Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science. 2024 vol. 26 no. 2 pp. 95–106
ISSN: 1994-6309 (print) / 2541-819X (online)
DOI: 10.17212/1994-6309-2024-26.2-95-106

NSTU NETI

Obrabotka metallov -
Metal Working and Material Science

Journal homepage: http://journals.nstu.ru/obrabotka_metallov

Determination of the rate of electrochemical dissolution of U10A steel under ECM conditions with a stationary cathode-tool

Vasiliy Yanpolskiy [1, a,*], *Maria Ivanova* [1, b], *Alexandra Nasonova* [1, c], *Alexander Yanyushkin* [2, d]

[1] Novosibirsk State Technical University, 20 Prospekt K. Marksa, Novosibirsk, 630073, Russian Federation
[2] I.N. Ulianov Chuvash State University, 15 Moskovsky Prospekt, Cheboksary, 428015, Russian Federation

[a] https://orcid.org/0000-0002-7728-7623, yanpolskiy@corp.nstu.ru; [b] https://orcid.org/0000-0002-2449-8638, ivanova777888@yandex.ru; [c] http://orcid.org/0009-0006-0194-8831, a.nasonova@corp.nstu.ru; [d] https://orcid.org/0000-0003-1969-7840, yanyushkinas@mail.ru

ARTICLE INFO

Article history:
Received: 15 December 2023
Revised: 03 April 2024
Accepted: 06 May 2024
Available online: 15 June 2024

Keywords:
Electrochemical dissolution rate
Tool steel
Current output
Performance
Stationary cathode tool
Hole machining

ABSTRACT

Introduction. In blank production, when replacing hard alloys with tool steels, difficulties arise in shaping surfaces to ensure the required parameters of productivity, quality and accuracy, due to the presence of incomplete information for assigning electrochemical processing modes for this class of materials. This fact requires additional research to determine rational processing modes that provide the necessary technological parameters (productivity, dimensional accuracy and surface roughness). **The purpose of the work** is to conduct research to establish the patterns of electrochemical shaping of tool steels and determine the modes of the shaping process. **The work investigated** the features of anodic dissolution of *U10A* tool steel in an aqueous *NaCl* solution of 10 % concentration. The range of potential changes was from 0 to 8 V. Technological performance parameters were determined (current output for the main reaction and the rate of electrochemical dissolution at a voltage of 8 V and an electrolyte pressure of 0.1 MPa). **Research methods.** For polarization studies, a potentiodynamic research method was chosen. Technological experiments were carried out using the model of piercing holes with a stationary cathode-tool made of stainless steel without insulation. A circular cross-section with outer diameters of 0.908 mm and inner diameters of 0.603 mm was chosen as a cathode tool. **Results and discussions:** it is revealed that the electrochemical dissolution of *U10A* tool steel in a 10 % aqueous solution of *NaCl* is active in the studied potential range from 0 to 8 V. The technological experiments carried out made it possible to establish the dimensions of the resulting holes — an average diameter of 1.433 mm and a depth of 0.574 mm. The current efficiency was 70.83 %. Based on the analysis of the experimental data obtained, it is established that in order to ensure high productivity of the process of electrochemical forming of *U10A* steel in a solution of 10 % *NaCl*, the feed of the cathode tool should be 0.2232 mm/min, which corresponds to the rate of electrochemical dissolution under the studied forming conditions.

For citation: Yanpolskiy V.V., Ivanova M.V., Nasonova A.A., Yanyushkin A.S. Determination of the rate of electrochemical dissolution of U10A steel under ECM conditions with a stationary cathode-tool. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2024, vol. 26, no. 2, pp. 95–106. DOI: 10.17212/1994-6309-2024-26.2-95-106. (In Russian).

Introduction

The cost of a finished product is determined by a number of factors, including the initial cost of the workpiece and the cost of its machining. Currently, in order to make the most efficient use of material resources in mechanical engineering, expensive and difficult-to-process alloys are being replaced with a more economical alternative [1–5]. Consequently, the optimal use of resources enables the enterprise to enhance its economic profit and disseminate the principles of lean production [6–11]. In the context of limited raw materials and the ongoing escalation in the cost of transport logistics, energy, and other related

*** Corresponding author**
Ivanova Maria V., Senior Lecturer
Novosibirsk State Technical University,
20 Prospekt K. Marksa,
630073, Novosibirsk, Russian Federation
Tel.: +7 383 346-11-71, **e-mail:** ivanova777888@yandex.ru

expenses in the production system, the imperative to conserve material resources is becoming increasingly urgent.

A typical example of this practice is the replacement of hard alloys with tool steels. Most often, the principle is applied to blank production, which includes the use of products with high accuracy and surface quality, such as matrices, punches, etc. In addition, the replacement of hard alloys with tool steels causes certain issues, both during the operation of products and during its manufacture. In particular, the direct transfer of processing modes of carbide dies to tool steels does not provide the required performance, accuracy, and quality parameters. In the processing of carbide dies, electrochemical and mechanical action-based methods are typically employed [12–15]. The studies [16–23] describe the application features of dimensional electrochemical machining (*DECM*) for *R6M5*, *HVG*, and other steels. The works [12, 14, 16–19, 23] indicate that the accuracy of the *DECM* is determined by the manufacturing errors of the cathode tool, the installation of the workpiece, the temperature of the working medium, the flow rate of the electrolyte, the irregularities in the electrode movement, etc. However, there is no data for shaping *U10A* tool steel.

Additional research is required to determine efficient processing modes that ensure the required performance, accuracy, and quality parameters for products made of tool steels that are shaped by electrochemical means.

Thus, the ***purpose of this work*** is to conduct research to establish the patterns of electrochemical shaping of tool steels (polarization studies) and to determine the modes of the electrochemical machining process (technological experiment).

The work is relevant and has practical significance for blank production.

Research methodology

Specimen preparation

The *U10A* tool steel, which is widespread in blank production, was chosen as the material for research. Specimens for conducting polarization studies were made by means of electric erosion machining of parallelepipeds with dimensions of 1×1×20 mm. The working surface of the specimen for polarization studies is shown in Fig. 1.

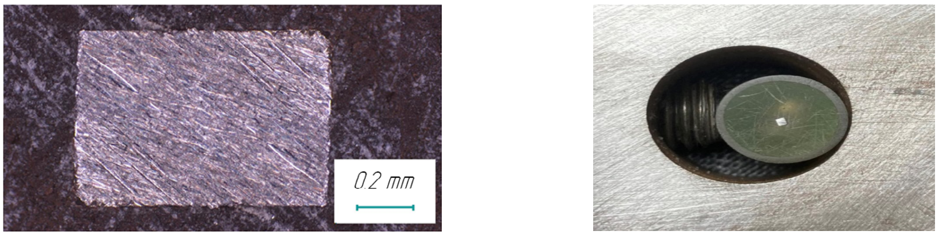


Fig. 1. Appearance of the specimen working surface for polarization studies

To localize the dissolution process and evaluate the current parameters, the side surfaces of the specimens were isolated according to the scheme shown in Fig. 2. The specimen (**1**) was connected to the contact wire (**2**) by soldering and placed in a dielectric fixture (**3**), followed by pouring epoxy resin with a hardener (**4**).

The specimen for conducting technological experiments was a parallelepiped of a model material with the dimensions of 50×50×50 mm.

Polarization studies

The anodic dissolution of *U10A* steel was studied using the potentiodynamic method, with the current density as the dependent variable and the anode potential as the independent variable. The range of anode potentials was from 0 to 8 V.

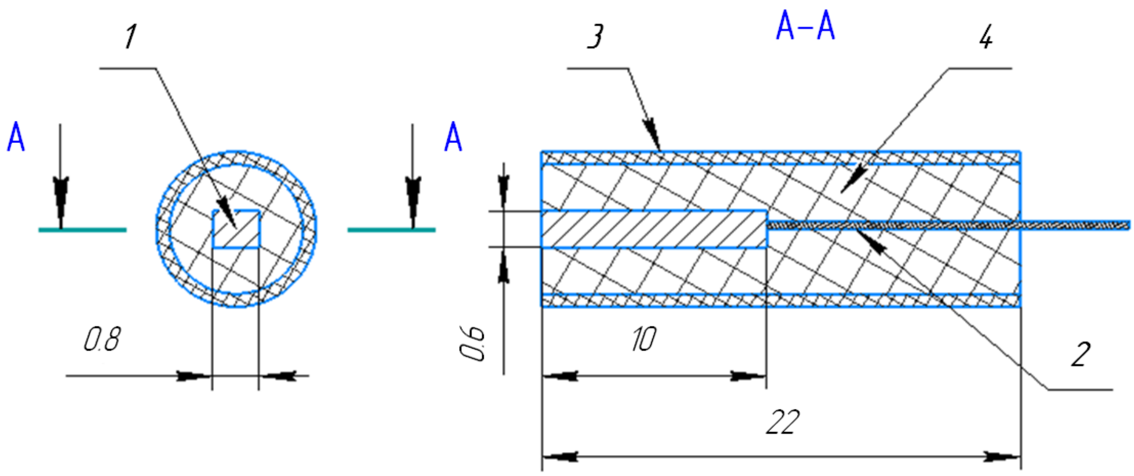


Fig. 2. Specimen for polarization studies:
1 – specimen; **2** – contact wire; **3** – dielectric mandrel; **4** – epoxy resin with hardener

Polarization studies were carried out on an experimental installation, the scheme and appearance of which are shown in Fig. 3. The installation consists of a three-electrode electrochemical cell (**1**), a potentiostat-galvanostat *Elins P-20X* (**2**), and a *PC* (**3**) for measurement, recording, and data processing. A copper ring with the following dimensions was used as a cathode: width 10 mm, outer and inner radii 35 and 31 mm, respectively.

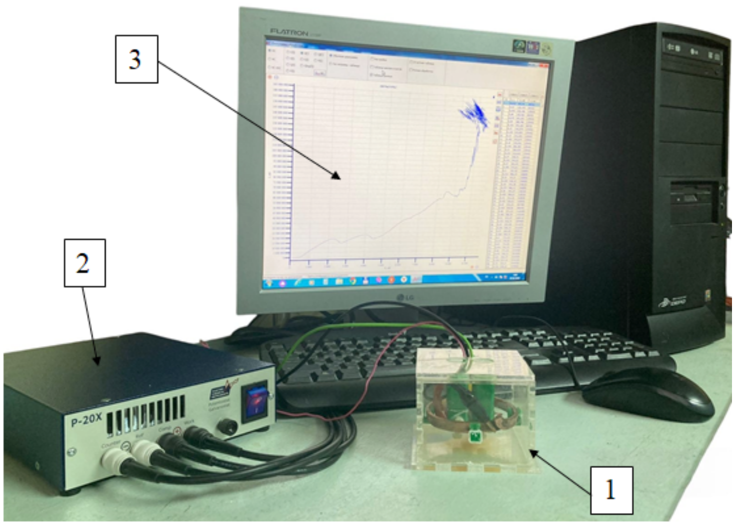


Fig. 3. Scheme and appearance of the experimental setup for potentiodynamic studies:
1 – three-electrode electrochemical cell; **2** – potentiostat-galvanostat *Elins P-20X*; **3** – *PC*

The scanning speed was 1,000 mV/s with increments of 0.011 mV. The gap between the anode and the platinum reference electrode was 0.1 mm. After each experiment, the surface of the test specimen was cleaned with abrasive paper with a grain size of 20–28 μm (*R600*). The working medium for the electrochemical processing was a conductive electrolyte solution. In the electrochemical treatment, the most widely used solution was a neutral salt of sodium chloride (*NaCl*) in water [17–20, 27–29]. The electrolyte concentration of 10 % was chosen, according to the literature sources [29–33]. The kinematic viscosity (v) of the electrolyte was $1.11 \cdot 10^{-6}$ m^2/s [30].

Schemes for perforation by the DECM method

The following schemes were considered for shaping deep holes [32], shown in Fig. 4.

The chosen research scheme employs a cathode tool without insulation, with a supply set to zero. This allows for the determination of the technological parameters of the current output for the main reaction and the rate of electrochemical dissolution under selected initial conditions. The characteristics that emerge when determining the current output are presented in the work of *Y. M. Kolotyrin* and *G. M. Florianovich* [34]. The calculation of the current output was carried out according to the method presented in [29, 31–34].

The calculation assumes that the change in the temperature of the electrolyte and its heating during electrolysis is insignificant and is not taken into account, and the axis of the cathode coincides with the axis of the resulting hole.

Hollow circular needles made of stainless steel with outer and inner diameters of 0.908 mm and 0.603 mm, respectively, were used as the cathode tool. The area of the outlet was $0.362 \cdot 10^{-6} m^2$. The appearance of the cathode tool and tooling is shown in Fig. 5.

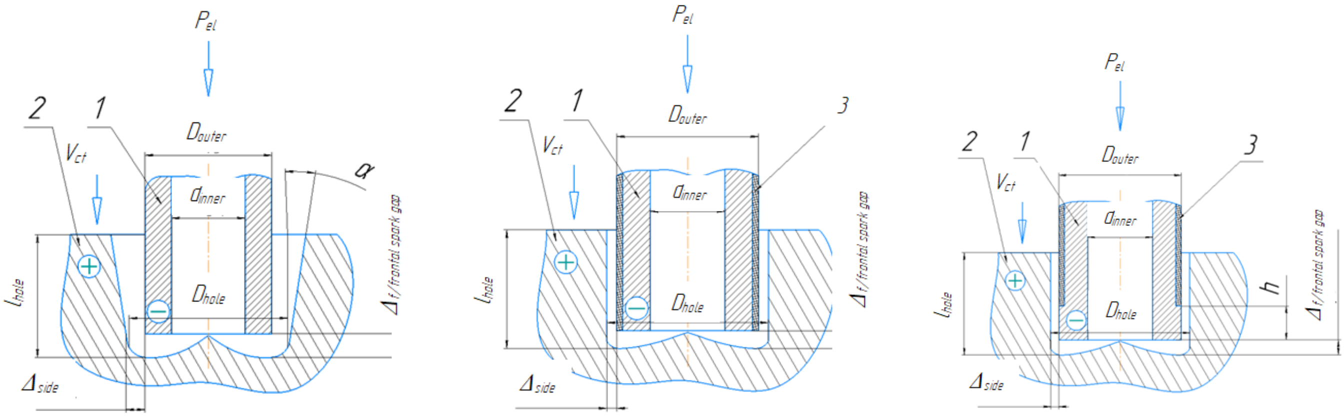


Fig. 4. Hole shaping schemes:

a – with a cathode-tool without insulation; *b* – with an insulated cathode-tool; *c* – with an insulated cathode-tool with a working belt (shoulder): **1** – cathode; **2** – anode; **3** – insulating layer

Fig. 5. Appearance of:

a – the cathode tool; *b* – tooling for cathode tool

An experimental installation for electrochemical hole processing is shown in Fig. 6 and consists of the following elements: an electrolyte supply system (**1**), an electrochemical cell (**2**) with an anode (**3**) and a cathode tool (**4**), a three-coordinate machine (**5**), and a technological current source (**6**).

Implementing electrochemical processing assumes that the electrolyte supply to the zone between the electrodes is uniform to ensure the stability of the electrochemical dissolution process of the workpiece. The rate of electrolyte flow and the rate of electrochemical processes depend on the pressure in the system and hydraulic losses. The influence of hydrodynamic parameters on the performance of anodic dissolution is described in [16, 23, 28–30]. During experimental studies, the pressure in the system was pumped by a diaphragm pump and was equal to 0.9 MPa. The electrolyte supply system (**1**), in addition to the pump, includes a power supply unit for the pump, hoses and containers for supplying and draining electrolyte.

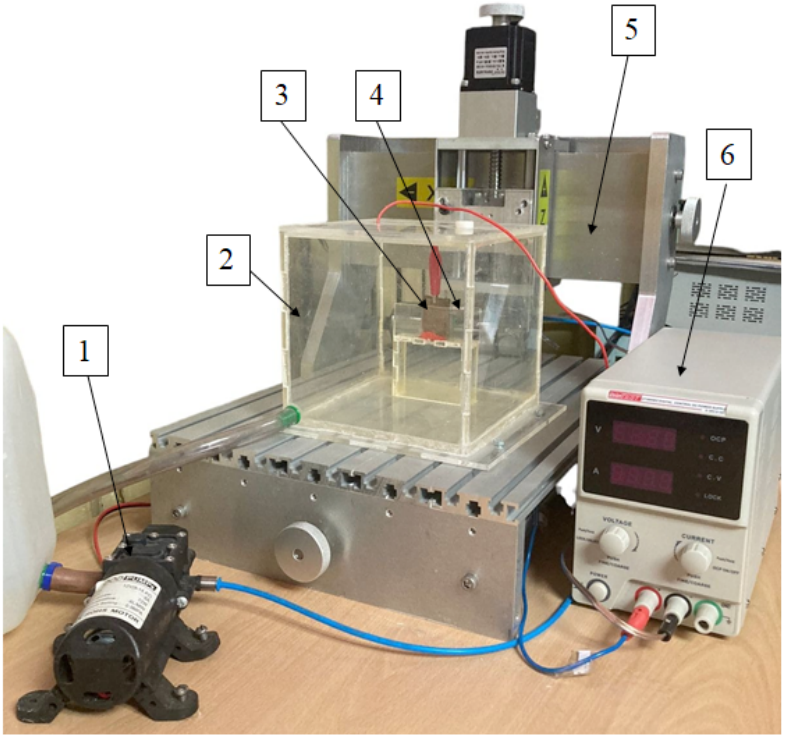


Fig. 6. Experimental setup for electrochemical hole machining:
1 – electrolyte supply system; **2** – electrochemical cell; **3** – anode (blank); **4** – cathode-tool; **5** – three-coordinate machine; **6** – technological power source

The gap between the anode and the cathode during the technological experiment was 0.1 mm [29, 31–34].

Following the experiment, the sample was placed in an ultrasonic sludge cleaning bath and subsequently weighed on high-precision laboratory scales (the division value is 0.1 mg). The depths of the holes were measured by digital micrometer *GRIFF* (0–12.7 mm; with the division value of 0.001 mm). Photographs of the specimen were taken using a *Nikon MM-400* microscope with 30× magnification.

Results and discussion

The results of polarization studies have enabled the features of anodic dissolution of tool steel *U10A* to be established (Fig. 7). The anodic behavior of the steel under study in a 10 % solution of a neutral salt of *NaCl* in water exhibits a characteristic curve. This curve indicates that the active dissolution of steel occurs within a specific potential range between **φ** = 0.3...8.0 V with slight inhibition in the potential range **φ** = 2.1...2.6 V and **φ** = 3.9...4.3 V. This is probably due to phenomena that occur during the electrolysis of steel in an aqueous salt solution, such as the oxidation of the material under study and the decomposition of water [28–30, 31–33]. The general nature of the electrochemical dissolution of *U10A* steel in 10 % *NaCl* in water indicates the absence of passivation sites. This is due to the fact that during the electrochemical dissolution of materials in sodium chloride, passivation phenomena are removed by increasing the voltage without introducing additional activating processes [28–34].

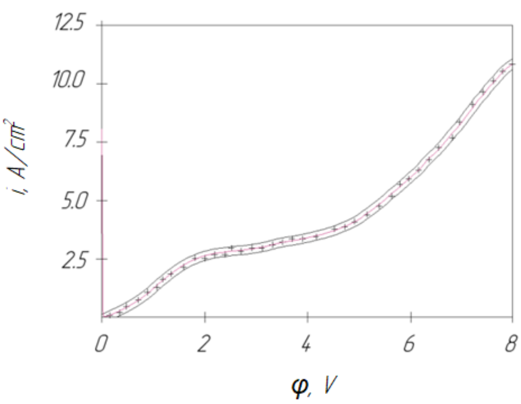


Fig. 7. Anodic polarization curve of *U10A* tool steel in 10 % aqueous *NaCl* solution

Thus, the dissolution of tool steel *U10A* in a 10 % aqueous *NaCl* solution has an active character within the potential ranges **φ** = 0.3...2.1 V, **φ** = 2.7...3.8 V and **φ** = 4.4...8.0 V. Thus, a voltage of 8 V was chosen to determine the output technological performance parameters, namely, the current output for the main reaction and the rate of electrochemical dissolution.

To calculate the current output according to the formula [29], we determine the necessary values.

Experimental studies were carried out to determine the volume of the removed metal, which in turn allowed for determining the mass of the dissolved material during electrochemical dissolution of *U10A* steel. Fig. 8 shows that the average value of the current with an interelectrode gap of 0.1 mm at the initial time was 0.099 A. The duration of the experiment equal to 7 minutes is due to the stabilization of the current value, i.e. the interelectrode gap increased by the maximum permissible value at the specified initial parameters.

To determine the mass of the dissolved material, a series of experiments was carried out at a constant current **I** = 0.099 A and an initial end-to-end interelectrode gap Δ_f = 0.1 mm. Figure 9 shows a graph of voltage versus time for a series of experiments for 3 minutes.

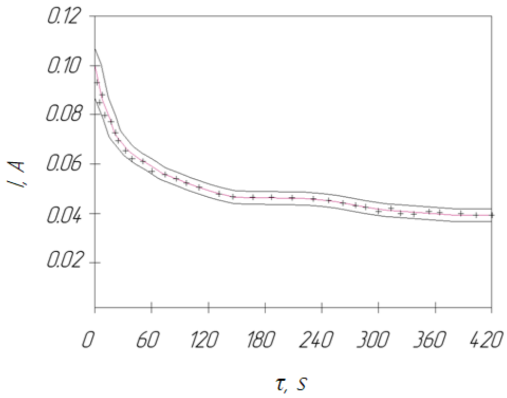


Fig. 8. Graph of current versus time at constant voltage

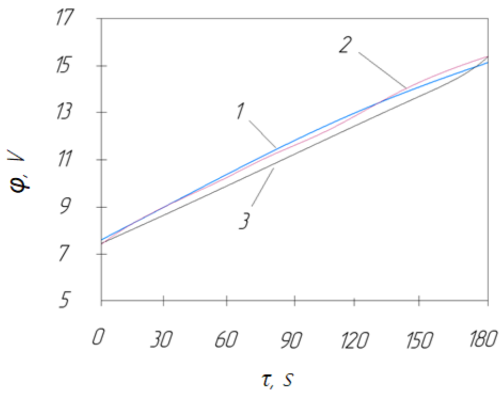
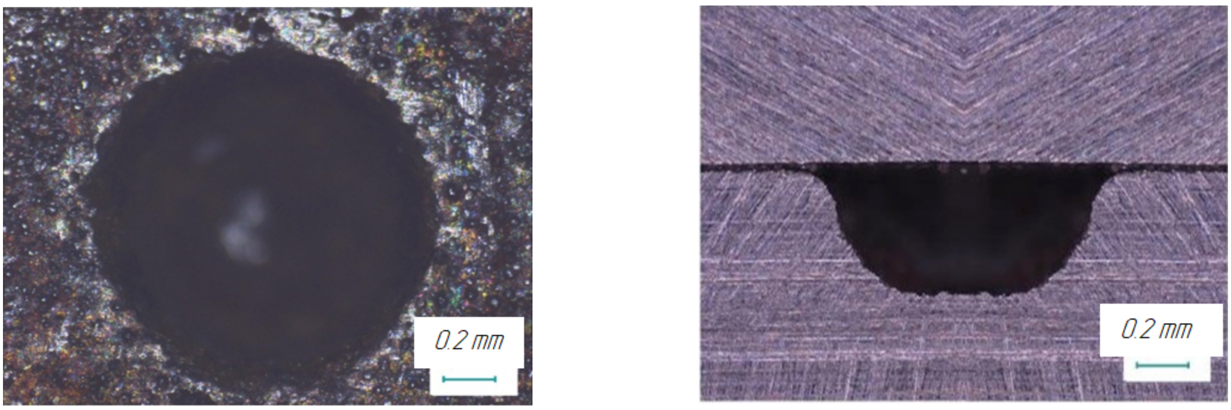


Fig. 9. Graph of voltage versus time at a constant current of 0.099 A

As a result of weighing, the following masses m_{fact} were obtained: for the first experiment, 0.0054 g; for the second experiment, 0.0047 g; for the third experiment, 0.0053 g. Thus, the arithmetic mean mass is 0.0051 ± 0.0009 g.

Figure 10 shows photos of the resulting hole and its profile. Notably, the formation of a taper is typical for processing with a fixed cathode tool.



a *b*

Fig. 10. A hole in 10 % *NaCl* with a stationary cathode-tool of circular cross-section with outer and inner diameters of 0.908 mm and 0.603 mm with a duration of 7 minutes:

a – top view; *b* – profile

Figure 11 shows the cross-sectional dimensions of the hole measured in increments of 0.027 mm, the diameter of the chamfered hole is 1.433 mm, the diameter of the bottom of the hole is 0.389 mm, the depth of the hole $\boldsymbol{h_{av}}$ was 0.574 mm.

The calculation of the electrochemical equivalent of *U10A* steel requires taking into account the mass fraction of the main elements related to metals: iron (98.47 %) and manganese (0.23 %) [35]. The chemical composition of the ladle analysis is taken from the regulatory and technical documents [32]. Table shows the weight and volume electrochemical equivalents of *U10A* steel.

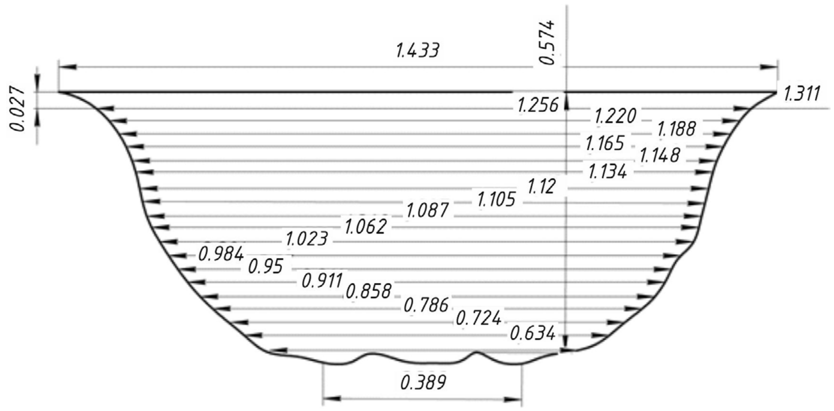


Fig. 11. Hole dimensions in 10 % *NaCl* with a stationary cathode-tool of circular cross-section with outer and inner diameters of 0.908 mm and 0.603 mm for a duration of 3 minutes

Electrochemical equivalents of *U10A* tool steel

Element	Electrochemical equivalent	
	ε_m, g/A·min	ε_V, cm^3/A·min
Fe	0.01736	2.22279
Mn	0.01708	2.18693
U10A	0.01759	2.25198

Thus, based on calculations carried out according to the formula presented in [29], the current output is 70.83 %, or 0.708. If the metal current output coefficient n is within the range of 0.5 to 1.0, it means that the anode is actively dissolved during electrolysis [29, 31–33]. This fact is consistent with the data obtained on the basis of polarization studies of the electrochemical dissolution of *U10A* steel in 10 % aqueous *NaCl* solution.

The experiments performed and calculations of the current output made it possible to evaluate the performance of the *U10A* steel electrochemical machining process in the selected electrolyte composition.

In the processing scheme with a fixed cathode, the size of the interelectrode gap $\boldsymbol{a_0}$ at the beginning of the process corresponds to the set end-to-end gap, while at the end of processing, the value of the interelectrode gap increases by an amount equal to the technological allowance $\boldsymbol{z}$, and is equal to the expression, $a_k = a_0 + z$. When the electrode tool is fixed, the rate of electrochemical dissolution and processing performance decrease with an increase in the interelectrode gap value. The formula presented below [31–32] is valid provided that the value of the current output does not change with fluctuations in the current density.

$$\vartheta_{DECM} = \frac{\varepsilon_V U \theta \eta}{\sqrt{a_0^2 + (\varepsilon_V U \theta \eta \tau)}}, \text{ mm/min},$$

where ε_V is the volumetric electrochemical equivalent of steel *U10A*, cm^3/A·min (0.00225198 cm^3/A·min); U is the voltage at the electrodes, V (8 V); θ is the specific electrical conductivity of the electrolyte $cm \cdot m^{-1}$, (12.11 $cm \cdot m^{-1}$) [31–32]; η is the current output coefficient; a_0 is the interelectrode gap at the beginning of processing or end-to-end gap, mm (0.1 mm); τ is the processing time or electrolysis time, min (3 min).

Then the rate of electrochemical dissolution at the end of the 3rd minute is 0.2232 mm/min. Maintaining this rate of electrochemical dissolution requires the interelectrode gap and other parameters affecting the performance of the process to remain unchanged. The hole depth at *DECM* in 3 minutes in 10 % *NaCl* in the scheme with a fixed cathode instrument was 0.574 mm.

Conclusion

The results of the work demonstrate that the electrochemical dissolution of *U10A* tool steel in a 10 % aqueous *NaCl* solution occurs actively during the entire studied potential range. The highest current density is observed at a potential of φ = 8 V.

Under the conditions of electrochemical shaping of the hole in the *U10A* tool steel in a 10 % aqueous *NaCl* solution with a fixed hollow circular cathode tool with outer and inner diameters of 0.908 mm and 0.603 mm, respectively (the area of the outlet is $0.362 \cdot 10^{-6}$ m^2), the current output was 70.83 %.

The experimental data obtained made it possible to determine the main parameter of the *DECM* mode: the rate of electrochemical dissolution of *U10A* steel at 8 V and a pressure of 0.1 MPa in a 10 % aqueous *NaCl* solution for electrochemical shaping conditions with a hollow cathode tool, which is 0.2232 mm/min. The conducted studies allowed us to form recommendations regarding the supply of the cathode tool, which ensures the maximum rate of electrochemical dissolution of *U10A* steel in a 10 % aqueous *NaCl* solution.

References

1. Dubrovina N.A., Rotman E.G. Osnovnye faktory ekonomii resursov na predpriyatiyakh mashinostroeniya [The basic factors of resource saving on the enterpises of mechanical engineering]. *Vestnik Samarskogo gosudarstvennogo universiteta. Seriya: Ekonomika i upravlenie = Vestnik of Samara State University. Series: Economics and Management*, 2012, no. 10, pp. 20–26.

2. Emelyanova D.S., Kolesnichenko-Ianushev S.L., Tokarev M.A. Organizational and economic problems of applying quality management systems at engineering companies. *Nauchno-tekhnicheskie vedomosti SPbGPU. Ekonomicheskie nauki = St. Petersburg State Polytechnical University Journal. Economics*, 2019, vol. 12, no. 2, pp. 92–102. DOI: 10.18721/JE.12209.

3. Avdeev S.V., Zolkin A.L., Podolko P.M. Analiz strategicheskikh trendov razvitiya promyshlennosti [Analysis of strategic trends in industrial development]. *Ekonomika i predprinimatel'stvo = Journal of Economy and entrepreneurship*, 2023, no. 9, pp. 455–458. DOI: 10.34925/EIP.2023.158.09.083.

4. Belorusova N., Studenikina S. Vliyanie normirovaniya na effektivnost' ispol'zovaniya material'nykh resursov [The effect of normalization on the efficiency of using material resources]. *Vestnik Polotskogo gosudarstvennogo universiteta. Seriya D, Ekonomicheskie i yuridicheskie nauki = Vestnik of Polotsk State University. Part D. Economic and legal sciences*, 2019, no. 5, pp. 32–35.

5. Mrugalska B., Ahmed J. Organizational agility in industry 4.0: a systematic literature review. *Sustainability*, 2021, vol. 13, pp. 1–23. DOI: 10.3390/su13158272.

6. Pimenova E.M., Arutyunyan A.A. Berezhlivoe proizvodstvo kak odin iz sposobov povysheniya ekonomicheskoi bezopasnosti predpriyatiya [Lean manufacturing as a path toward greater business security]. *Kreativnaya ekonomika = Journal of Creative Economy*, 2023, vol. 17, no. 11, pp. 4141–4152. DOI: 10.18334/ce.17.11.119405.

7. Fernandes M., Correia D., Teixeira L. Lean maintenance practices in the improvement of information management processes: a study in the Facility. *Procedia Computer Science*, 2024, vol. 232, pp. 2269–2278. DOI: 10.1016/j.procs.2024.02.046.

8. Karch S., Lüder A., Listl C., Nowacki N.S., Hassan K., Werner R., Hohmann T., Müller S. Lean Engineering – Identifying waste in engineering chains. *Procedia CIRP*, 2023, vol. 120, pp. 463–468. DOI: 10.1016/j.procir.2023.09.020.

9. Suetina T.A., Odinokov M.Y., Safina D.M. Benefits of project management at lean manufacturing tools implementation. *Asian Social Science*, 2014, vol. 10 (20), pp. 62–66. DOI: 10.5539/ass.v10n20p62.

10. Sundararajan N., Terkar R. Imp roving productivity in fastener manufacturing through the application of Lean-Kaizen principles. *Materials Today: Proceedings*, 2022, vol. 62 (2), pp. 1169–1178. DOI: 10.1016/j.matpr.2022.04.350.

11. Botti L., Mora C., Regattieri A. Integrating ergonomics and lean manufacturing principles in a hybrid assembly line. *Computers & Industrial Engineering*, 2017, vol. 111, pp. 481–491. DOI: 10.1016/j.cie.2017.05.011.

12. Rahimyanov Kh.M., Krasilnikov B.A., Yanpolsky V.V., Krasilnikov D.B. Elektrokhimicheskaya obrabotka bezvol'framovykh tverdykh splavov [Electrochemical processing of tungsten carbide]. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2010, no. 3 (48), pp. 3–7.

13. Zhang X., Huang R., Liu K., Kumar A.S., Deng H. Suppression of diamond tool wear in machining of tungsten carbide by combining ultrasonic vibration and electrochemical processing. *Ceramics International*, 2018, vol. 44, pp. 4142–4153. DOI: 10.1016/j.ceramint.2017.11.215.

14. Katiyar P.K., Randhawa N.S. A comprehensive review on recycling methods for cemented tungsten carbide scraps highlighting the electrochemical techniques. *International Journal of Refractory Metals and Hard Materials*, 2020, vol. 90, p. 105251. DOI: 10.1016/j.ijrmhm.2020.105251.

15. Denkena B., Krödel A., Lang R. Fabrication and use of Cu-Cr-diamond composites for the application in deep feed grinding of tungsten carbide. *Diamond and Related Materials*, 2021, vol. 120, p. 108668. DOI: 10.1016/j.diamond.2021.108668.

16. Rakhimyanov Kh.M., Yanpolskiy V.V., Yusupov A.S. Struinaya elektrokhimicheskaya obrabotka stali 110G13L [Jet electrochemical machining of the steel 110G13L]. *Sistemy. Metody. Tekhnologii = Systems. Methods. Technologies*, 2016, no. 2 (30), pp. 34–38. DOI: 10.18324/2077-5415-2016-2-34-38.

17. Liu Z., Qiu Z.J., Heng C., Qu N.S. Electrochemical micro drilling of stainless steel with tool electrode jump motion. *Materials Science Forum*, 2009, vol. 626–627, pp. 333–338. DOI: 10.4028/www.scientific.net/MSF.626-627.333.

18. Anasane S.A., Bhattacharyya B. Experimental investigation on suitability of electrolytes for electrochemical micromachining of titanium. *The International Journal of Advanced Manufacturing Technology*, 2016, vol. 86, pp. 2147–2160. DOI: 10.1007/s00170-015-8309-2.

19. Singh R.P., Trehan R. Electrochemical machining and allied processes: a comprehensive review. *Journal of Solid State Electrochemistry*, 2023, vol. 27, pp. 3189–3256. DOI: 10.1007/s10008-023-05610-x.

20. Wang M., Zhang Y., He Z., Peng W. Deep micro-hole fabrication in EMM on stainless steel using disk micro-tool assisted by ultrasonic vibration. *Journal of Materials Processing Technology*, 2016, vol. 229, pp. 475–483. DOI: 10.1016/j.jmatprotec.2015.10.004.

21. Xu Z., Liu J., Zhu D., Qu N., Wu X., Chen X. Electrochemical machining of burn-resistant Ti40 alloy. *Chinese Journal of Aeronautics*, 2023, vol. 28, pp. 1263–1272. DOI: 10.1016/j.cja.2015.05.007.

22. Liu G., Gong Z., Yang Y., Shi J., Liu Y., Dou X., Li C. Electrochemical dissolution behavior of stainless steels with different metallographic phases and its effects on micro electrochemical machining performance. *Electrochemistry Communications*, 2024, vol. 160, pp. 1–13. DOI: 10.1016/j.elecom.2024.107677.

23. Zanjani M.Y., Hackert-Oschätzchen M., Martin A., Meichsner G., Edelmann J., Schubert A. Process control in jet electrochemical machining of stainless steel through inline metrology of current density. *Micromachines*, 2019, vol. 10, pp. 245–272. DOI: 10.3390/mi10040261.

24. Puchkov Yu.A., Poklad V.A., Shkretov Yu.P. A study of coatings on high-temperature nickel alloys by the potentiodynamic method. *Metal Science and Heat Treatment*, 2005, vol. 47, pp. 239–243. DOI: 10.1007/s11041-005-0059-6.

25. Wang M.H., Liu W., Peng W. Multiphysics research in electrochemical machining of internal spiral hole. *The International Journal of Advanced Manufacturing Technology*, 2014, vol. 74, pp. 749–756. DOI: 10.1007/s00170-014-5938-9.

26. Evans K.J., Rebak R.B. Repassivation potential of alloy 22 in chloride plus nitrate solutions using the potentiodynamic-galvanostatic-potentiostatic method. *Materials Research Society Symposia Proceedings*, 2006, vol. 985, pp. 1–7. DOI: 10.1557/PROC-985-0985-NN03-13.

27. Davydov A.D., Volgin V.M., Lyubimov V.V. Electrochemical machining of metals: Fundamentals of electrochemical shaping. *Russian Journal of Electrochemistry*, 2004, vol. 40, pp. 1230–1265. DOI: 10.1007/s11175-005-0045-8.

28. Freiman L.I., Makarov V.A., Bryskin I.E. *Potentsiostaticheskie metody v korrozionnykh issledovaniyakh i elektrokhimicheskoi zashchite* [Potentiostatic methods in corrosion research and electrochemical protection]. Leningrad, Khimiya Publ., 1972. 240 p.

29. Sedykin F.V. *Razmernaya elektrokhimicheskaya obrabotka detalei mashin* [Dimensional electrochemical processing of machine parts]. Moscow, Mashinostroenie Publ., 1976. 302 p.

30. Volosatov V.A., ed. *Spravochnik po elektrokhimicheskim i elektrofizicheskim metodam obrabotki* [Handbook of electrochemical and electrophysical processing methods]. Leningrad, Mashinostroenie Publ., 1988. 719 p. ISBN 5-217-00267-0.

31. Baisupov I.A., Volosatov V.A. *Spravochnik molodogo rabochego po elektrokhimicheskoi obrabotke* [The young worker's guide to electrochemical machining]. 2nd ed., rev. Moscow, Vysshaya shkola Publ., 1990. 176 p. ISBN 5-06-000932-7.

32. Baisupov I.A. *Elektrokhimicheskaya obrabotka metallov* [Electrochemical processing of metals]. Moscow, Mashinostroenie Publ., 1981. 220 p.

33. Poduraev V.N., Kamalov V.S. *Fiziko-khimicheskie metody obrabotki* [Physico-chemical processing methods]. Moscow, Mashinostroenie Publ., 1973. 346 p.

34. Kolotyrin Ya.M., Florianovich G.M. Anomal'nye yavleniya pri rastvorenii metallov [Anomalous phenomena during the dissolution of metals]. *Itogi nauki. Elektrokhimiya = Results of science. Electrochemistry*, 1971, no. 7, pp. 5–64.

35. GOST 1435–99. *Prutki, polosy i motki iz instrumental'noi negelirovannoi stali. Obshchie tekhnicheskie usloviya* [State Standard 1435–99. Bars, strips and reels of tool unalloyed steel. General specifications]. Minsk, Standards Publ., 1999. 23 p.

Conflicts of Interest

The authors declare no conflict of interest.