TRANSPORT PROBLEMS 2023 Volume 18 Issue 1
PROBLEMY TRANSPORTU DOI: 10.20858/tp.2023.18.1.10

Keywords: impulse thermal energy method; honing; superfinishing; surface finishing; electrochemical machining

Valeriy SIKULSKIY[1], Kateryna MAIOROVA[2]*, Yurii VOROBIOV[3], Petro FOMICHEV[4], Svitlana MYRONOVA[5]

CONVERGENCE TECHNOLOGY FOR VEHICLE PART SURFACE FINISHING

Summary. The subject of this research is convergence technology for the surface finishing of vehicle parts. A literature review has been conducted to carry out a comparative analysis of existing methods for the surface finishing of parts used in the manufacturing of aircraft, hydraulic and pneumatic devices, and other vehicles. Prospects are shown for further research on methods with the aim of creating a complex technology (i.e., convergence) that combines information technologies; nanotechnologies; and thermochemical, electrochemical, and mechanical processing methods. A method is proposed for selecting and combining surface finishing methods according to a five-point expert assessment, which allows the batch processing of vehicle parts. Based on this method, the concept of convergence technology for the surface finishing of vehicle parts is proposed, which includes the impulse thermal energy method, honing, superfinishing, and electrochemical processing. An expanded process is presented for manufacturing parts with high-precision, low-roughness surfaces and a specified microrelief by using electrochemical superfinishing and electrochemical honing. A scheme of the concentration (focusing) of the current flow during electrochemical superfinishing due to the movement of the electrode relative to the part surface is proposed, which enables the effect of surface polishing and the removal of oxidation products. Convergence technology for the surface finishing of vehicle parts will provide parts' geometric dimensions with micro- and nano-precision and allow the precision machining of small-diameter holes and complex profiles, increased machining accuracy (up to 0.001 microns), the possibility of batch processing, and the possibility of process automation.

1. INTRODUCTION

The aerospace industry is one of the most scientific knowledge-intensive and high-tech industries in the national economy. The most advanced and cutting-edge technologies are implemented in the aircraft industry, with the further use of this experience in the manufacturing of other engineering products. The introduction and improvement of methods and technologies for manufacturing and finishing (cleaning and surface finishing) of such produced items are determined by several factors:

[1] National Aerospace University "Kharkiv Aviation Institute"; Chkalova 17, 61000 Kharkiv, Ukraine; e-mail: vsikulskij@gmail.com; orcid.org/0000-0002-5944-4728
[2] National Aerospace University "Kharkiv Aviation Institute"; Chkalova 17, 61000 Kharkiv, Ukraine; e-mail: k.majorova@khai.edu; orcid.org/0000-0003-3949-0791
[3] National Aerospace University "Kharkiv Aviation Institute"; Chkalova 17, 61000 Kharkiv, Ukraine; e-mail: i.vorobiov@khai.edu; orcid.org/0000-0001-6401-7790
[4] National Aerospace University "Kharkiv Aviation Institute"; Chkalova 17, 61000 Kharkiv, Ukraine; e-mail: p.fomichevkhai@gmail.com; orcid.org/0000-0002-5624-4851
[5] National Aerospace University "Kharkiv Aviation Institute"; Chkalova 17, 61000 Kharkiv, Ukraine; e-mail: s.mironova@khai.edu; orcid.org/0000-0002-5981-1620
* Corresponding author. E-mail: k.majorova@khai.edu

- the use of new alloys based on nickel, chromium, and titanium, as well as composite and intermetallic materials with improved physical, mechanical, and thermal properties;
- complications in the parts' shapes due to the tendency to reduce the number of assembly components;
- increased requirements for accuracy, surface finishing, and roughness;
- the need for precision in the geometry of parts of micron and nanometer sizes.

Today, there are more than a hundred surface finishing methods used for materials of various shapes, sizes, and materials in products and aggregates in the aerospace and defense industry [1]. This situation is due to the fact that the microgeometry of a part's surface, which results from surface finishing, determines its future functional properties and product service life [2]. Product service life can be extended up to 70...90% by applying modern technological methods of deburring. The need to use surface finishing and cleaning technologies in manufacturing engineering has been assessed by researchers in different ways, depending on the technologies recommended for achieving the required parameters of parts. Therefore, in each case, it is necessary to create the desired surface finish individually to achieve a high level of functional properties of hydraulic components, devices, and contact surfaces in friction. The choice of surface finishing technology for cleaning and forming a microrelief depends on the material, shape, size, and accuracy of the parts; subsequent processing; the degree of surface contamination; their purpose; the operating conditions; etc. Despite the variety of existing surface finishing methods, the main task that should be solved by any such method (or a combination of them) is to ensure the specified functioning, service life, and reliability of mechanical engineering components [3]. As a result, for the complex processing of parts at a medium-sized mechanical engineering manufacturing enterprise, it is necessary to use at least two to three different advanced technologies. Such an approach significantly affects the cost of components and products. In this regard, a relevant problem is related to improving the parts' accuracy (determining the form and position tolerances of parts, determining the surface roughness of parts, and forming a roughness profile of finished surfaces, including micro- and nano-roughness) due to the need to create a single convergence technology based on computer-aided technologies, as well as nanotechnologies and thermochemical, electrochemical, and mechanical methods, for the surface finishing of various vehicle parts.

2. PURPOSE AND OBJECTIVES OF THE STUDY

The purpose of the present study is to improve the specified quality of vehicle parts (aircraft, hydraulic, and pneumatic components; devices; and other mechanical engineering products) by using a convergence technology to combine finishing methods for cleaning, smoothing, and deburring. The following objectives were proposed to achieve this purpose:

1. Conduct a comparative analysis of existing methods for the surface finishing of parts used in the manufacture of various vehicles.
2. Analyze promising surface finishing methods that allow batch processing.
3. Explain the concept of convergence technology for vehicle parts.

3. LITERATURE REVIEW AND THE STATE OF THE ART

3.1. Comparative analysis of existing part surface finishing methods

An attempt to systematize a variety of surface finishing processes was made in [4], which presented the state of the art of highly productive effectively computer-controlled production methods for the mechanical and physical-technical finishing processing of parts' surfaces. Such methods include turning and grinding with tools made of superhard materials and magnetic-abrasive and magnetorheological polishing. The abilities of advanced cutting and abrasive methods have been shown, and examples of their highly effective complex application in the production of parts made of difficult-to-cut materials have been given. The authors of [5] identified energy methods as the most promising and progressive methods for part surface finishing, while a number of methods directly associated with surface finishing (superfinishing, honing, polishing, etc.) have been insufficiently covered. More detailed presentations of the surface finishing methods for vehicle parts processing by means of selecting the appropriate XEBEC tool (Japan) were given in [6-8], which presented a variety of tools for surface finishing: parts deburring, edge filleting after machining, and electroerosive processing. The tool is a brush with bristles made of a special ceramic material, which is suitable not only for deburring but also for removing cutter tracks and polishing, for example, cylinder heads, cylinder blocks, and beds.

The complete automation of surface finishing would allow operations to be performed without humans, including:

- programmable brush length adjustment;
- the maintenance of optimal cutting efficiency with reduced downtime;
- provision of adjustable pressure control on the tool;
- a more uniform surface finish and longer brush service life for heavy-duty applications, including cross-holes' surfaces.

The holes are machined with an abrasive stone on a flexible ceramic fiber shaft with soft contact.

If the intersection of internal or external diameters is machined, a CNC milling machine with a ball nose cutter, which moves along a curved path, is used for deburring the edges of the inlets and outlets in one tool pass.

For various materials processing applications, brushes of different bristle hardnesses or brush projections are used, which differ in terms of the color of the brush: A13 Pink, A21 White, A11 Red, and A32 Blue.

Using a mechanical tool for removing burrs and improving the quality of surfaces was the first, but not the best, solution to this problem in mechanical engineering for several reasons. First, mechanical processing requires the use of additional equipment. Second, such processing requires a large number of specialized tools, which are mostly made individually for the particular manufacturing conditions and peculiarities of the manufactured product. Third, conventional machining processes cannot be used for batch processing. Fourth, many conventional machining processes are manual, which presents a challenge because high-skilled workers are necessary. Fifth, mechanical surface finishing does not provide high-quality manufactured parts; therefore, their service life is short, and thus, additional surface finishing operations are necessary for part-manufacturing technologies. These five factors have increased the cost of manufacturing technology for parts and entire products.

The use of some mechanical tools is unacceptable for deburring the inlets and outlets of holes drilled in structures made of polymer composite materials because of the appearance of delaminations and chips [9–10]. For the surface finishing of ceramics, superalloys, and polymer composite materials, a surface finishing medium is used by means of a magnetic field or any other medium. A previous paper [11] proposed a finishing medium called a magnetorheological fluid, which is a mixture of abrasive particles, a binder, and additives. The obvious advantages of abrasive blasting (abrasive flow finishing), chemical mechanical polishing, magnetic abrasive finishing, etc. were noted, and studies on surface finishing method combinations led to improvements in part surface finishing technology.

The authors of [12] pointed out that, despite the dire need of many manufacturers and industries, there is no information in the public domain or literature regarding the methods used for deburring and edge processing parts made of aluminum, which is one of the most usable materials in the world. In [12], the mechanism of burr formation and the factors influencing burr formation for aluminum alloys are presented by means of full-scale experiments, numerical analysis, and analytical models. Based on this analysis, a classifier of technologies for burr removal by mechanical surface finishing methods was compiled, considering the burrs' sizes and shapes. This paper presents several mechanical methods for deburring, including robotic, CNC, and manual deburring. Recommendations are also given regarding the use of mechanical deburring processes that are not included in the classifier but which nevertheless can be used, either additionally or independently. It should be noted that in experimental, numerical, and analytical models, as well as in the classifier, the influence of the lubricants used on the efficiency of deburring is not taken into account. The article draws an important conclusion indicating that not removing burrs and processing the intersections of surfaces (edges) are both important for ensuring the part service life. Despite the practical significance of the obtained results, the authors of [12] did not consider precision deburring and edge processing sufficiently. This is due to the fact that even fine surface finishing methods of mechanical groups do not provide the required precision of parts' edges and surfaces. As stated in the article, the close collaboration among machinery manufacturers, CAD/CAM programmers who plan rational tool paths, and the research community in the field of deburring and edge finishing is critical for the successful transition to the next generation of precision deburring and edge finishing techniques [13].

Previous works [4-12] focused on the processes of deburring and the formation of product edges. Another noteworthy study is [14], in which the authors stated the goal of eliminating the very possibility of burr formation. The authors confirmed that burrs are one of the most undesirable phenomena that occur during the processing of a workpiece, which results in a reduction in the quality and service life of the processed part. The expediency of surface finishing methods, according to scientists [14], should be economically reasonable. Thus, the best option is to reduce the risk of burr formation from the very first stage of part manufacturing instead of removing them during later stages. This approach reduces the time and number of surface finishing operations required to ensure that the precision of the part's surfaces and edges is acceptable. This study presents the mechanisms and variants for burr formation in the most common machining processes, namely drilling, milling, turning, and grinding, which complements the work of [12]. Of particular interest was the analysis of the existing problems of burr formation depending on the part-manufacturing technology, as well as methods for minimizing burr formation. This means that the number of burrs can be minimized by choosing the right tool geometry and material, machining parameters (which take into account the properties of the workpiece material), coolant, process plan, and tool path.

Today, hand tools, abrasive blasting, magnetic abrasive processing, rotary drum processing, thermal melting, electrochemical effects, and vibro-abrasive and plasma processing are widely used for part surface finishing and deburring.

In [15], the authors implemented a complete cycle as proposed by the authors of [12, 14], using the example of manufacturing an aluminum pipe with a band saw and subsequent vibro-abrasive processing to smooth sharp edges and remove burrs. There is a purpose for such research: The complex approach to technology development minimizes the formation of sharp edges and burrs, which allows one to determine the main conditions for burr formation during machining, not only at the edges of the workpieces but also at the tool exit point. The authors of [15] also showed the effect of the time of the vibro-abrasive treatment on the final result of aluminum part deburring.

An alternative experience emerges when special coatings other than the material of the substrate part are used to improve the part's surface finish by using plasma technologies. The main disadvantage of this process is the lack of sufficient knowledge and experience to apply the method to parts with holes with a small diameter and complex profile, as well as on parts of different materials and sizes [16-17].

In [18], the authors studied burr formation during the machining of a Ti6Al4V alloy, which is known for having poor machinability, a high risk of burr formation, and, as a result, a short tool service life and poor part surface quality. Experimental studies were carried out to determine the characteristics of upper burr formation on the Ti6Al4V alloy during face milling. This work used information technologies involving scanning electron microscopy, which identified a burr formed on the processed surface. A new method was introduced to accurately measure the top burr width by the width equivalent. The equivalent width of a burr is calculated as the ratio of the total area of the resulting burr to its total height. The authors noted that the equivalent burr width increased by 120% during up milling and decreased by 50% during climb milling when a change was made from normal to high speed. In addition, the influences of various cutting parameters and tool parameters on the formation of top burr were analyzed in order to find any correlations between them. It should be noted that there is a commonality in the approaches followed by the authors of [14] and [15], who analyzed burr formation depending on the technology and cutting mode in the part-manufacturing process.

In [19], it was proposed to examine burrs using a microscope in automatic mode to identify internal and hidden defects in the burrs and in the workpiece structure. This article proposed a method for the automatic detection of these defects and the assessment of the edge processing quality based on full vision using image processing and linear regression. The process was examined using a calculated function and compared to obtain quality assessment limits. The results confirmed the good capability of the proposed method for the three main types of burrs. Such research makes it possible to influence the technology and cutting conditions used in vehicle part manufacturing, which is a promising direction for further studies. However, the full vision method proposed in [19] contains an imperfect model that does not provide a complete understanding of all types of burrs.

Particular attention should be paid to the edging and deburring of intersecting surfaces (e.g., inputs and exits through holes and cross-holes) of parts.

In [20], the authors presented an analysis of the processes of burr formation at the inlet and outlet while processing through holes. It was noted that deburring these cross holes is difficult due to limited access. The same work also presented a model that generates a tool path suitable for the precision deburring of cross holes using a ball nose cutter. The presented model was developed using a computer-aided engineering system. It created a three-axis tool path associated with the geometry of the intersection of the main hole and cross hole, which removes burrs and produces a permanent chamfer. The adequacy of the model was confirmed experimentally using three different samples with cross holes in the AlSi7Mg material. It should be emphasized that the studies presented in [20] refer to mechanical surface finishing methods and are consistent with works [4] and [5].

Despite the theoretical and practical significance of the results of the works analyzed above, the following points have not been sufficiently considered:

- batch processing of parts with burrs, which, in mass production, affects the cost of the final product;
- the prospect of compatibility or a combination of surface finishing methods to ensure the specified characteristics of vehicle parts.

Taking into account the experience of developed countries in terms of vehicle part surface finishing, research could be conducted to create an integrated technology (i.e., convergence) that may combine information technology, nanotechnology, thermochemical, electrochemical, and mechanical processing methods.

3.2. Analysis of advanced surface finishing methods that allow the batch processing of parts

The solution to the problem of the batch deburring of vehicle parts in modern manufacturing is reduced to the use of thermal energy and impulse thermal methods. The authors of [20] suggested ways to improve these methods for machine part deburring to ensure the desired quality of the edges and surfaces while batch processing the parts in one cycle. The main problem occurred when burrs were removed from parts (i.e., the uniform distribution of thermal and pressure effects on a batch of parts). Another study [21] presented ways to automate cleaning operations using technological contaminants in the form of particles, burrs, and easily worn-out elements of the parts through microrelief, which resulted in a practically absolute degree of surface and edge cleanness. However, there is no approbation of the performed theoretical studies, and the model's adequacy has been confirmed only by the results of simulating processes but not by full-scaled experiments.

Regarding high-precision (nanoprecision) parts of radio-electronic equipment made of coaxial radio components (brass, beryllium bronze, etc.), the authors of [22] concluded that it is necessary to ensure not only the dimensions' and edges' accuracy and the burrs' absence but also other factors (e.g., the proper micro- and nano-roughness of surfaces, the absence of microparticles, the required physical and chemical state of the material, and its ability to withstand friction wear) to achieve a significant extension of such parts' service lives. Therefore, the authors of this article believe that the specified requirements can be achieved by the sequential processing of the part by mechanical, impulse thermal energy, and electrochemical methods.

In another study [23], the authors:

- considered the impulse thermal energy method-based technological processing capabilities, control parameters, and factors that determine the rational choice of processing modes for parts of machines and mechanisms;

- determined the factors influencing the selection of the optimal modes of cleaning parts' edges and surfaces
- determined factors that allow the formation of the technical characteristics of the heat source and equipment, thereby realizing optimal modes with self-regulation properties.

The work [23] is distinguished by presenting the results of full-scale experiments with parts processed by the impulse thermal energy method and comparing this method with the thermochemical method. The authors noted that explosive gas technologies are very promising due to their versatility and flexibility when applied to parts with complex configurations of internal and external surfaces.

A contemporary alternative to the thermochemical method is the electrochemical method, which combines a slight thermal and mechanical effect on the processed surface [24]. Electrochemical machining is based on the process of the anodic electrochemical dissolution of materials in an electrolyte due to the action of a high-density current. Thus, in [25], the technology of electrochemical honing was presented using an example of processing the parts of gas turbine engines. Experiments have shown the high potential of electrochemical honing when drilling EDM of small holes and holes with complex geometric shapes, processing the pressure side of thin-walled compressor blades and blisks, microstructuring and texturing parts' surfaces, shaping the elements of perspective seals, and processing parts made from difficult-to-cut materials.

Another article [26] reported positive results related to the finishing of parts, such as gear wheels, using the electrochemical method. The authors noted that the utilized method has great potential for microfinishing with material removal by anodic dissolution combined with the mechanical action of abrasive grains. This study contains a detailed description of the process principle, technological capabilities, equipment design, influences of input parameters, developed regression models, and aspects of the machined surface integrity.

The prospects and importance of surface finishing operations in mechanical engineering, which are used in the final stage of surface processing, have been confirmed by scientists from many countries [27-29]. However, the main drawback of these operations is the almost exclusive use of manual labor; thus, all developments are related to process automation and improvements to tools and processing modes.

The analysis of the literature shows the prospects for developing a convergence technology for the finishing manufacturing of vehicle parts.

The implementation of intellectual and information technologies into the convergence system would provide the specified precision parameters for the surfaces' and edges' micro-accuracy and the microroughness of such parts' surfaces while preserving their structure and geometry. Thus, considering the global experience with part processing methods to achieve precision for parts and increase vehicle parts' service lives, there is a need for further research and the creation of a unified, integrated convergence technology.

4. CONVERGENCE TECHNOLOGY FOR VEHICLE PART SURFACE FINISHING

The concept of convergence technology for the batch surface finishing of vehicle parts includes several technological methods for their joint processing. The main problem involves picking up these methods rationally to ensure the specified quality parameters of the parts' edges and service lives. Based on the analysis of this issue, in Table 1, an expert assessment is presented with promising and popular methods for vehicle parts' surface finishing in terms of their technological capabilities.

The expert assessment was carried out according to a five-point system, which helped to determine the compatibility of the peculiarities of the considered technological processes and draw a conclusion about the simultaneous use of these processes to achieve the specified objective.

After the analysis of Table 1, the concept of convergence technology for surface finishing vehicle parts with high-precision surfaces, low surface roughness, and a specified microrelief is proposed based on the following processes:

1. Machining of the part with the required limit deviations and allowance for processing by surface finishing operations.

2. Impulse thermal energy method-based processing of external surfaces and cavities of parts to remove burrs, traces of processing, and microparticles, including inside channels and holes.
3. Honing and superfinishing, including electrochemical superfinishing, of fit surfaces and assembly bases.
4. Electrochemical processing of all parts' surfaces for achieving an accuracy of up to 0.001 mm and removing the micro- and nanoparticles that resulted from the previous stages of processing.

Table 1

Comparison of processing methods for use in convergent technology
(expert assessments are given based on a five-point system)

Technological capabilities	Impulse thermal energy method	Honing	Superfinishing	Electrochemical machining
Capable of machining nickel, chromium, and titanium-based alloys	3	4	4	5
Ability to process complex shapes	5	4	4	5
Ensuring the part surfaces quality	4	4	4	5
Processing of parts' features' geometries with micro- and nanometric precision	4	4	4	5
Precision machining of holes with small diameters and complex profiles (narrow and long ones 160/1230 μm, curved ones)	5	3	3	5
Improving the processing accuracy (up to 0.001 μm)	3	4	5	5
Possibility of batch processing	5	3	3	5
Possibility of the nanomaterials additional using	5	5	5	5
Possibility of automation	5	3	3	5
Economic efficiency	5	4	4	5
Ability to process large parts	3	4	4	5

Machining of parts with the required deviations and machining allowance is performed before impulse thermal energy method-based processing in accordance with the specified requirements. In some cases, the machining process can be simplified by taking into account the possibility of removing the burrs in holes by the impulse thermal energy method. For example, it is possible to exclude the operations of milling the edges formed by crossing the internal holes. Then, the machining process should be performed while taking into account the impulse thermal energy method's processing capabilities.

It should be noted that for workpieces with a surface roughness of about R_z 10...40, it is not sufficient to use only the impulse thermal energy method-based treatment to obtain the fit surfaces with low roughness; thus, honing and superfinishing are compulsory subsequent operations. Meanwhile, the processing of smoother surfaces by the impulse thermal energy method, especially after honing and superfinishing, worsens the surface roughness, which was experimentally confirmed by the authors of [23].

Electrochemical treatments of all surfaces of parts are carried out as a final operation, the purpose of which is to increase the smoothness of the parts' surfaces and remove micro- and nanoparticles by their chemical dissolution while achieving the accuracy of individual dimensions' deviations of up to 0.001 mm.

Taking into account the existing experience in electrochemical processing [24-29], the authors proposed the mode of electrochemical superfinishing and electrochemical honing shown in Fig. 1.

For processing the parts of shaft types, it is advisable to use electrochemical superfinishing; for parts with internal surfaces and holes, electrochemical honing should be used. These processes are based on the anodic dissolution of the workpiece surface. During processing, there is a rapid dissolution of the peaks on the surface with rough relief. In the valleys of parts, the dissolution is slow. The rougher side becomes smooth due to the unbalanced dissolution rate, resulting in an additional decrease in roughness. As a solution, it is recommended to use universal electrolytes that are used in electrochemical polishing: phosphoric acid, sulphuric acid, chromic anhydride, and water.

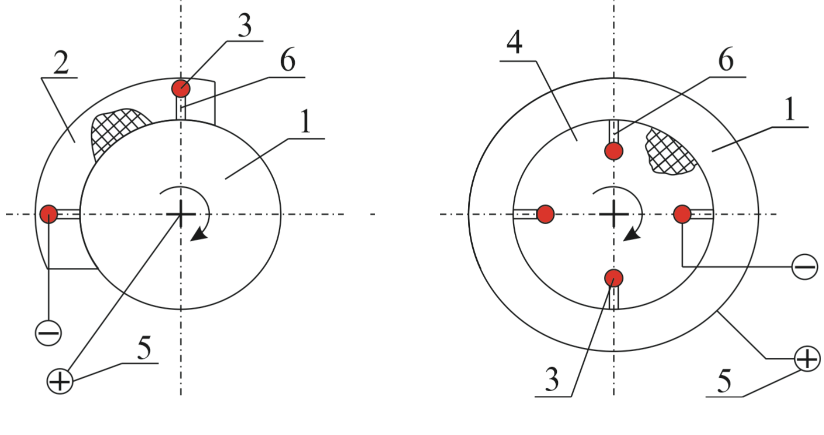

Fig. 1. Schematic diagram of electrochemical superfinishing (a) and electrochemical honing (b): 1 – part; 2 – holder with electrodes; 3 – cathodes; 4 – electrochemical honing tool; 5 – anodes; 6 – current focusing channels

Glycerine is also used when electrochemical superfinishing parts are made of stainless steel. Baths are administered at temperatures up to 90 °C, the anode current density is as high as 80 A/dm^2, and the voltage is as high as 8 V. These solution components do not yield the best performance, but they are relatively safe. Productivity, in this case, may be neglected since the processing allowance is within the height of microroughnesses and the processing time is several minutes.

Compared with the superfinishing process, the electrochemical superfinishing process (Fig. 2) is based on a focused high-density current of a direct or pulsed power source type, which moves relative to the part's surface.

The current flow is concentrated (focused) while moving over microroughnesses and, by its action, dissolves the peaks' tops. The product immersed in the electrolyte is coated with an oxide film, which is a protective medium applied between the metal and the electrolyte. During the process, it constantly dissolves and re-forms. Metal is processed immediately under the film. It is carried out due to the exchange of electrons and ions between the anode and electrolyte. The thickness of the formed film is always smaller at the peaks of the surface roughness. The process of metal dissolution starts from the peaks. In the valleys of the surface roughness, the film layer is thicker, and the exchange processes of charged particles are slower. The rate of surface polishing can be influenced by changing the temperature, current magnitude, and electrolyte mixing.

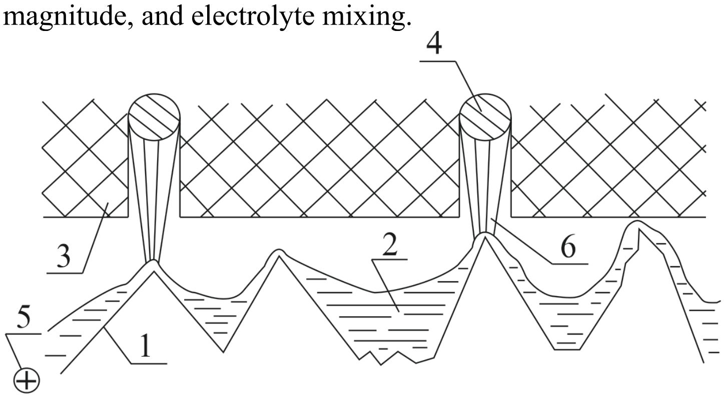

Fig. 2. Scheme of the concentration (focusing) of the current flow during electrochemical superfinishing: 1 – profile of the part roughness; 2 – top contour of the oxide film; 3 – superfinishing tool holder; 4 – cathode; 5 – anode (processed part); 6 – focused current flow

A distinctive feature of the proposed scheme for the concentration (focusing) of the current flow during electrochemical superfinishing is the movement of the electrode with respect to the part surface, which allows the following:

- an increase in the current density by reducing the width of the cathode gap;
- the use of a direct current power source instead of a pulsed one, which results in a surface polishing effect;
- the removal of oxidation products while keeping the parts' surfaces clean;
- the intensive mixing of the solution electrolytes and the formation of an oxide film with a consistent size.

Further improvements to the presented convergence technology for vehicle part surface finishing can be achieved by researching technologies for applying nanomaterials that provide the specified physical and chemical properties of parts' surfaces. The coating of the substrate surfaces with nanomaterials by 3D printing is a promising derivation of the proposed surface finishing convergence technology.

5. CONCLUSIONS

1. A comparative analysis of the existing methods for surface finishing parts manufactured for vehicles revealed these methods' advantages and disadvantages. The main factors to consider while choosing a method are (i) the specified characteristics of vehicle parts, (ii) the possibility of the batch processing of parts with burrs in mass production in order to reduce these parts' production times and technological expenses, and (iii) the compatibility or combination of methods to ensure the specified characteristics of surfaces. The prospects for further research on methods with the aim of creating a complex technology (i.e., convergence) that merges various technologies (e.g., information, thermochemical, electrochemical, mechanical processing, and nanotechnologies).
2. The analysis of prospective surface finishing methods allowing the batch processing of vehicle parts indicates the relevance of using the impulse thermal energy method-based processing, honing, superfinishing, and electrochemical processing for all surfaces of vehicle parts. It has been revealed that creating a convergence technology based on these methods provides the specified precision parameters of the micro-accuracy and microroughness of vehicle parts' surfaces and edges while preserving their structure and geometry and extending the product's service life.
3. A method was proposed for selecting and combining surface finishing processes according to a five-point expert assessment that allows batch processing for vehicle parts. The concept of convergence technology based on this method for the surface finishing of vehicle parts was proposed. The convergence technology consists of impulse thermal energy method-based processing, honing, superfinishing, and electrochemical processing. An expanded technological process is presented for manufacturing (by electrochemical superfinishing and electrochemical honing) parts with high-precision, high-level roughness surfaces of a specified microrelief. A scheme of concentration (focusing) of the current flow during electrochemical superfinishing based on the movement of the electrode relative to parts' surfaces is proposed that increases the current density by reducing the width of the cathode gap, which results in surface polishing and the removal of oxidation products. A distinctive feature of the proposed convergence technology is the possibility of the batch processing of parts in mass production.

References

1. Gupta, K. & Gupta, M.K. Developments in nonconventional machining for sustainable production: A state-of-the-art review. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*. 2019. Vol. 233. No. 12. P. 4213-4232. DOI: 10.1177/0954406218811982.

2. Khorasani, A.M. & Yazdi, M.R.S. & Safizadeh, M.S. Analysis of machining parameters effects on surface roughness: a review. *International Journal of Computational Materials Science and Surface Engineering*. 2012. Vol. 5. No. 1. P. 68-84.
3. Gillespie, L.K. *Deburring and Edge Finishing Handbook*. Dearborn: Society of Manufacturing Engineers. 1999. 404 p.
4. Unune, D.R. & Mali, H.S. Current status and applications of hybrid micro-machining processes: a review. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*. 2015. Vol. 229. No. 10. P. 1681-1693. DOI: 10.1177/0954405414546141.
5. Yuan, J. & Lyu, B. & Hang, W. & Deng, Q. Review on the progress of ultra-precision machining technologies. *Frontiers of Mechanical Engineering*. 2017. Vol. 12. No. 2. P. 158-180. DOI: 10.1007/s11465-017-0455-9.
6. *XEBEC Deburring Technologies: Innovative Deburring & Surface Finishing Solutions*. XEBEC. 2019. Available at: https://deburringtechnologies.com/literature/XEB-CAT19-digital.pdf.
7. Rodríguez, A. & González, M. & Pereira, O. & et al. Edge finishing of large turbine casings using defined multi-edge and abrasive tools in automated cells. *The International Journal of Advanced Manufacturing Technology*. 2021. P. 1-11. DOI: 10.1007/s00170-021-08087-y.
8. Matuszak, J. Comparative analysis of the effect of machining with wire and ceramic brushes on selected properties of the surface layer of EN AW-7075 aluminium alloy. *Advances in Science and Technology. Research Journal*. 2022. Vol. 16. No. 2. P. 50-56. DOI: 10.12913/22998624/146211.
9. Maiorova, K. & Vorobiov, I. & Andreev, O. & et al. Forming the geometric accuracy and roughness of holes when drilling aircraft structures made from polymeric composite materials. *Eastern-European Journal of Enterprise Technologies*. 2022. No. 2(116). P. 71-80. DOI: https://doi.org/10.15587/1729-4061.2022.254555.
10. Devin, L.N. & Grechuk, A.I. & Lupkin, B.V. Drilling of composites using tools of polycrystalline superhard materials. *Journal of Superhard Materials*. 2018. Vol. 40. No. 1. P. 58-64. DOI: 10.3103/S1063457618010094.
11. Bhattacharyya, B. & Doloi, B. Advanced finishing processes. In: *Modern Machining Technology*. London: Academic Press, 2020. P. 675-743. DOI: 10.1016/B978-0-12-812894-7.00008-6.
12. Niknam, S.A. & Davoodi, B. & Davim, J.P. & Songmene, V. Mechanical deburring and edge-finishing processes for aluminum parts – a review. *The International Journal of Advanced Manufacturing Technology*. 2018. Vol. 95. No. 1. P. 1101-1125. DOI: 10.1007/s00170-017-1288-8.
13. Kritskiy, D. & Pohudina, O. & Kovalevskyi, M. & Tsegelnyk, Y. & Kombarov, V. Powder mixtures analysis for laser cladding using OpenCV library. In: Nechyporuk, M. & Pavlikov, V. & Kritskiy, D. (eds.). *Integrated Computer Technologies in Mechanical Engineering - 2022. Lecture Notes in Networks and Systems*. 2022. Vol. 367. P. 924-937. DOI: 10.1007/978-3-030-94259-5_72. Cham: Springer.
14. Jin, S.Y. & Pramanik, A. & Basak, A.K. & et al. Burr formation and its treatments – a review. *The International Journal of Advanced Manufacturing Technology*. 2020. Vol. 107. No. 5. P. 2189-2210. DOI: 10.1007/s00170-020-05203-2.
15. Bańkowski, D. & Krajcarz, D. & Młynarczyk, P. Deburring and smoothing the edges using vibro-abrasive machining. *Procedia Engineering*. 2017. Vol. 192. P. 28-33. DOI: 10.1016/j.proeng.2017.06.005
16. Levchenko, I. & Xu, S. & Cherkun, O. & Baranov, O. & Bazaka, K. Plasma meets metamatertials: three ways to advance space micropropulsion systems. *Advances in Physics.* 2021. Vol. 6. No. 1. Available at: https://www.tandfonline.com/doi/full/10.1080/23746149.2020.1834452.
17. Plankovskyy, S. & Breus, V. & Voronko, V. & et al. Review of methods for obtaining hardening coatings. In: Nechyporuk, M. & Pavlikov, V. & Kritskiy, D. (eds.). *Integrated Computer Technologies in Mechanical Engineering - 2020. Lecture Notes in Networks and Systems*. 2021. Vol. 188. P. 332-343. Cham: Springer. DOI: 10.1007/978-3-030-66717-7_28.
18. Kumar, M. & Bajpai, V. Experimental investigation of top burr formation in high-speed micro-milling of Ti6Al4V alloy. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal*

of Engineering Manufacture. 2020. Vol. 234. No. 4. P. 730-738. DOI: 10.1177/0954405419883049.
19. Castillo, V.R. & Sánchez-González, L. & Fernández-Robles, L. & Castejón-Limas, M. Burr detection using image processing in milling workpieces. In: Herrero, Á. & Cambra, C. & Urda, D., & et al. (eds.). *15th International Conference on Soft Computing Models in Industrial and Environmental Applications (SOCO 2020)*. *Advances in Intelligent Systems and Computing*. 2021. Vol. 1268. P. 751-759. Cham: Springer. DOI: 10.1007/978-3-030-57802-2_72.
20. Abele, E. & Schützer, K. & Güth, S. & Meinhard, A. Deburring of cross-drilled holes with ball-end cutters – modeling the tool path. *Production Engineering*. 2018. Vol. 12. No. 1. P. 25-33. DOI: 10.1007/s11740-017-0781-0.
21. Plankovskyy, S. & Popov, V. & Shypul, O. & et al. Advanced thermal energy method for finishing precision parts. In: Gupta, K. & Pramanik, A. (eds.). *Advanced Machining and Finishing*. 2021. P. 527-575. Amsterdam: Elsevier. DOI: 10.1016/B978-0-12-817452-4.00014-2.
22. Karlina, Y.I. & Kargapoltsev, S.K. & Gozbenko, V.E. & et al. Overview of electro physicochemical methods for deburring small-sized high-precision details of coaxial radio components. *Journal of Physics: Conference Series*. 2020. Vol. 1582. No. 1. P. 1-7. DOI: 10.1088/1742-6596/1582/1/012041.
23. Losev, A. & Bychkov, I. & Selezneva, A. & Shendryk, V. & Shendryk, S. Cleaning of Parts with Detonating Gas Mixtures. In: Tonkonogyi, V. & Ivanov, V. & Trojanowska, J. & Oborskyi, G. & Pavlenko, I. (eds). *Advanced Manufacturing Processes III. Lecture Notes in Mechanical Engineering*. 2022. P. 602-612. Cham: Springer. DOI: https://doi.org/10.1007/978-3-030-91327-4_58.
24. Ruszaj, A. & Gawlik, J. & Skoczypiec, S. Electrochemical machining – special equipment and applications in aircraft industry. *Management and Production Engineering Review*. 2016. Vol. 7. No. 2. P. 34-41. DOI: 10.1515/mper-2016-0015.
25. Misra, J.P. & Jain, P.K. & Dwivedi, D.K. Electrochemical honing – a novel technique for gear finishing. In: Katalinic, B. (ed.). *DAAAM International Scientific Book*. 2011. P. 365-383. Vienna: DAAAM International. DOI: 10.2507/daaam.scibook.2011.29.
26. Voronko, V. & Tkachenko, I. & Dyachenko, Y. & et al. Methodology for calculating the productivity of electrochemical machining in stationary electrolyte. In: Nechyporuk, M. & Pavlikov, V. & Kritskiy, D. (eds.). Integrated Computer Technologies in Mechanical Engineering - 2021. *Lecture Notes in Networks and Systems*. 2022. Vol. 367. P. 47-56. Cham: Springer. DOI: 10.1007/978-3-030-94259-5_5.
27. Zhang, Y. & Xu, Z. & Xing, J. & Zhu, D. Effect of tube-electrode inner diameter on electrochemical discharge machining of nickel-based superalloy. *Chinese Journal of Aeronautics*. 2016. Vol. 29. No. 4. P. 1103-1110. DOI: 10.1016/j.cja.2015.12.016.
28. Kar, S. & Patowari, P.K. Electrode wear phenomenon and its compensation in micro electrical discharge milling: a review. *Materials and Manufacturing Processes*. 2018. Vol. 33. No. 14. P. 1491-1517. DOI: 10.1080/10426914.2018.1453144.
29. Choi, S.H. & Kong, K.J. & Cho, Y.T. Development of superfinishing machine to polish the inner surfaces of aircraft hydraulic oil reservoirs. *Journal of the Korean Society of Manufacturing Process Engineers*. 2020. Vol. 19. No. 8. P. 110-116. DOI: 10.14775/ksmpe.2020.19.08.110.

Received 13.07.2021; accepted in revised form 29.02.2023