Design technique of highly efficient technological processes for preparation of polymeric composite parts for adhesive bonding

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Abstract. This paper presents the results of technological machining of polymer composite parts with the flexible flap wheels for further adhesive bonding. The peculiarities of polymer composite materials and their application field are revealed. Constructions that use polymer composite material parts are described. The article identifies the process of gluing parts made of polymer composites, as well as features of ensuring the strength of the adhesive joint after mechanical processing of bonded parts. Methodology of modes processing selection and structural-geometric tool parameters for the processing of surface parts under the adhesive bonding is elaborated. Theoretical studies of processing the polymer composite parts with the help of flap wheels are conducted. The surface roughness model is developed. A considerable amount of experimental research has been carried out. The tools for machining and cutting modes are selected. The strength of the glue connection of the details processed by the flap wheels is examined. To compare the durability of the received glue connections and the combinations executed according to the factory technology, the reference surfaces of the samples used at comparative control of quality sanding are investigated. The theoretical and experimental results are compared. Their high convergence is established. The adequacy of the theoretical dependence in compliance with the Fisher criterion is checked. Effective methodology for designing highly efficient technological processes tested in industrial conditions is presented. It allowed to reduce the processing time in more than 2 times, while providing the high strength adhesive bonds.

1. Introduction

The parts from polymeric composite materials (PCM) such as glass-, carbon, organoplastic are efficiently used in many branches of modern machine-building production. PCM is a heterogeneous system composed of two or more separated components differentiated by chemical composition, physical-mechanical characteristics. Moreover, some of the components are used as reinforcing elements, and the others are binding them matrix. These materials have valuable properties: low weight, dielectric and insulating properties, high mechanical properties, corrosion resistance, which, no doubt, contributes to the wide application of PCM for the parts manufacturing in the current period and in the near future. With the high functionality, PCMs reduce products weight (replacing traditional metal alloys, polymeric composite materials decrease the weight of the product by 20-40%) while increasing its reliability, making possible its operation even in extreme working conditions [1-21].

Constructions that use PCM parts are diverse: parts of the aviation industry (Fig. 1) (the blades of bearing and tail rotors of helicopters, wing panels, body parts of the fuselage, stringers, longerons, etc.), instrumentation (insulators, plugs, piping, protects flanges, contacts, connectors, etc.), road construction...
Details and automotive equipment (flanges, handles, fittings, etc.). Details of the PCM are widely applied for household appliances and devices.

This paper scrutinizes fiberglass parts, that are compositions composed of thermosetting synthetic resins (epoxies, hardeners and accelerators) and a fiberglass filler, which is based on SiO$_2$ silica. The fillers of non-orientable fiberglass are short glass fibers. It allows to produce parts with a metal matrix, which is called glass-metal. This material has strength characteristics that are rather higher compared to other PCMs [6-18].

One of the most common technology for PCM parts connection is adhesive bonding technology. It allows to get a permanent connection by the adhesive interaction of glue (adhesive) and the substrate (glued surfaces). Adhesive bonding is a relatively new type of fixed, one-piece joint that have been widely used. The high bonding strength and a significant resistance to fatigue, as well as the ability to connect dissimilar materials, made this technology attractive for many industries.

More frequently PCM parts are bonded together by overlapping splicing method (Fig. 2). This makes it possible to bond together parts of different thicknesses and stiffness. In this case the external load is distributed over the entire area of the adhesive joint. External loads influence the adhesive-bonded joint, as a result, the shear stress arises in it, most of all at the interface and in the adhesive layer. The structural parameters of the joint are influenced by the load-bearing ability and the adhesive joint condition.

![Figure 1. Basic parts from PCMs](image1)

![Figure 2. The scheme of the adhesive bonding overlap (B1 and B2 – bonded parts from PCM, $G\delta$ - adhesive layer, l - the length of the adhesive bond).](image2)
To provide the required adhesive durability the bonded surfaces must undergo machining and have some optimum roughness value. The surface machining for adhesive bonding consists in microroughness creation of a certain form that is filled with the adhesive of the required fill rate and bonded joint creation in compliance with the strength characteristics. To remove the release layer and create optimal surface roughness the parts are subjected to hand grinding with the usage of the sand paper to sanding. In the modern assembly production, the processing of the surface parts made of PCMs under adhesive bonding is done by hand grinding and bear the high workload connected with a low level of automation and mechanization of this operation. The majority of enterprises uses as a tool for the production of polymer articles the abrasive paper GOST 13344-79, GOST 5009-82 and GOST 10054-82. Processing is done manually to remove the gloss. It is important not to damage the fibers. The appearance of uneven or excessive sanding and undersanding leads to defect. Depending on the number of defects the part is rejected or subjected to repair at a special technology. This leads to deterioration in the products quality and increase of its manufacture cost. In connection with the foregoing, the authors have performed the work review in search of necessary tools for mechanization the abrasion parts from PCMs for bonding. The work reviews in the field of machining of composite materials and the impact of surface microprofile on the quality of the connection showed that the process of the surface preparation for polymer composite bonding of parts is insufficiently investigated. The roughness parameters of the reference surfaces are lacking. To generate a desired surface microprofile the cutting tool is required. It should be fitted for the mechanization process and provide the required parameters of roughness, but the linear dimensions of the part in its turn should be changed within the dimension limit.

2. Materials and methods

The studies of polymer composite parts preparation for adhesive bonding were conducted. Technological bonding process consists of the following operations:

1. Incoming parts inspection. Visual inspection of the part surfaces after molding and decompression for defects (glue stains, cracks, shagreens, bubbles, seals, etc.).
2. Surface cleaning. The surface is cleaned from the products of polymerization with a dry clean cotton cloth.
3. Mechanical surface treatment. The processing is up to the gloss removal.
4. Surface cleaning. The surface cleaning from sanding is conducted with a clean dry cotton cloth.
5. Control of the surface dressing. The processed surface is subjected to a comparative visual control. The surface is compared with the reference sample, which is a piece or the whole part with the processed surface for bonding in compliance with the approved technology. The sample manufacturing is done in the presence of the commission, consisting of engineer, constructor, foreman, metallurgist, inspector. All stages of the operation are monitored and controlled on a lack of technology violations. The test sample appearance is approved by the commission. It should be noted that this type of control is the main method of the polymer composite surface quality assessment for bonding. Manufacturing of quality control sample is provided for the most part by the competence and professionalism of workers and engineers (metallurgists, technologists, designers). The professional experience and high qualification of workers, numerous strength tests of the samples lead to the production of good adhesive bonding.

Based on the experience of processing fiberglass parts for machine-building enterprises, the production tooling search was performed in the group of tools on a flexible basis (sand paper, elastic finishing discs, endless sanding belts, flap circles, flexible honing bars, mesh and fibre discs, brushes from abrasive fibers, etc.). This tool is widely used in many fields of engineering for many years. It is used both in general-purpose equipment and in manual handling. Unlike the abrasive wheels with the stiffening foundation the flexible tool allows a wide variation of the contact cutting surface with the treated, that creates the ability to manage the processes in accordance with the physico-mechanical properties of the parts and technical conditions of processing. Tools on a flexible basis are also called the elastic grinding tools. Such tools have the following advantages:
• grain springing on the material;
• decrease of thermal release in the cutting process;
• elimination of the surface layer microcrazing;
• decrease in the rate of clogging of the working surface;
• increase of the time interaction of the abrasive grain with the machined surface;
• ability to process long and shaped components.

In accordance with the study results, the flexible sanding flap wheel with a splitted lamellae of the firm Klingspor was selected from the range of elastic grinding tools for the processing.

![Figure 3. Flap wheel with a splitted lamellae of the firm Klingspor](image)

Processing with a flexible grinding tool is described in detail in many works, among which the works of V. A. Schegolev, A. N. Gdalevich are highlighted [19]. The authors gave efficient recommendations on the choice of grinding modes for a wide range of materials and processing schemes; the design of flap wheels, materials on parameters optimization, recommendations on the equipment selection and its upgrade, as well as technical and economic rationale of final processing with the flap wheels. All the studies are mostly experimental in nature. Moreover, attention was paid to the metal material processing, but not to the covered PCMs. The formation of the required micro profile of the polymer composite parts surface for the further bonding has not so far received all the attention it deserves.

The authors carried out theoretical studies on the surface roughness profile formation of a PCMs part in the process of machining with the flexible flap wheels [1,2]. The theoretical dependence for the surface roughness calculation of parts in machining with the flap wheels reflects the physical essence of the phenomena and takes into account the cutting profile formation of the flap wheel:

\[
Ra = 0,09 \sqrt{\frac{a_z L_{ed}}{n_0}}
\]  

(1)

where \(a_z\) – average scratch depth; \(L_{ed}\) – unit length; \(n_0\) – the nominal number of abrasive grains per unit of the surface bond.

To determine \(a_z\) we use the formula proposed by A.I. Gdalevich [2], for direct profile flap wheels:

\[
a_z = 10 - \frac{t_c v_s l_f}{60v_k L_k}
\]  

(2),

where \(t_c\) – the thickness of the material layer removed in one pass; \(v_s\) – feed rate; \(l_f\) – the actual distance between the contact grains; \(v_k\) – wheel speed; \(L_k\) – total length of the flaps.

Inserting the formula (2) into the formula (1) we get the following expression for determining the surface roughness of PCMs processed with the flap wheel:
\[
Ra = 0.9 \sqrt{\frac{t_c v_s l_f^3 L_{ed}}{60v_k L_k}}
\]  

(3).  

To confirm the adequacy of the obtained dependence, experimental studies of the processing parts from PCMs for bonding with the flexible flap wheels of Klingspor were carried out.  

The comparative study of theoretical and experimental data is presented in Fig. 4 and Fig. 5. The roughness parameters are calculated by the formula (3). Dependencies at various processing modes are built. The solid lines show the theoretical dependencies, and the dashed lines show the results of experimental studies. The solid sector on the graphs is the recommended surface roughness.  

**Figure 4.** Roughness Ra of the surface parts made of PCMs depending on the feed of the flap wheel with the grain size according to FERA 180 (No. 3 - 900 rpm, No. 4 - 1120 rpm, No. 5 - 1400 rpm)  

**Figure 5.** Roughness Ra of the surface parts made of PCMs depending on the frequency of the flap wheel rotation with the grain size according to FERA 180 (S1 - 100mm / min, S2 - 200mm / min, S3 - 500 mm / min)
The efficient results convergence of the theoretical and experimental study is observed. The discrepancy does not exceed 20%.

The adequacy of the theoretical dependence according to the Fisher criterion has been done. It is established, that the obtained theoretical dependence for calculating the roughness parameters processed with the flexible flap wheels is adequate.

To compare the adhesive joints strength, the reference surfaces of the samples used in the comparative quality control of the sanding parts were studied. They present a fragment of a fiberglass product, the surface of which is processed according to the current technology: processing is carried out manually with a sandpaper to remove gloss and defects without damaging the composite fibers. The reference sample has a matte surface with the visible traces of the individual abrasive grains aisle.

It is visually seen that on all the samples treated with a grinding sand, there are zones of under-grinding and excessive grinding of the polymer. This is due to the different pressure of the worker’s hand on the grinding paper during processing. The experimental data in compliance with the arithmetic mean deviation of the roughness profile, lead to the following conclusions:

With an increase of the grain size of the grit paper, the roughness parameters of the treated surface also increase.

There are visualized scratches on the treated surface; the surface roughness has a distinct focus.

The quality of the processed surface is affected not only by the granularity of the grit paper, but also by the degree of manual pressure on it, as well as the intensity of sanding.

Then the samples are further processed with Klingspor flap wheels. A visual analysis of the treated surfaces has led to the following results:

All the samples have a uniform matte surface. The scratches from the abrasive grains are less visualized compared to the samples processed with the grit paper.

1. When processing samples with the pneumatic tools the flap wheels show the competitive edge. The processing may be carried out under various angles of the axis inclination of the tool to the workpiece (from 0° to 60°). Mobility tools and the elasticity of the grinding wheel give the ability to handle large and bulky parts (fuselages, hulls, tanks, etc.) and use directly on the assembled product during repair.

2. As in case of treatment with the grit paper, the increase in the grain effect of the flap wheel causes the increase in the roughness parameters of the machined surface.

3. With the increase of the cutting speed, the cutting forces are monotonically increase and respectively, the cutting ability of the flaps wheels increases, which in its turn leads to the surface roughness increase.

4. Reduction of the working radius of the wheel (the working radius is the distance from the center of the wheel rotation to the workpiece) has a positive effect on the quality of the processed surface. By the increase of the contact area of the flap wheel the total length of working areas of the flaps increases and at the expense of the grains height leveling, the number of simultaneously working grains increases.

5. The feed rate reduction leads to an almost proportional increase in the thickness of the material layer removed per stroke and thereby in the roughness increase of the machined areas.

3. Results

To assess the adhesive joints quality of parts and PCMs, control samples of the adhesive joints were made and their durability test was carried out. The test results of the samples processed with Klingspor flap wheels are shown in Table 1. Similar tests were also carried out for the samples processed manually with the grit paper.
Analyzing the experimental results of the control adhesive joint samples processed manually with a grit paper, the following conclusions can be drawn:

1. The adhesive joint samples without processing haven’t passed the test and showed low values of both retardation and cleavage strength.
2. The strength of the adhesive joint depends on the roughness parameters of the bonded surfaces and changes in the process of machining with a tool of different grain sizes. The bonded parts processed with the grit paper No. 6, then with the grit paper No. 8 and No. 12 have the best indicators.
3. Behavior of the adhesive joint strength of the rough fiberglass surfaces with the increasing roughness is determined.

The results of analyzing the experimental data of control adhesive joint samples processed with Klingspor flap wheels are as follows:

1. The samples with a roughness value of 1.8–2.5 mkm in Ra showed the maximum bond strength.
2. The behavior of the adhesive joint strength with the increasing roughness is determined.
3. The strength of the adhesive bond depends not only on the surface roughness parameters, but also on the levelness of the processing.

Based on experimental data, it was discovered that the increase in cutting speed and the decrease in the tool feed lead to the surface roughness increase. The forced deformation of the flap wheel during processing (the value of its working radius) also has a significant impact on the processing result. When studying the process of grinding fiberglass parts with a flap wheel, permanent process parameters were chosen: the wheel rotation frequency, feed and value of the working radius. Based on the research results, the required surface roughness was determined, that should be provided on PCM parts to create a strong adhesive bond.

4. Conclusion
The comparison of theoretical and experimental data is conducted. It has been established, that theoretical dependences accurately describe the grinding process of the PCM surfaces with the flexible flap wheels. These PCM parts are subjected to bonding. Theoretical dependencies are adequate, that is confirmed by their verification in compliance with the Fisher criterion.

The obtained dependences are recommended to determine sanding treatment modes, tool selection, technological study of the adhesive joint manufacture and design of technological processes.

Based on the studies, technological recommendations are given for the final abrasive processing of PCM parts for bonding and the engineering methodology for the structural and geometric parameters.
calculation of the grinding tool has been put forward. Table 2 illustrates the recommended cutting modes for final abrasive processing of parts made of PCMs for bonding.

**Table 2. The recommended cutting modes for final abrasion of parts made of PCMs for bonding**

| Required roughness, mkm | Recommended grain size of the flap wheel material according to FERA | Grain effect of abrasive material in accordance with GOST 3647-80 | Re*, mm | 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  |

* Re – for the flap wheels of Klingspor

For the selection of the processing parameters it is necessary to know the desired roughness of the surface under bonding. This value is taken from the engineering drawings, manufacturing instructions on the adhesive composition or in their absence in the drawings. The tool selection is assured in compliance with the following table: depending on the desired roughness the grain effect of the flexible flap wheel is selected. Furthermore, according to the same table, the selected processing modes and the working radius of the wheel is selected.

The application of the technological process mechanization technology of the final abrasive finishing of parts made of PCMs under the bonding has been tested in the conditions of manufacturing. The processing time reduction in more than 2 times was presented, while the average value of the adhesive strength was significantly increased.

**References**

[1] Benson, A.-F. Adhesives advance assembly Assembly. 1991. 12–15.

[2] Dimov Yu. V. Interaction of Lobed Wheel with Machined Surface 2011 Russian Engineering Research 7, 707–711.

[3] Karlsson H. Quality Assurance in Adhesive Joining Technology 1997 Assembly Automation 17, 1, 48–55.

[4] Tamarkin M. A. The optimization of theological processes of details processing by free abrasives. - Key Engineering Materials. 2005. 291-292. 319-322.

[5] Packham D.-E. Work of adhesion: contact angles and contact mechanics 1996 International Journal of Adhesion and Adhesives 16. 121-128.

[6] Mechanization of the abrasive processing of parts from composite materials 2017 Bulletin of the RSATU P.A. Solovyova 2 (41) 75-82.

[7] Mechanization of the abrasive processing of parts from polymer composite materials under the operation "bonding" 2018 Vestnik DGTU 18 (2) 179-189.

[8] Study of the final abrasive processing of parts from polymer composite materials (PCM) / N.V. Kozulko, K.V. Seminichenko 2019 Scientific and Technical Bulletin of the Volga Region 1 55-59.
[9] The choice of the efficient method of the surface preparation of parts from composite materials for the adhesive bonding 2014 Processes of abrasive processing, abrasive tools and materials. Gridabrasiv collection of articles of the International scientific and technical conference. 134-136.

[10] Comparative analysis of the adhesive bonds of parts from polymer composite materials (PCM) processed in various ways 2014 Young scientists - the basis of the future engineering and construction: a collection of scientific papers of the International scientific and technical conference. 162-167.

[11] The grain size effect of the grid paper for the surface preparation of parts made of polymer composite materials (PCM) on the durability of the adhesive joint / N.V. Kozulko // Collection of scientific papers of the XIth International Scientific and Practical Conference "Modern Instrumental Systems, Information Technologies and Innovations", in 4 volumes, Volume 2 (Kursk, March 19-21, 2014) - Kursk: South-West. State Univ., 2014 - pp. 205-210.

[12] The quality parameters of the part surfaces made of fibrous composite materials, processed in various ways under bonding / N.V. Kozulko // Status and the development perspectives of agricultural engineering: Collection of articles 10th international scientific and practical conference (Rostov-on-Don, March 1-3, 2017) - Rostov-on-Don: DSTU, 2017 - pp. 222-225.

[13] Processing of parts from polymeric composite materials with the flap wheels of various grain sizes for bonding / N.V. Kozulko, A.V. Gordienko // Technologies, innovations and entrepreneurship: collection of scientific papers based on the materials of the I International Scientific and Practical Conference, May 31, 2017. - St. Petersburg: NGO Professional Science, 2017 - p. 69-78.

[14] Parameters of surface fiberglass parts roughness processed with the flap wheels of various grain sizes for bonding / N.V. Kozulko, K.V. Seminichenko // High technologies and modernization of the economy: achievements and new development vectors: a collection of scientific papers based on the materials of the I International Scientific and Practical Conference, October 31, 2017. - Moscow: “Professional Science”, 2017. - p. 304-312.

[15] The study of possibilities of abrasive processing mechanization of parts from polymer composite materials under the operation "bonding" 2017 Journal of Aerospace Engineering, High Technology and Innovation. 257-267.

[16] Investigation of the abrasive machining process of parts from polymer composite materials with the flap wheels for the adhesive bonding / N.V. Kozulko, K.V. Seminichenko // Mechanical Engineering and Technosphere of the 21st century. Proceedings of the XXV MET Volume 1 - Donetsk, 2018

[17] Construction of the efficient technological processes of polymer composite parts machining for bonding / M.A. Tamarkin, E.E. Tishchenko, N.V. Kozulko // XI International Scientific and Technical Conference of the Technologists and Engineers Association “Innovative Engineering Technologies in the Transport Complex”, Kaliningrad, 2019

[18] The study of the adhesive joints durability of polymer composite parts processed with the flap wheels / M.A. Tamarkin, E.E. Tishchenko, N.V. Kozulko, A.N. Burlo // Fundamentals of physics, chemistry and dynamics of the high technological systems of shaping and parts assembling: collection of articles of the scientific Symposium of mechanical engineers / Don state. tech. university. - Rostov-on-Don: DSTU, 2019.- pp. 71-76.

[19] Finishing processing with the flap wheels / A. I. Gdalevich - M.: Mechanical Engineering, 1990 – 112p.

[20] Abrasive Tool For Processing Components Made From Chrome-Nickel Steels And Alloys 2019 E3S Web of Conferences 01040.

[21] Technological effect of vibroprocessing by flows of organic granular media 2018 IOP Conference Series: Materials Science and Engineering. Processing Equipment, Mechanical Engineering Processes and Metals Treatment. 042061.