness allows to determine whether part's finishing is required and what allowance size is needed.

Theoretical studies were carried out on the formation of the surface roughness profile of the cutting surface during hydro-abrasive cutting of PCM. The regularities were revealed describing the interaction of particles with the surface of the treated part. Influence of technological parameters of treatment on roughness of cut surface is investigated, and mechanism of formation of zones of wavy and smooth cuts into which obtained cut is conditionally divided is described. Maximum depth of particle penetration is determined [1-3]:

$$h_{\text{max}} = DK_L \sin \alpha \sqrt{\frac{2P_{\text{cut}} \rho_{ch}}{3c \rho_{\text{sm}} k_s \sigma_s}}$$

(1)

where $\rho_{ch}$ is the density of the particle material; $k_s$ is a factor that takes into account the effect of the roughness of the surface of the part on the area of actual contact, $K$ is the volume concentration of
particles in the working fluid, $P_{din}$ is the dynamic pressure of the mixture; $\rho_{sm}$ is the density of the working mixture of liquid and particles, $\sigma_s$ is the yield strength of the part material, $D$ is the diameter of the particle; $K_L$ is a loss factor that takes into account the distance from the nozzle to the surface of the workpiece, $c$ is a coefficient that estimates the bearing capacity of the contact surface, $\alpha$ is the contact angle of the particle with the surface of the workpiece.

Since the probability of micro-cutting by particles at a fixed time interval depends on the length of the interval and does not depend on the beginning of its reference, or on the possibility of previous or subsequent similar acts, there is reason to consider the flow of abrasive particles under consideration as a flow of events corresponding to the Poisson distribution. In Poisson's Law $\lambda$ is the intensity of the flow of events. Let us assume that $\lambda$ is the number of useful interactions per unit time per square area of the package. Then $\sqrt{\lambda}$ quantity of particles will pass through the party of a square of packing $2R$, and $\frac{L_{ed}}{2R}$ of particles will pass through the unit length. With this in mind, dependence is obtained to determine the arithmetic average deviation of the profile of the established surface roughness during hydroabrasive cutting of PCM [1,2]:

$$Ra = 13.01 K^{Ra}_{\alpha} \cdot R \sqrt{K_{L} \cdot \sin \alpha \cdot \frac{P_{din} \cdot \rho_{ch}}{\sqrt{\lambda \cdot c \cdot \rho_{sm} \cdot k_{S} \cdot \sigma_{S}}}}$$

(2)

where $K^{Ra}_{\alpha}$ is the coefficient taking into account the angle of incidence of the jet, $R$ - the radius of the particle.

The number of useful interactions $\lambda$ can be represented as a function of the supply, flow rate of the abrasive, depth due to the measurement of roughness $\lambda = f(S, Q, h)$. The value $\lambda$ is difficult to describe theoretically, so experimental studies were carried out to find a set of regression dependencies to determine it.

Experimental research was carried out on the basis of a machine-building enterprise at the Flow 5-coordinate hydroabrasive cutting plant. Garnet sand was used as an abrasive. Experimental studies were carried out on fiberglass VPS-7 reinforced with titanium foil OT4-0-0,1 $\times$ 220 which is used to manufacture the longeron of the rotor blade of the Mi-28 helicopter.

Roughness measurements were performed on Taylor Hobson's Surtronic 25 digital profilometer. The effects of water exposure during PCM cutting were examined on a differential scanning calorimeter DSC 200 F3 Maia manufactured by NETZSCH. Statistical processing of research results was carried out using a program of applied and scientific calculations, MathCad.

Data from experiments show that as the nozzle feed increases, the roughness of the cut surface-stack deteriorates, and the ratio of the height of the wavy cut zone to the smooth cut zone increases. It was established which quality of the surface and under which treatment modes can be obtained during hydroabrasive cutting of PCM. The samples were cut by stepwise varying the feed of the cutting head nozzle from 5 to 480mm/min. Considering the anisotropy of the material properties and the laminate structure, the roughness of the cut surface was measured in two directions: perpendicular and along the feed direction.

Based on the obtained data, a regression analysis was carried out, the result of which is an single-factor model of cutting surface formation when measuring the roughness across the section of the cut (3) and a two-factor model describing the formation of the roughness profile of the cutting surface when measuring roughness along the section of the cut and changing the depth of measuring roughness (4):

$$Ra = 3.538 \cdot 10^{-6} + 4.721 \cdot 10^{-6} \cdot S$$

(3)
The effects of water on thermophysical properties of the composite during hydroabrasive cutting were investigated. Fiberglass-based PCMs are very sensitive to moisture absorption, so differential scanning calorimetry studies were carried out to ensure that this type of material can be treated in a hydroabrasive processing. To do this, dry material was compared with a layer of material where contact with a hydroabrasive jet occurred. Studies were carried out both immediately after cutting and a week after drying the samples. The chip layer was removed in the area of 1mm from the edge of the cut. The results of the experiment show that during the cutting process, the water of the layers of material adjacent to the hydroabrasive jet is absorbed. This is evidenced by the change in temperature of the transition of the material to another phase state. However, a week after drying, the material again assumes the original characteristics. Thus, it can be considered that the use of hydroabrasive cutting technology is possible for PCM.

Studies were carried out to determine the roughness of the cut surface according to the theoretical model (2). The difference in the results of theoretical and experimental studies does not exceed 15%, which indicates that the obtained theoretical dependencies adequately describe the process of forming surface roughness and make it possible to determine the roughness of the cut surface during PCM processing.

As previously noted, the resulting polymer composite blanks are often glued together. At many machine-building enterprises, abrasive grinding paper (GOST 13344-79, GOST 5009-82 and GOST 10054-82) is used to prepare the surface for the "gluing" operation [4-5]. The processing is done manually until the gloss is removed. A thin layer of polymerized binder is removed from the surface of the part. At the same time, it is important not to damage the fibers. A significant disadvantage of such processing is the high labor intensity of the operation, which is performed manually, which requires a large processing time. In addition, during the treatment of the PCM with a grinding paper, rapid wear of the tool occurs due to its salting. The sheets of the grinding paper must be changed as they wear, so that they retain their cutting ability.

The human factor has a significant influence on the processing process. During smoothing, the performer must monitor the pressing on the grinding tool. With insufficient pressure, the processing depth will be small, which leads to the least wetting of the substrate with glue. Excessive pressure can damage the composite fibers and disrupt the geometry of the part.

An alternative to smoothing can be the use of grinding heads and flapwheels that do not damage the fibers of the composite. At the same time, the process will be mechanized, which will lead to a reduction of the processing time of the workpiece, and, therefore, the total labor input of the part.

When solving the problem of reducing labor intensity and the proportion of manual labor, while simultaneously increasing the tool resistance and ensuring stable surface characteristics, two approaches are effective: studying the processes of forming the surface roughness of parts from PCM with various processing methods (it is necessary to obtain an optimal surface roughness for gluing, and not minimal as for metal products) and selecting an optimal grinding tool for mechanizing the smoothing process. Work on the study of relevant technological capabilities and processes was carried out on the basis of a machine-building enterprise. Products from polymers used for the production of aircraft parts were studied.

For the mechanization of the grinding process, it was decided to use elastic grinding tools, the design and properties of which allow significant movement of grains during operation from the static position in the direction of the normal component of the cutting force [7]. This ensures the stability of the tool, the reduction of heat flux intensity, the absence of micro-cracking of the surface layer in comparison with "rigid" grinding with abrasive paper [8]. Many products made of polymeric composite materials (sheath, shells, caps, etc.) have low rigidity. For them, it is advisable to use an
elastic grinding tool. The elastic base of such a tool is a kind of shock absorber introduced into the technological system, which is capable of quenching oscillations and vibrations arising during abrasive processing [4-7]. As noted above, most polymeric composite materials are hygroscopic, so the use of cooling liquids in processing is unacceptable. The design of the tool on a flexible basis allows to apply it during grinding without using a coolant.

Theoretical studies were carried out on the formation of the surface quality of a part made of PCM intended for further gluing.

To determine surface roughness, the technique developed by professor Korolev A.V. [8] was used to describe the formation of the roughness profile under the treatment with bonded abrasives. Based on the studies presented in [8], a relationship was obtained to determine the surface roughness of the PCM treated with flexible flapwheels:

$$\frac{t_c \cdot v_s \cdot I_j \cdot L_{sd}}{60 \cdot v_k \cdot L_K}$$

(5)

where $t_c$ is the thickness of the layer of material removed in one pass, $v_s$ is the feed speed, $I_j$ is the actual distance between the contact grains, $L_{sd}$ is the width of the treated area, $v_k$ is the speed of the circle, $L_K$ is the total length of the lamellae.

To check the adequacy of the obtained dependence, a large set of experimental procedures for preparing polymer composite parts for the “gluing” operation was carried out. Samples were made of PCM. The material of the samples is fiber glass VPS-7, consisting of a composition of a woven fiberglass web and a polymerized epoxy binder. The flexible abrasive flapwheel of the Klingspor model MM 630 with dissected lamellae was chosen as the processing tool (Figure 1).

Figure 1. Klingspor flapwheel model MM 630: diameter - 180 mm; width - 50 mm; grain - electrocorundum; binder - synthetic resin.

The Klingspor flapwheel is a grinding mandrel of Ø6 mm, on which the lamellae of the grinding paper are radially fixed. Each lamel is dissected into 10 equal segments. The length of the segment is 50 mm. The lamellae are wrapped in one direction. The design of the lamellae and their attachment to the mandrel allows us to attribute this circle to a very elastic tool. This model has a grain size according to FERA 240 standard, which corresponds to GOST 3647-80 [10] grain size М63 and grinding paper No 6.

The effectiveness of the grinding process depends on the processing modes: cutting speed, feed speed, specific pressure. It is necessary to select the speed of rotation of the wheel at which the processing process stabilizes, that is, under the influence of centrifugal and elastic forces, the grinding lobes have the best contact with the surface to be processed. Changing the feed speed and specific pressure during grinding (changing the diameter radius $r_d$ of the wheel, which is the distance from the center of the wheel to the surface of contact of the lamellae of the wheel with the workpiece when the machine is turned off) also affects the surface quality. [7, 9-15].
To select optimal processing modes, a flexible grinding wheel was installed in the spindle of a vertical-milling machine, and PCM samples were processed. The ranges of rotation speed (450-1400) rpm, feed speed (100-800) mm/min were selected.

Considering the design and elasticity of the wheel, processing was carried out at three values of dynamic radius: \( r_d = 55 \text{ mm}, 60 \text{ mm}, 65 \text{ mm} \). These \( r_d \) values were chosen to provide the maximum, average and minimum area of contact of the lamellae with the processed surface when the machine is turned off. Samples were installed in special cradles and were fixed using pressure plates.

During experimental studies, it was found that samples treated with the flapwheel have a uniform, matte, glossy surface. There is no violation of fiber integrity. After processing, roughness measurements were performed on a Tailor Hobson profilometer and visual inspection. Value of roughness parameter at selected processing modes \( Ra = 1.22 \mu m \) is shown on profilogram (Figure 2).

![Figure 2. Profilogram of the surface treated with a flapwheel at a frequency of 1400 rpm, feed speed of 315 mm/min and dynamic radius of \( r_d = 55 \text{ mm} \).](image)

The results of theoretical and experimental studies were compared. Their high convergence was established.

3. Results
The procedure for designing and optimizing the technological processes of hydroabrasive cutting of PCM and preparing their surface for further gluing has been developed, taking into account the given roughness of the cutting surface and the glued surface while ensuring the minimum cost of the product \([1-4, 9-12]\). The calculation of the roughness of the cut surface is made by the mathematical dependence (2) presented above. Setting the initial processing parameters \( P_{din}, R, \rho_{ch}, h, L, S, Q \) we calculate the number of useful impacts \( \lambda \). The roughness value \( Ra \) is then calculated. Next, we eliminate the processing modes that do not meet the condition: the roughness of the processed surface is less or equal than the specified one. After calculating the cost of cutting we select the combination of processing parameters at which the cut cost will be minimal.

The design of the part preparation operation made of PCM for gluing begins with a technological evaluation of the part design and the adhesive joint in which this part is involved. For each type of adhesive joint and type of adhesive, the developer must specify the required surface roughness class to be glued, from which the technician selects the grinding tool grain and machining modes. The treated surface shall be uniform and processed evenly over the entire area for gluing. The quantity indicator of quality of treatment is the surface roughness parameter \( Ra \). This parameter can be measured using a probe type profilometer. The required value of surface roughness is provided technologically due to correct assignment of machining modes and selection of tool.

The part arriving to the surface preparation operation for gluing must be clean and have no residue of moulding materials (separation materials, materials of vacuum bags, sealants, etc.). Technological
allowances, if not required in subsequent operations, are to be removed. The surface prepared for grinding is inspected for influxes, shagrens and other defects that are to be removed as well.

The graininess of the abrasive wheel is selected depending on the required part's roughness to ensure the strength of the adhesive joint. It is recommended to use FERA 240, 220, 180, 150 grain grinding wheels for less rigid and thin-walled parts for surface preparation for gluing. For the processing of parts with a rather thick surface epoxy layer (0.01 mm or more), it is recommended to use grain grinding wheels according to FERA 40, 80, 100, 120. For smoothing of surface defects (influxes, shagrens, swings, etc.) with simultaneous preparation of the surface for gluing, it is recommended to perform smoothing with grinding flapwheels of grain size according to FERA 80, 100, 120, which will be more productive compared to circles of less grain.

Processing modes are selected. The number of tool passes is calculated basing on the surface area to be ground. Machining of the complex parts with angled surfaces, roundings, curvilinear surfaces, etc. should start from the processing of these surfaces and then pass to the flat surfaces grinding. Mechanical processing of curved parts can be carried out on high-tech equipment: machines and installations with CNC. In this case, the tool movement is controlled by the program and the tool path repeats the detail's theoretical contour.

When studying the grinding process of fiberglass parts with a flapwheel the process parameters were selected: wheel rotation speed \( n \) (rpm), feed speed \( S \) (mm/min) and \( r_d \) (mm) value. Recommendations for the selection of processing modes for Klingspor flapwheels are summarized in Table 1.

Table 1. Recommended cutting modes for final abrasive machining of PCM parts for gluing.

| Required roughness, \( \mu m \) | Recommended graininess of the flapwheel according to FERA | Abrasive graininess according to GOST 3647-80 | \( Rc^* \) | \( S \) (mm/min) | \( n \) (rpm) |
|--------------------------------|-------------------------------------------------------|---------------------------------------------|---------|----------------|---------|
| 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                                                  | 4; M50                                      | 46      | 350-500         | 1100-1200  |

* \( Rc^* \) – specified for the flapwheels considered in this study

After finishing of the processing, the detail's surface is to be cleaned of grinding products. Cleaning should be done with a cotton napkin or a brush-sweep with soft bristles, removing fiberglass dust without air pollution.

The control of the processed surface consists of visual inspection of the surface for the absence of unobstructed areas (gloss on the surface), bare and destruction of composite fibers.

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