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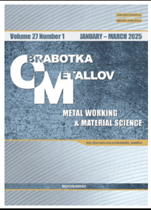

Development of a device for studying and simulating the electrochemical grinding process

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ABSTRACT

Introduction. When manufacturing critical parts from high-strength and difficult-to-process steels in various industries, the final quality is usually formed during finishing operations. The efficiency of the process is significantly higher when using combined, hybrid methods of influencing the surface being processed. When processing some complex-shaped parts, more attention in finishing operations is usually paid to reducing roughness while maintaining previously achieved dimensional accuracy indicators. For this purpose, abrasive tools on a rigid base are often used, placing it in a less rigid technological system. To increase the efficiency of the process, it is necessary to establish optimal modes of mechanical and electrochemical processing of parts. In the absence of the possibility of using industrial equipment for hybrid technologies at the initial stage, taking into account the need to modernize existing technological equipment for the implementation of the electrochemical grinding process, it is advisable to study this process by simulating it on simulator devices. **The purpose of the work** is to develop a device for studying and simulating the process of electrochemical grinding of conductive parts with abrasive heads on a metal bond. **Research methodology.** To simulate the process of electrochemical grinding of conductive parts using abrasive heads on a metal bond, we have developed a special device. It allows for the basing of the workpiece and the tool, implementation the electrochemical grinding process, its kinematic and electrical conditions: main motion, linear displacement of working bodies, mechanical and electrical modes, ensuring the necessary conditions for the implementation of the technology, and implementing a control system. **Results and discussion**. To determine the influence of mechanical cutting modes on the roughness of the machined surface of a part made of corrosion-resistant steel *0.12 C-18Cr-10 Ni-Ti*, empirical studies were carried out on the designed device. Planning and processing of experimental results were carried out using standard methodology for preparing and conducting a full factorial experiment. The resulting model makes it possible to determine rational mechanical cutting conditions and evaluate its influence on the quality of the surface being processed.

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Introduction

When manufacturing critical parts from high-strength and hard-to-machine steels in various industries, the final quality is typically achieved during finishing operations. These parts often operate under specific operating conditions. Consequently, they are made of hard-to-machine, corrosion-resistant, and heat-resistant steels and alloys based on titanium and nickel. If there is a requirement to minimize the mass of products, many parts are thin-walled and have a complex profile.

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At the final stage of the technological process of machining, it is necessary to minimize the force and heat generation in the contact zone between the workpiece and the abrasive tool in order to achieve the required quality of the processed surfaces.

Such requirements impose restrictions on the choice of finishing methods and conditions. Process efficiency is significantly increased when using combined, or hybrid, methods to affect the surface being processed [1-19].

When machining complex shaped parts, increased attention is given to finishing operations, particularly to reducing roughness while maintaining previously achieved dimensional accuracy indicators. For this purpose, rigid-base abrasive tools (abrasive heads on a metal bond) are often used and integrated into a less rigid technological system are often used, and integrated into a less rigid technological system.

The tool can be edited electrochemically, continuously with the use of an additional electrical circuit or intermittently without its use. Feed alternating with a certain interval of reverse polarity current pulses is made directly to the operating circuit. To increase the efficiency of the process, it is necessary to establish optimal modes of mechanical and electrochemical processing of parts [20-27]. If there is no possibility to use industrial equipment for hybrid technologies at the initial stage, and considering the need to modernize existing technological equipment for performing the electrochemical grinding process, it is advisable to study this process by modelling it on simulators [28-31].

The aim of the work is to develop a device to study and simulate the process of electrochemical grinding of conductive parts with abrasive heads on a metal bond.

To achieve this goal, the following tasks were formulated:

1) to identify, based on modeling, the operating parameters of the system under study and the applicability of the device for studying the roughness of processed parts in the process of electrochemical grinding with abrasive heads on a metal bond.

2) to conduct empirical studies of the roughness of the processed surfaces depending on the modes of electrochemical grinding.

3) to substantiate the possibility of using the developed device to study the process of electrochemical grinding of conductive parts with abrasive heads on a metal bond.

Methods

To simulate the process of electrochemical grinding of conductive parts with abrasive heads on a metal bond, a special device was developed. The block diagram of this device is shown in Fig. 1.

The proposed device allows positioning the workpiece and tool, implement the process of electrochemical grinding, its kinematic and electrical conditions: the primary motion, linear motion of working elements, mechanical and electrical modes, provide the necessary conditions for the implementation of the technology (electrolyte and its supply to the processing zone), and implement a control system.

To determine the model of the engraver that gives the rotary motion of the abrasive head and the drive for linear motion of the abrasive head, the cutting forces and cutting power were calculated. The abrasive grinding modes were selected in accordance with the modes used in the study of hybrid technology for electrochemical processing of *0.12C-18Cr-10Ni-Ti* stainless steel with a diamond cylindrical head with a working part diameter of 3 mm and a shank diameter of 2 mm. Cutting speed ranged from 4.7 m/s to 6.05 m/s, cutting depth from 0.04 mm to 0.06 mm, longitudinal feed rate from 230 mm/min to 250 mm/min [32]. As a result, the maximum cutting power values of 0.128 kW were obtained. Tool deformation calculations were performed additionally using the *ANSYS* software. The model with boundary conditions for the study is shown in Fig. 2.

Table 1 shows the calculation examples. The tool deformation ranged from 0.14 to 0.23 mm.

Fig. 3 shows a general view of the linear drive of the working body. It serves to provide a longitudinal feed of the tool and consists of a *DC* motor, a screw-nut transmission, and a slider.

Table 2 shows the technical characteristics of the linear drive.

The *Zubr ZG-160EK* engraver is used to give the main cutting motion to the abrasive head.

Technical characteristics of the engraver *Zubr ZG-160EK* are given in Table 3.

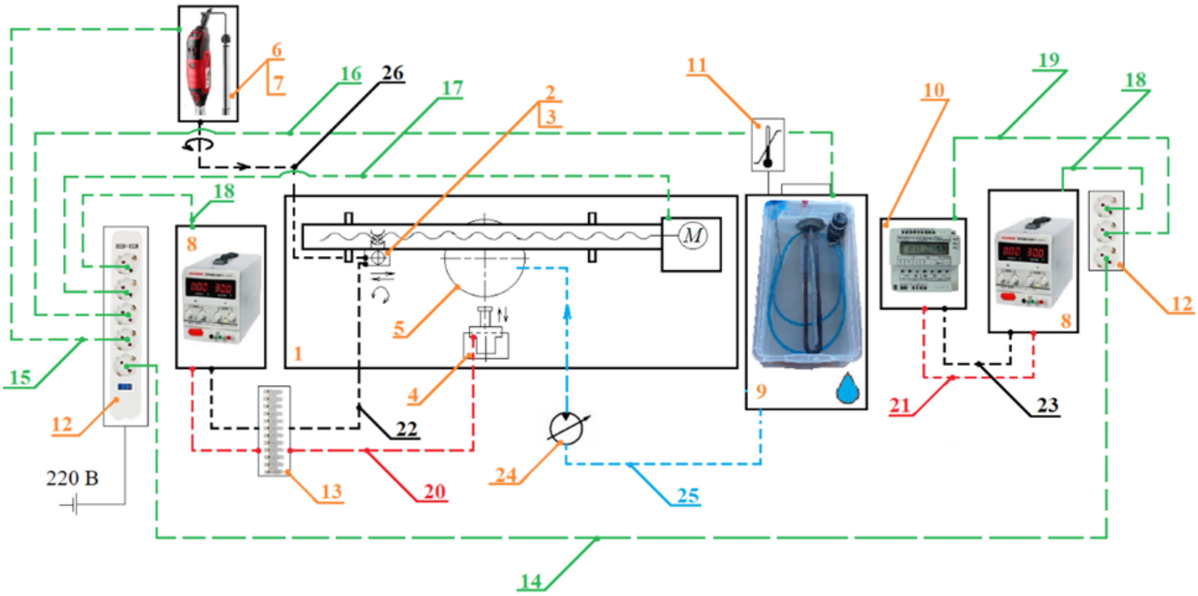


Fig. 1. Structural diagram of the device for simulating the electrochemical grinding process:

1 – device housing; 2 – collet mechanism of the engraver; 3 – abrasive head; 4 – part holding device; 5 – container for electrolyte; 6 – engraver; 7 – engraver stand; 8 – *DC* source; 9 – container for electrolyte; 10 – time relay; 11 – thermometer, 12 – surge protector; 13 – terminal block; 14 – filter electrical network; 15 – engraver electrical network; 16 – electric heater electrical network; 17 – linear motion drive motor electrical network; 18 – *DC* source electrical network; 19 – time relay electrical network; 20 – electrical network for supplying current to the part; 21 – *DC* source electrical network for a time relay; 22 – electrical network for supplying current to the abrasive head; 23 – electrical network for connecting a *DC* source to a time relay; 24 – electric pump; 25 – electrolyte supply line; 26 – flexible engraver shaft

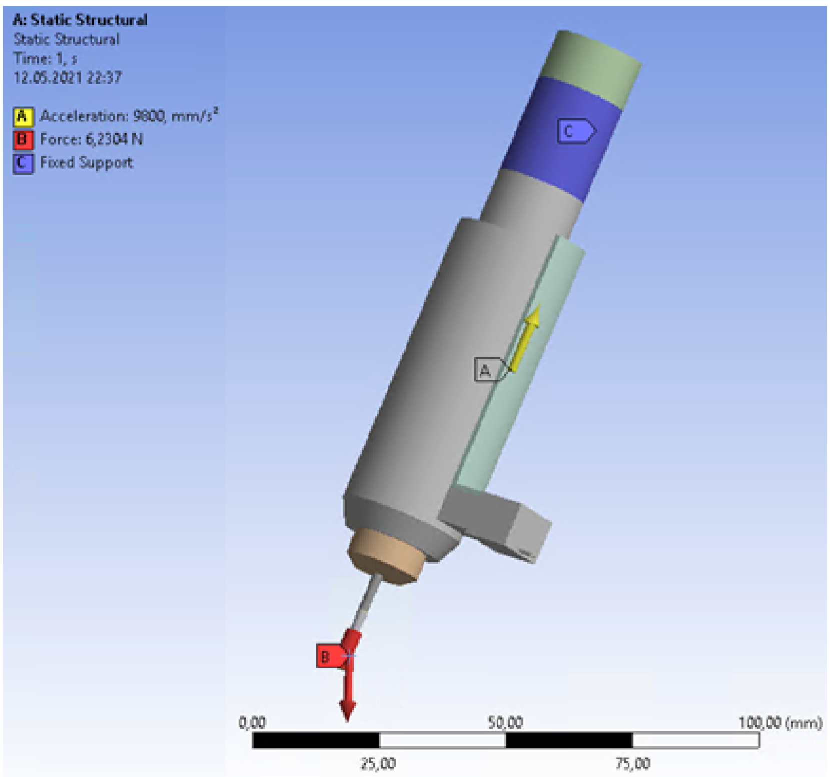
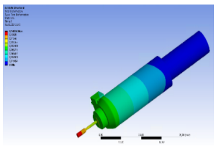
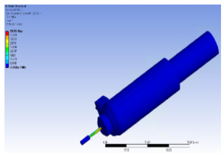
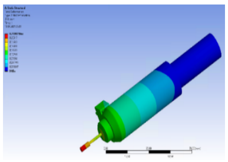
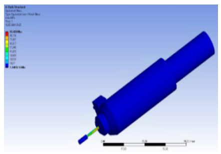


Fig. 2. Tool deformation model with boundary conditions for analysis

Table 1

Tool deformation calculation results

Cutting modes		Tool deformation, mm		Shear stress, MPa
$\boldsymbol{V}$ = 4.7 m s^{-1}, $\boldsymbol{t}$ = 0.04 mm, $\boldsymbol{S}$ = 230 mm/min		0.148		59.551
$\boldsymbol{V}$ = 6.05 m s^{-1}, $\boldsymbol{t}$ = 0.06 mm, $\boldsymbol{S}$ = 250 mm/min		0.230		92.426

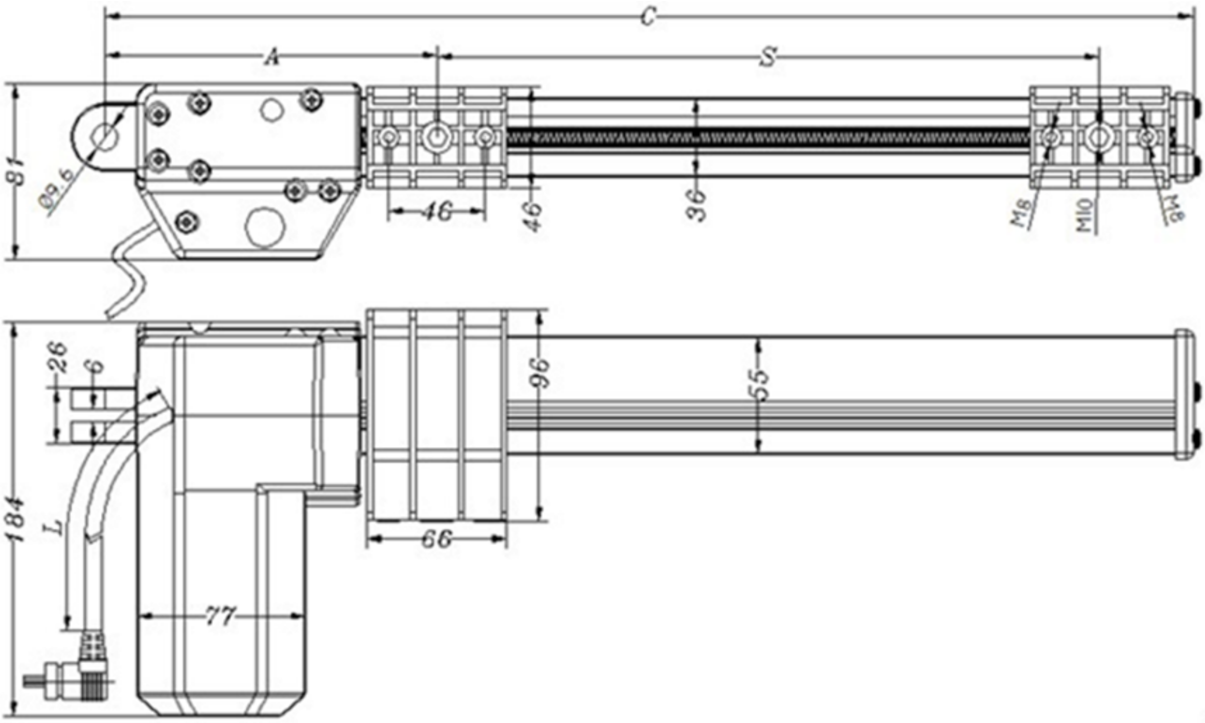


Fig. 3. Linear drive: $\boldsymbol{C}$ = 700 mm, $\boldsymbol{A}$ = 160 mm, $\boldsymbol{S}$ = 500 mm

Table 2

Linear drive specifications

Name	Meaning
Input voltage, V	12
Load capacity, N	1,500
Minimum slider travel speed, mm s^{-1}	4
Maximum slider travel speed, mm s^{-1}	36
Stroke motion, mm	500

Table 3

Engraver Specifications

Name	Meaning
Supply voltage, V	220
Frequency, Hz	50
Power consumption, W	160
Rotation speed, rpm	15,000-35,000
Collet diameter, mm	2.4; 3.2
Weight, kg	2.1

For mounting the abrasive head, a collet chuck, modified for combined processing, is used. Special equipment is used to mount the processed sample; this equipment allows for cross-feed of the sample. The working area of the installation is shown in Fig. 4.

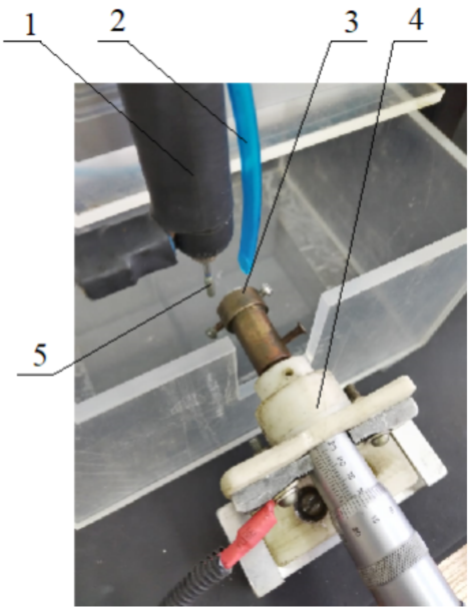


Fig. 4. External view of the working area of the installation: 1 – upgraded collet chuck; 2 – electrolyte feed tube; 3 – sample being processed; 4 – sample basing and feed equipment; 5 – abrasive head

The cartridge is isolated from the engraver and mounted on the slider of the feed motion drive. A flexible shaft transmits the primary motion from the engraver to the chuck. Specially designed tooling, isolated from the main body of the device, is used to position the processed experimental sample and enable transverse feed (cutting depth t). The device used to study and simulate the electrochemical grinding process is shown in Fig. 5.

Results and Discussion

Empirical studies were conducted using the designed device to determine the effect of mechanical cutting modes on the surface roughness of a part sample made of corrosion-resistant *0.12C-18Cr-10Ni-Ti* steel. Electrical modes and experimental conditions for studying the electrochemical grinding process were selected based on prior experiments [32]. These included a voltage of 12 V at the process current source, a n etching current density of 1.5 A/cm², and a water-based electrolyte ($NaNO_3$ – 3 %, $NaNO_2$ – 1 %, Na_2CO_3 – 0.5 %).

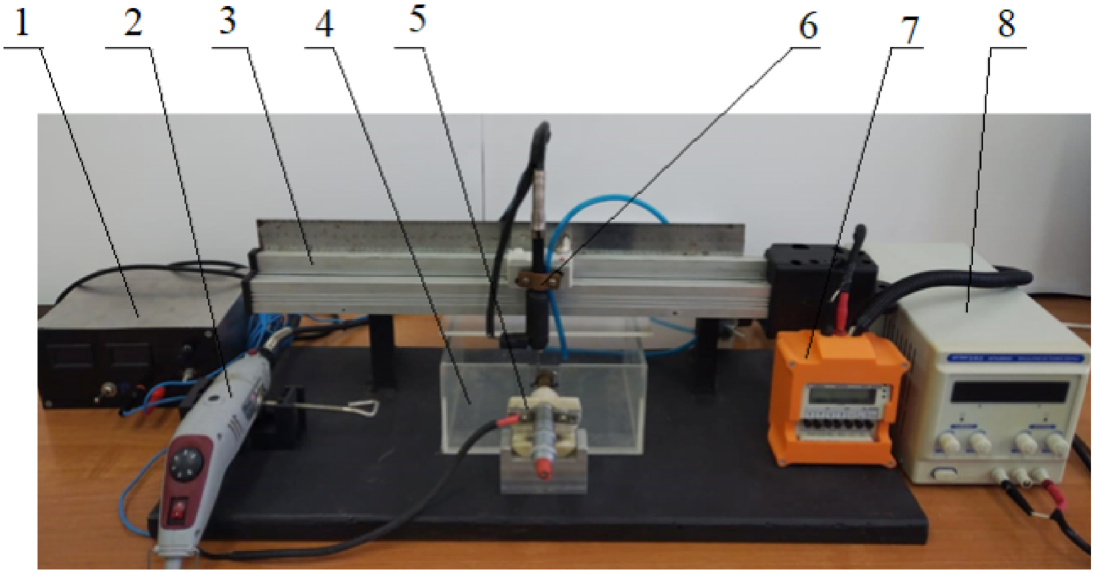


Fig. 5. External view of the device for studying and simulating the electrochemical grinding process:
1 – current source for electrochemical process; 2 – engraver; 3 – linear drive; 4 – electrolyte container; 5 – sample basing and feeding equipment; 6 – upgraded collet chuck; 7 – time relay; 8 – current source for linear drive electric motor

The planning and processing of experimental results were performed using the standard methodology for preparing and conducting a full factorial experiment. The initial data for planning and processing experimental results are presented in Table 4.

Table 4

Initial data for planning and processing experimental results

Factors	Levels			Variation interval
	Upper $X_i = +1$	Primary (Zero) $X_i = 0$	Lower $X_i = -1$	
X_1 – cutting depth, t (mm)	0.06	0.05	0.04	0.01
X_2 – feed rate, S (mm/min)	250	240	230	10
X_3 – cutting speed, V (m/s)	6	5	4	1

The regression equation obtained from the analysis of experimental data reflects the dependence of surface roughness on mechanical processing modes and is expressed as follows:

$$\mathbf{Ra} = -2.67 + 106.17t - 0.43tS - 19{,}55tV + 0.013S - 0.004SV + 0.94V + 0.08tSV.$$

The resulting model enables the determination of optimal mechanical cutting conditions and the assessment of their impact on the quality of the machined surface. Specific cases of the system response surfaces with constant cutting parameters at the zero level of variation are shown in Figs. 6–8.

The obtained model and response surfaces enable the prediction of surface roughness variation depending on grinding modes and represent an empirical model of the system under consideration.

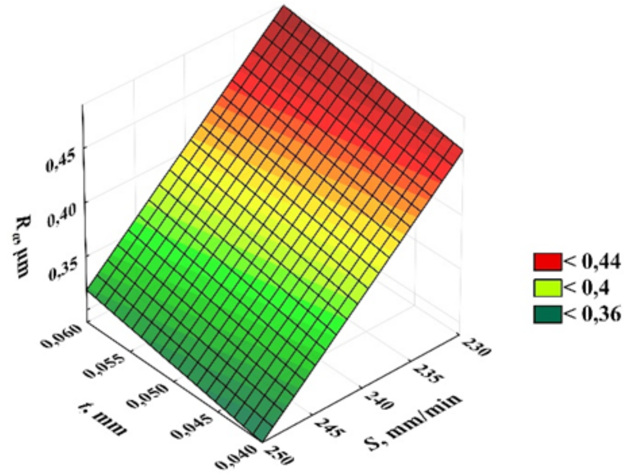


Fig. 6. Graphs of the influence of feed rate and depth of cut on the surface roughness ***Ra*** of the machined *0.12C-18Cr-10Ni-Ti* steel at ***V*** = 5 m/sec

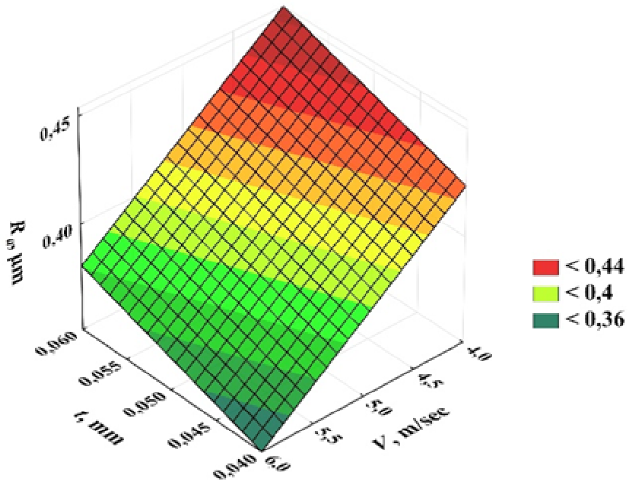


Fig. 7. Graphs of the influence of cutting speed and depth of cut on the surface roughness ***Ra*** of the machined *0.12C-18Cr-10Ni-Ti* steel at ***S*** = 240 mm/min

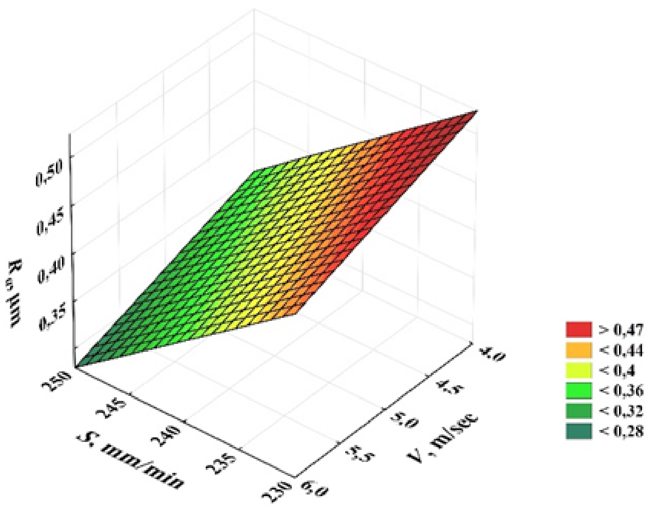


Fig. 8. Graphs of the influence of cutting speed and feed rate on the surface roughness ***Ra*** of the machined *0.12C-18Cr-10Ni-Ti* steel at ***t*** = 0.05 mm

Conclusions

1. Calculations have established that when modeling the machining of *0.12C-18Cr-10Ni-Ti* stainless steel parts with a diameter of 10 mm using a diamond cylindrical head with a 3 mm working diameter, the maximum cutting power reached 0.128 kW, and the maximum tool deformation was 0.23 mm, with

the cutting speed varying from 4.7 m/s to 6.05 m/s, the cutting depth from 0.04 mm to 0.06 mm, and the longitudinal feed rate from 230 mm/min to 250 mm/min. Therefore, the developed device is suitable for investigating the relationship between the quality indicators of the machined surface and the cutting modes. To further investigate machining accuracy, the system rigidity should be increased.

2. Studies of the electrochemical grinding process of *0.12C-18Cr-10Ni-Ti* stainless steel parts with a diameter of 10 mm, conducted using the developed device with a diamond cylindrical head with a 3 mm working diameter under the specified cutting parameters, have enabled the construction of an empirical model that predicts surface roughness variation as a function of electrochemical grinding modes.

3. Theoretical calculations and practical experiments have confirmed that the developed device is applicable for studying and modeling the electrochemical grinding of conductive parts using abrasive heads on a metallic bond.

References

1. Borisov M.A., Lobanov D.V., Yanyushkin A.S., Skeeba V.Yu. Investigation of the process of automatic control of current polarity reversal in the conditions of hybrid technology of electrochemical processing of corrosion-resistant steels. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2020, vol. 22, no. 1, pp. 6–15. DOI: 10.17212/1994-6309-2020-22.1-6-15. (In Russian).

2. Lobanov D.V., Arkhipov P.V., Yanyushkin A.S., Skeeba V.Yu. The research into the effect of conditions of combined electric powered diamond processing on cutting power. *Key Engineering Materials*, 2017, vol. 736, pp. 81–85. DOI: 10.4028/www.scientific.net/KEM.736.81.

3. Bratan S.M., Kharchenko A.O., Vladetskaya E.A., Kharchenko A.A. Analysis and synthesis of vibration isolation system of a grinding machine with account of the operational reliability of its elements. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2019, vol. 21, no. 1, pp. 35–49. DOI: 10.17212/1994-6309-2019-21.1-35-49. (In Russian).

4. Kharchenko A., Chasovitina A., Bratan S. Modeling of regularities of change in profile sizes and wear areas of abrasive wheel grains during grinding. *Materials Today: Proceedings*, 2021, vol. 38 (4), pp. 2088–2091. DOI: 10.1016/j.matpr.2020.10.154.

5. Nosenko S.V., Nosenko V.A., Kremenetskii L.L. The condition of machined surface of titanium alloy in dry grinding. *International Conference on Industrial Engineering, ICIE 2017*, Saint-Petersburg, 16–19 May 2017, pp. 115–120. DOI: 10.1016/j.proeng.2017.10.446.

6. Gusev V.V., Roshchupkin S.I., Moiseev D.A., Melnikova E.P. Analysis of grinding process with the use of field theory. *IOP Conference Series: Materials Science and Engineering*, 2019, vol. 709 (2), p. 022001. DOI: 10.1088/1757-899X/709/2/022001.

7. Rechenko D.S. The study of the process of difficult-to-machine materials cutting at the micro-level. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2019, vol. 21, no. 2, pp. 18–25. DOI: 10.17212/1994-6309-2019-21.2-18-25. (In Russian).

8. Rechenko D.S., Popov A.Y., Titov Y.V., Balova D.G., Gritsenko B.P. Ultra-high-speed sharpening and hardening the coating of carbide metal-cutting tools for finishing aircraft parts made of titanium alloys. *Journal of Physics: Conference Series*, 2019, vol. 1260 (6), p. 062020. DOI: 10.1088/1742-6596/1260/6/062020.

9. Kozlov A.M., Kozlov A.A. Shaping the surface topology of cylindrical components by means of an abrasive tool. *Russian Engineering Research*, 2009, vol. 29 (7), pp. 743–746. DOI: 10.3103/S1068798X09070223.

10. Soler Ya.I., Kazimirov Yu.D. Predicting the supporting area of microrelief in machine parts of variable rigidity during plane grinding. *Journal of Machinery Manufacture and Reliability*, 2006, vol. 35 (3), pp. 260–265.

11. Niu L., Jin Z., Zhou Z., Dong Z., Zhu X. Study on electrochemical effect in electrochemical grinding of tungsten alloy. *ISAAT 2018 – 21st International Symposium on Advances in Abrasive Technology*, Toronto, 14–16 October 2018.

12. Bratan S.M., Sidorov D.E., Bogutskii V.B. [Synthesis of a Kalman-Bussy filter for assessing the state of a grinding operation]. *Sovremennye napravleniya i perspektivy razvitiya tekhnologii obrabotki i oborudovaniya v mashinostroenii* [Modern directions and prospects for the development of processing technologies and equipment in mechanical engineering]. Materials of the International Scientific and technical conference, Sevastopol, September 14–15, 2015, pp. 87–91. (In Russian).

13. Nosenko V.A., Belukhin R.A., Fetisov A.V., Morozova L.K. Ispytatel'nyi kompleks na baze pretsizionnogo profileshlifoval'nogo stanka s ChPU CHEVALIER modeli smart-B1224 III [Test complex based on a precision

CNC profile grinding machine CHEVALIER model smart-B1224 III]. *Izvestiya Volgogradskogo gosudarstvennogo tekhnicheskogo universiteta = Izvestia of Volgograd State Technical University*, 2016, no. 5 (184), pp. 35–39.

14. Gusev V.V., Moiseev D.A. Otsenka parametrov rabochei poverkhnosti almaznogo shlifoval'nogo kruga [Estimation of parameters of the working surface of a diamond grinding wheel]. *Progressivnye tekhnologii i sistemy mashinostroeniya = Progressive Technologies and Systems of Mechanical Engineering*, 2017, no. 4 (59), pp. 11–17.

15. Makarov V.F., Nikitin S.P. Povyshenie effektivnosti profil'nogo glubinnogo shlifovaniya lopatok turbin na mnogokoordinatnykh stankakh s ChPU [Increasing the efficiency of profile deep-depth grinding of turbine blades on multi-axis CNC machines]. *Naukoemkie tekhnologii v mashinostroenii = Science Intensive Technologies in Mechanical Engineering*, 2018, no. 4 (82), pp. 21–29.

16. Makarov V.F., Zhukotsky V.A., Bychina E.N. Problemy avtomatizatsii finishnoi obrabotki slozhnoprofil'nykh poverkhnostei lopatok GTD [Problems of automation of finishing processing of difficult profile surfaces of blades GTE]. *Izvestiya Tul'skogo gosudarstvennogo universiteta. Tekhnicheskie nauki = News of Tula State University. Technical Sciences*, 2016, no. 8-2, pp. 52–55.

17. Yanyushkin A.S., Popov V.Yu., Sur'ev A.A., Yanpol'skii V.V. *Prisposoblenie dlya izmereniya malykh sil pri elektroalmaznom shlifovanii* [Device for measuring small forces during electric diamond grinding]. Patent RF, no. 2215641 C2, 2003.

18. Yanyushkin A.S., Popov V.Yu., Sur'ev A.A., Yanpol'skii V.V. *Tenzometricheskaya vstavka dlya izmereniya malykh sil pri elektroalmaznom shlifovanii* [Strain gauge insert for measuring small forces during electric diamond grinding]. Patent RF, no. 2210749 C2, 2003.

19. Nosenko V.A., Nosenko S.V. *Tekhnologiya shlifovaniya metallov* [Metal grinding technology]. 4th ed. Staryi Oskol, Tonkie naukoemkie tekhnologii Publ., 2022. 616 p.

20. Lobanov D., Borisov M., Yanyushkin A., Skeeba V. Influence of the duration of current pulses on the roughness in the combined processing of corrosion steel 12H18N10T. *Key Engineering Materials*, 2022, vol. 910, pp. 397–402. DOI: 10.4028/p-gu270a.

21. Zaborski S., Łupak M., Poroś D. Wear of cathode in abrasive electrochemical grinding of hardly machined materials. *Journal of Materials Processing Technology*, 2004, vol. 149 (1–3), pp. 414–418. DOI: 10.1016/j.jmatprotec.2004.02.015.

22. Mogilnikov V.A., Chmir M.Y., Timofeev Y.S., Poluyanov V.S. Diamond – ECM grinding of ceramic-metal tungsten. *Proceedings of the Seventeenth CIRP Conference on Electro Physical and Chemical Machining (ISEM)*, Leuven, 08–12 April 2013, pp. 407–409. DOI: 10.1016/j.procir.2013.03.104.

23. Gusev V.V., Poltavets V.V., Molchanov A.D. [Technological support for processing hard-to-cut materials by diamond grinding by controlling the cutting ability of wheels]. *Innovatsionnye perspektivy Donbassa* [Innovative prospects of Donbass]. Materials of the 5th International Scientific and Practical Conference, Donetsk, May 21–23, 2019. Donetsk, 2019, vol. 3, pp. 119–123. (In Russian).

24. Gantsev R.Kh., Gunderov D.V., Atroshchenko V.V., Taimasova L.A., Vatuev M.V. Povyshenie kachestva abrazivnogo elektrokhimicheskogo shlifovaniya zharoprochnykh splavov na nikelevoi osnove [Improving the quality of abrasive electrochemical grinding of nickel-based heat-resistant alloys]. *Neftegazovye tekhnologii i novye materialy. Problemy i resheniya* [Oil and gas technologies and new materials. Problems and solutions]. Ufa, 2019, iss. 8 (13), pp. 322–326.

25. Zhetesova G.S., Bulatov D.Zh. Opredelenie naibolee optimal'nykh parametrov i uslovii elektromekhanicheskoi obrabotki [Determination of the most optimal parameters and conditions for electromechanical processing]. *Trudy Universiteta = University Proceedings*, 2014, no. 1 (54), pp. 24–26.

26. Yanyushkin A.S., Medvedeva O.I., Arkhipov P.V., Popov V.Yu. Mekhanizm obrazovaniya zashchitnykh plenok na almaznykh krugakh s metallicheskoi svyazkoi [The mechanism of formation of protective films on diamond wheels with a metal bond]. *Sistemy. Metody. Tekhnologii = Systems. Methods. Technologies*, 2010, no. 1 (5), pp. 132–138.

27. Popov V.Yu., Yanyushkin A.S. Formirovanie poverkhnostnogo sloya rezhushchego instrumenta pri almaznoi obrabotke krugami na metallicheskoi svyazke [Developing a surface layer of cutting tools in diamond grinding wheels on a metal bond]. *Reshetnevskie chteniya = Reshetnev readings*, 2014, vol. 1, pp. 306–308.

28. Kozlov A.M., Ambrosimov S.K., Kozlov A.A. Modeling abrasive grain interaction with machined surface. *Proceedings of the 6th International Conference on Industrial Engineering (ICIE 2020)*, Sochi, Russia, 18–22 May 2020. Springer, 2021, pp. 953–960. DOI: 10.1007/978-3-030-54817-9_110.

29. Bratan S., Bogutsky B., Roshchupkin S. Development of mathematical model of material removal calculation for combined grinding process. *Proceedings of the 4th International Conference on Industrial Engineering ICIE 2018*, Moscow, 15–18 May 2018. Springer, 2019, pp. 1759–1769. DOI: 10.1007/978-3-319-95630-5_189.

30. Gutsalenko Y., Bratan S., Roshchupkin S., Dyadichev V., Menyuk S. Investigation of the structure and properties of copper-tin bonding M2-01 in diamond grinding wheel introducing additional energy in the form of electric discharges into the processing zone. *Materials Today: Proceedings*, 2019, vol. 11 (1), pp. 586–590. DOI: 10.1016/j.matpr.2019.01.033.

31. Kozlov A.M., Bolgov D.V. Modelirovanie sovmeshchennoi abrazivnoi obrabotki [Modelling of fetch abrasive filtering]. *Fundamental'nye i prikladnye problemy tekhniki i tekhnologii = Fundamental and Applied Problems of Engineering and Technology*, 2010, no. 2 (280), pp. 50–53.

32. Lobanov D., Borisov M., Yanyushkin A., Skeeba V. Ways to implement hybrid finishing technology with a hand-held rotary tool. *IOP Conference Series: Materials Science and Engineering*, 2020, vol. 709 (4), p. 044075. DOI: 10.1088/1757-899X/709/4/044075.

Conflicts of Interest

The authors declare no conflict of interest.