BULETINUL INSTITUTULUI POLITEHNIC DIN IAȘI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iași
Volumul 63 (67), Numărul 2, 2017
Secția
CONSTRUCȚII DE MAȘINI

TOOL ELECTRODE MASSIC WEAR IN ELECTROCHEMICAL DISCHARGE DRILLING

BY

MARGARETA COTEAȚĂ[1,*], LAURENȚIU SLĂTINEANU[1], SERGIU OLARU[1], MIROSLAV RADOVANOVIC[2] and IRINA BEȘLIU-BĂNCESCU[3]

[1]"Gheorghe Asachi" Technical University of Iași,
Faculty of Machine Manufacturing and Industrial Management
[2]University of Niš, Serbia
[3]"Ștefan cel Mare" University of Suceava

Received: October 20, 2017
Accepted for publication: November 24, 2017

Abstract. When the part is made of a difficult-to-cut material, achieving holes in such a part could involve the use of one of the nonconventional drilling processes. Such a nonconventional drilling process is the electrochemical discharge drilling. Essentially, this process is based on the effects of material removal from the workpiece as a consequence of simultaneous developing of electrical discharges and electrochemical dissolution process. The research problem approached in this paper was to investigate the influence exerted by some process input factors on the tool electrode massic wear in the case of the electrochemical discharge drilling. By mathematical processing of the experimental results, two mathematical empirical models were determined. The empirical models highlight the influence exerted by the tool electrode diameter, the voltage applied to electrodes, the capacitance of the capacitors included in the discharge electric circuit and the density of electrolyte on the tool electrode massic wear.

Keywords: electrochemical discharge drilling; tool electrode massic wear; influence factors; experimental research; empirical mathematical models.

[*]Corresponding author; *e-mail*: mcoteata@tcm.tuiasi.ro

1. Introduction

The request of using more and more performant equipment led to the use of materials characterized by high mechanical properties; as a direct consequence of such a situation, the materials used to obtain the parts incorporated in the mechanical equipment were presenting a lower and lower machinability by classical machining methods. The techniques included in the classical machining methods were based essentially on the plastic deformation of the workpiece material up to the moment when a separation of the material by shearing processes were appearing and in this way the additional material was removed from the workpiece. To process the difficult-to-machine materials, new machining techniques were identified and developed. The main group of methods able to ensure the processing of difficult-to-cut materials and applicable inclusively in certain situations when the surfaces to be machined were less accessible by classical machining method received the name of *nonconventional machining methods*.

Taking into consideration the physical and chemical phenomena, the nonconventional machining methods were divided, for example, in electrical discharge machining methods, electrochemical machining methods, plasma and ion beam machining methods, ultrasonic machining methods, laser beam machining methods, electron beam machining methods etc. Since there were situations when a certain phenomenon was not completely performant from the point of view of technological requests, the researchers tried to combine two or many nonconventional processes, to join many physical and eventual chemical effects. In this way, hybrid or complex machining methods were defined.

One of the hybrid machining methods is *the electrochemical discharge machining method;* this method combines the material removal by electrical discharges and electrochemical dissolution, respectively. If the electrical discharges determines the evolution of a tool electrode wear, theoretically the integrity of the tool electrode is not affected as a consequence of developing the electrochemical dissolution process (Herman, 1998; Slătineanu *et al*., 2004; Slătineanu *et al*., 2012; Shrivastava and Dubey, 2013).

Over the last decades, various machining techniques belonging to the electrochemical discharge machining method were proposed and developed. For example, one could take into considerations various hybrid machining processes (based on the simultaneous use of effects specific to the electrical discharges and electrochemical dissolution): turning, drilling, milling, grinding, honing etc.

In the case of the electrochemical discharge drilling, a tool electrode is gradually advanced to the workpiece surface, were processes of material removal by electrical discharges and electrochemical dissolutions develop. Finally, a hole with established shape of cross section and having a certain depth and certain values characterizing the cross section could be obtained by electrochemical discharge drilling.

Various aspects concerning the machining accuracy, the surface roughness of the hole walls, the material removal rate, the tool electrode wear, the changes of the surface layer structure were investigated by the researchers working in the field of electrochemical discharge machining.

Thus, Yan *et al.* (2016) took into consideration the necessity of applying a high-speed electrochemical drilling process to obtain a fil-cooling hole in a nickel based single-crystal superalloy. They used the Taguchi method to find the optimal combination of the values corresponding to the process input factors (pulse duration, pulse interval, peak current, salt solution conductivity). One of the research conclusions was that the electrochemical discharge drilling facilitates the obtaining of a hole without a proper recast layer.

Skrabalak and Stwora (2016) developed an experimental investigation concerning the use of some noncontact drilling processes (electrical discharge machining, electrochemical machining, electrochemical-discharge drilling) to obtain multiple holes in test pieces made of INCONEL 617 alloy and stainless steel 4H13 and using tool electrodes manufactured by additive and subtractive processes. As comparison criteria, they used the machining time, the machining accuracy and the time for manufacturing of tool electrodes.

In the case of an electrochemical discharge drilling process applied when machining quartz, Laio *et al.* (2016) introduced sodium dodecyl sulfate surfactant in the electrolyte, obtaining an increase of the current density and a better stabilization of the pulse current. They noticed that a diminishing of the tapering phenomenon is possible, simultaneously with a certain oversizing of the hole. An improved model of bubble forming mechanism was proposed.

In precedent papers, an equipment for electrochemical discharge drilling based on the use of a rotating tool electrode and a passivating electrolyte was proposed (Coteață *et al.*, 2009; Coteață *et al.*, 2016). The equipment allows obtaining small diameter holes in parts made of difficult-to - cut materials.

The objective of this paper was to highlight some authors observations established as a consequence of studying the electrochemical discharge drilling process.

2. Theoretical Consideration Concerning the Tool Electrode Wear in the Electrochemical Discharge Drilling Process

As above mentioned, the electrochemical discharge drilling process involves a tool electrode gradually feed to the workpiece surface (Fig. 1).

Since the work fluid is an electrolyte, if the tool electrode and the workpiece are immersed in the liquid, immediately after the connection of the electrodes in the circuit of the direct current supply, a dissolution process starts on the workpiece surface where the intensity of the electric field is high enough to generate such a phenomenon. The products of the chemical reaction developed between the workpiece material and the electrolyte under the action of the electric current circulation could adhere to the workpiece surface, constituting there the so-called *passivating layer*. If the tool electrode continues its movement to the workpiece surface, there will be a moment for which the distance s between the closest asperities existing on the tool electrode and workpiece surfaces (work gap) is lower than a certain value:

$$s < U/E, \tag{1}$$

where U is the voltage applied to the electrodes and E is the dielectric strength of the fluid found in the gap.

In such a situation, electrical discharges develop between the electrodes asperities; as a consequence, the temperature increases faster on the asperities peaks, exceeding even the workpiece material melting or even vaporizing temperature. Small explosions could appear due to the explosive character of melting and vaporising phenomena. As a result, small quantities of the tool electrode and workpiece materials are discarded in the work fluid as liquid or vapour particles. A re-solidification process appears and the eventual circulation of the work fluid could determine the solid particles removal from the work gap. In the zones where the passivating layer was broken as a consequence of the electrical discharges, the electrochemical dissolution process develops again.

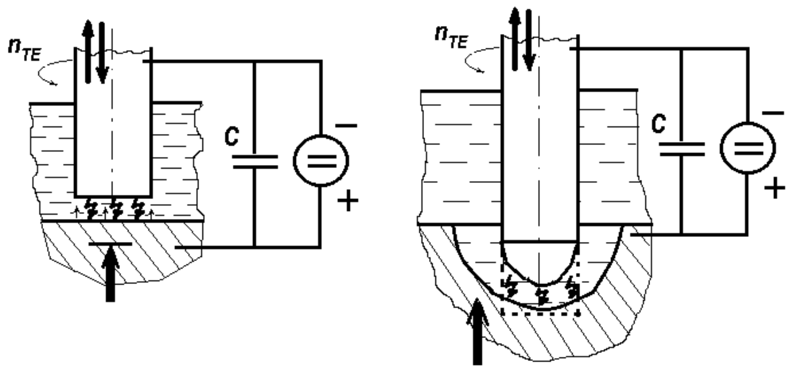

Fig. 1 – Evolution of the cylindrical tool electrode wear: *a* – tool electrode when the electrochemical discharge machining process starts; *b* – tool electrode wear after a certain duration of the machining process.

If the material removal from the workpiece is just one the objectives of the electrical discharge drilling process, the material removal from the tool active surface is an unwanted phenomenon ant it generates the so-called *tool electrode wear.* There are various possibility of the tool electrode wear evaluation:

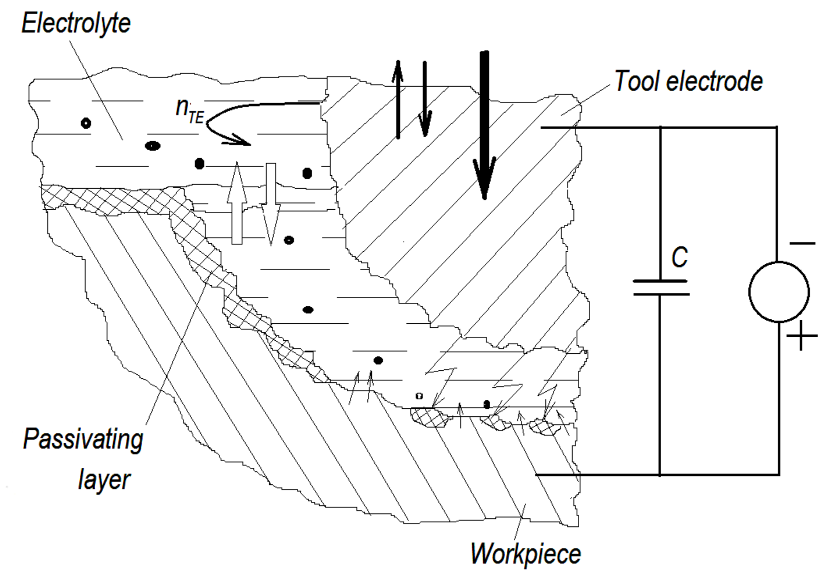

Fig. 2 – Phenomena in the work gap microspace at electrochemical discharge drilling process.

– By taking into consideration the changes of the shape and of the dimensions of the tool electrode active surface. For example, if there is a possibility of measuring the decrease of the tool electrode length at certain time intervals, the values thus obtained are able to offer information concerning the evolution of the tool electrode wear;

– By weighting the tool electrode at certain time of intervals; the decrease of the tool electrode mass could be also a way of its wear evaluation.

A graphical representation of the phenomena developed in the work gap (Fig. 2) could take into consideration a periodical removal of the tool electrode from the workpiece surface, for example as a consequence of a periodical alternating movement achieved by the tool electrode. In this way, the absorption and the discharge process develops in the work gap, determining the circulation of the work fluid and, thus, the refreshment of the work liquid. Some solid metallic particles found in the liquid could facilitate the generation of additional electrical discharges along trajectories including the tool electrode, the workpiece, the metallic particle and the plasma channels generated by the electrical discharge in the work liquid. In this way, the work gap could became larger around the tool electrode in comparison with the work gap size in the frontal zone of the tool electrode.

One could observe that as a result of developing the tool electrode wear process, its active zone changes its shape. Instead, sharp edges, rounded zones are generated (Figs. 1 and 2).

Many factors could be able to affect the intensity of the tool electrode wear process: the voltage U applied to electrodes, the capacitance C of the capacitors included in the discharge electric circuit (such capacitors increase the discharge energy, determining, for example, an increase of the material removal rate from the workpiece material), the conductivity of the work fluid, the machining scheme, the dimensions characterising the active zone of tool electrode etc. For example, it is expected that an increase of the tool electrode diameter will increase the capacity of faster removal of the heat generated by the electrical discharges, determining a diminishing of the tool electrode wear. On the other hand, the increase of the voltage applied to the electrodes and of the electrical discharge circuit capacitance could determine an increase of the electrical discharge intensity and a tool wear acceleration.

3. Experimental Conditions

An experimental research was thought on the base of the machining scheme presented in Figs. 1 and 2. The cylindrical tool electrode made of high speed steel (whose chemical composition was included 0.8% C, 4% Cr, 0.85% Mo, 12% W, 2.4% V) was clamped in a chuck attached to the slotting slide of a workshop milling machine and it achieves an alternating movement, contacting periodically the workpiece surface. Due to the fact that recipient where the test pieces were clamped and immersed were placed on a device including a spring, the tool electrode was pressing for a short period on the test piece. When the contact between the tool electrode and the test piece surface was interrupted due to the tool electrode alternating movement, electrical discharge were developed between the electrodes surfaces asperities, generating the material removal from the workpiece. The additional material removal from the workpiece as a result of the electrochemical dissolution process develops immediately after the tool electrode penetration into the work liquid, the both electrodes being connected in the discharge circuit of the direct current supply.

The test piece material was a sintered carbide type ISO P25, this being a material in which holes of small diameter could be obtained only by using nonconventional machining processes. As a passivating electrolyte, an aqueous solution of soluble sodium silicate with distinct densities was used.

Intending to develop a factorial experiment with four independent variables at two levels, adequate and practical values were selected for each of four considered independent variables: in the case of voltage, U_{max} = 45 V, U_{min} = 35 V, in the case of capacitance C_{max} = 840 µF, C_{min} = 33 µF, in the case of the electrolyte density δ_{max} = 1.20 g/cm^3, δ_{min} = 1.05 g/cm^3, in the case of tool electrode diameter d_{max} = 0.88 mm, d_{min} = 0.48 mm.

The masses of tool electrodes were determined before and after applying the electrochemical discharge machining process by means of a digital analytical balance type Precisa (Switzerland).

The values of the process input factors and of the experimental results were included in the Table 1.

Table 1
Experimental Conditions and Results

Exp. no.	Tool electrode diameter, d_{TE}		Voltage, U		Capacitance, C		Work liquid density, δ		Tool electrode mass decrease, Δm_{TE}, mg
	Codi-fied value	Real value, mm	Codi-fied value	Real value, V	Codi-fied value	Real value, μF	Codi-fied value	Real value, g/cm^3	
1	+1	0.86	+1	45	+1	840	+1	1.20	0.02542
2	+1	0.87	+1	45	-1	33	+1	1.20	0.00828
3	+1	0.86	-1	35	+1	840	+1	1.20	0.01272
4	+1	0.88	-1	35	-1	33	+1	1.20	0.00549
5	+1	0.88	+1	45	+1	840	-1	1.05	0.00701
6	+1	0.86	+1	45	-1	33	-1	1.05	0.00214
7	+1	0.88	-1	35	+1	840	-1	1.05	0.00455
8	+1	0.86	-1	35	-1	33	-1	1.05	0.00153
9	-1	0.49	+1	45	+1	840	+1	1.20	0.01568
10	-1	0.47	+1	45	-1	33	+1	1.20	0.00634
11	-1	0.47	-1	35	+1	840	+1	1.20	0.01500
12	-1	0.48	-1	35	-1	33	+1	1.20	0.00487
13	-1	0.49	+1	45	+1	840	-1	1.05	0.01815
14	-1	0.49	+1	45	-1	33	-1	1.05	0.00343
15	-1	0.48	-1	35	+1	840	-1	1.05	0.00492
16	-1	0.48	-1	35	-1	33	-1	1.05	0.00107

4. Experimental Results

The experimental results included in table 1 were mathematically processed by means of a specialized software (Crețu, 1992). This software takes into consideration the possibility of using a certain type of mathematical empirical model, among five possible such models (polynomial of first and second degree, power function, exponential function, hyperbolic function). The adequacy of the selected mathematical empirical model to the experimental results could be tested by means of the Gauss's criterion. One could mention that the value of the Gauss's criterion is based on the sum of squares of differences between the values of ordinates corresponding to the points offered by the proposed model and the experimental points, for the same values of the process input factors. As a result, the following mathematical empirical model was determined as the best adequate to the experimental results:

$$\Delta m_{TE} = 0.0107 + 0.718 d_{TE} - 0.532 d_{TE}^2 - 0.00242 U + 3.436 \cdot 10^{-5} U^2 - 2.76. \cdot 10^{-4} C + 3.283 \cdot 10^{-7} C^2 - 0.364\delta + 0.181\delta^2, \quad (2)$$

for which the value of the Gauss's criterion is $S_G = 9.142304 \cdot 10^{-6}$.

Considering that a power type function offers a more direct and suggestive information concerning the general influences exerted by the process input factors on the tool electrode massic wear, such a function was also determined by means of the abovementioned software:

$$\Delta m_{TE} = 1.663 d_{TE}^{-0.00664} U^{2.133} C^{0.351} \delta^{7.193}, \tag{3}$$

in this case the value of the Gauss's criterion being $S_G = 1.456626 \cdot 10^{-5}$.

On the base of this empirical mathematical model, the graphical representations from Figs. 3 and 4 were elaborated.

The analysis of the mathematical empirical model represented by the relation (3) and the graphical representations from Figs. 3 and 4 allowed the statement of some general remarks.

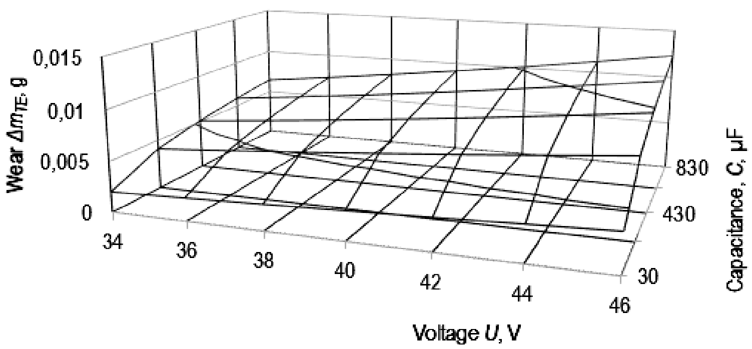

Fig. 3 – Influence exerted by the voltage U applied to electrodes and by the capacitance C of the discharge electric circuit on the tool electrode massic wear (d_{TE} = 0.7 mm, δ = 1.1 g/cm^3, machining process duration t = 6 min).

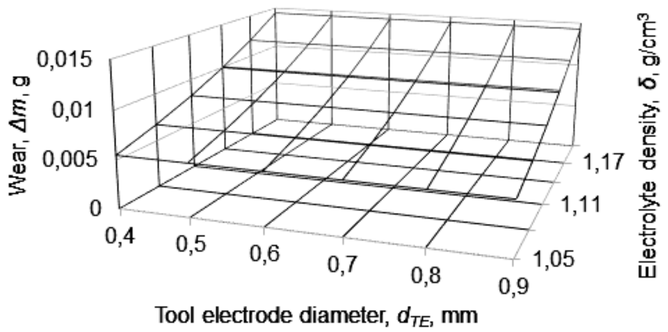

Fig. 4 – Influence exerted by the tool electrode diameter d_{TE} and by the passivating electrolyte density δ on the tool electrode wear in the case of drilling test pieces made of sintered carbide ISO P25 (U = 40 V, C = 500 µF, drilling process duration t = 6 min).

Thus, one noticed that the work fluid density δ exerts the highest influence on the tool electrode wear, since the exponent attached to this process input factor in the relation (3) has the maximum absolute value. The order of the influence size corresponding to the considered process input factors is the following: work fluid density δ (whose exponent, as abovementioned, has the maximum value of 8.054), the voltage U applied to the electrodes (exponent: 2.766), the tool electrode diameter D (exponent: -1.316) and the capacitance C (exponent: 0.368). As expected, the increase of the tool electrode diameter determines a diminishing of the tool electrode wear, while the increase of the voltage U applied to the electrodes and of the capacitors capacitance C has as a result an increase of the tool wear Δm_{TE}. A little surprising is the high influence exerted by the work liquid density δ, whose increase generates a significant increase of the tool electrode massic wear Δm_{TE}.

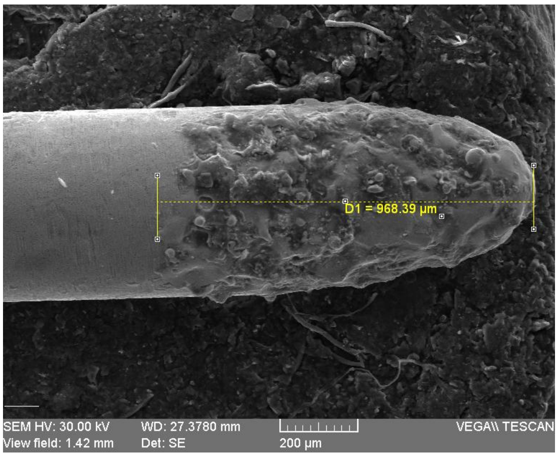

Fig. 5 – Image of the tool electrode wear (U = 45 V, C = 840 µF, δ = 1.20 g/cm^3, d_{TE} = 0.5 mm, magnification: 200x).

An image of the toole electrode wear generated in certain drilling conditions is presented in Fig. 5. The image was obtained by means of an electron scanning microscope Hitachi S4800.

5. Conclusions

The electrochemical discharge drilling is a nonconventional drilling process applied when it is necessary to obtain holes in difficult-to-cut materials. Essentially, the electrochemical discharge drilling involves the simultaneous developing of processes of material removal from workpiece by electrical discharges and the electrochemical dissolution of the workpiece material. In order to investigate the influences exerted by the tool electrode diameter, the voltage applied to electrodes, the capacitance of the capacitors included in the discharge circuit of the direct current supply and electrolyte density, an experimental research in accordance with the principles specific to a planned factorial experiment with four process input factors at two levels was thought. By the mathematical processing of the experimental results using a specialized software, a power type empirical mathematical model was determined. The empirical model showed that on the tool electrode wear, the highest influence was exerted by the passivating electrolyte density, followed by the voltage applied to the electrodes and by the tool electrode diameter. One noticed also that the increase of the voltage, of the capacitance and of the passivating electrolyte density led to an increase of the tool electrode massic wear, while the increase of the tool electrode diameter generates a decrease of its massic wear.

REFERENCES

Coteață M., Ciofu C., Slătineanu L., Munteanu A., Dodun O., *Establishing the Electrical Discharges Weight in Electrochemical Discharge Drilling*, International Journal of Material Forming, **2**, 673-676 (2009).

Coteaţă M., Pop N., Schulze H.-P., Slătineanu L., Dodun O., *Investigation on Hybrid Electrochemical Discharge Drilling Process Using Passivating Electrolyte*, Procedia CIRP, **42**, 778-782 (2016).

Creţu G., *Bazele cercetării experimentale. Îndrumar de laborator*, "Gheorghe Asachi" Technical University of Iaşi (1992).

Herman R.I.E., *Prelucrarea prin eroziune electrică complex*, Editura Augusta, Timișoara, 1998.

Laio Y.S., Wu L.C., Peng W.Y., *A Study to Improve Drilling Quality of Electrochemical Discharge Machining (ECDM) Process*, Procedia CIRP, **6**, 609-614 (2013).

Shrivastava P.K., Dubey A., *Electrical Discharge Machining–Based Hybrid Machining Processes: A Review*, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, **228**, 799-825 (2013).

Skrabalak G., Stwora A., *Electrochemical, Electrodischarge and Electrochemical Discharge Hole Drilling and Surface Structuring Using Batch Electrodes, Structuring Using Batch Electrodes*, Procedia CIRP, **42**, 766-771 (2016).

Slătineanu L., Nagîţ G., Dodun O., Coteaţă M., Chinesta F., Gonçalves-Coelho A., Pamies Teixeira J., San Juan M., Santo L., Santos F. *Non-Traditional Manufacturing Processes*, Editura Tehnica Info, Chişinău, **72**, 2004.

Slătineanu L., Schulze H.-P., Dodun O., Coteaţă M., Gherman M., *Electrode Tool Wear at Electrical Discharge Machining*, Key Engineering Materials, **504**, 1189-1194 (2012).

Skrabalak G., Stwora A., *Electrochemical, Electrodischarge and Electrochemical Discharge Hole Drilling and Surface Structuring Using Batch Electrodes Structuring Using Batch Electrodes*, Procedia CIRP, **42**, 766-771 (2016).

Yan Z., Zhengyang X., Yun Z., Di Z., *Machining of a Film-Cooling Hole in a Single-Crystal Superalloy by High-Speed Electrochemical Discharge Drilling*, Chinese Journal of Aeronautics, **29**, 2, 560-570 (2016).

UZURA MASICĂ A ELECTRODULUI SCULĂ LA GĂURIREA PRIN EROZIUNE COMPLEXĂ, ELECTRICĂ ȘI ELECTROCHIMICĂ

(Rezumat)

Atunci când o piesă este realizată dintr-un material dificil de prelucrat prin așchiere, obținerea găurilor într-o astfel de piesă ar putea implica utilizarea unor procedee neconvenționale de găurire. Unul dintre aceste procedee neconvenționale de găurire este procedeul electrochimic. În esență, procedeul electrochimic se bazează pe efectele de îndepărtare a materialului din semifabricat ca urmare a dezvoltării simultane a descărcărilor electrice și a procesului de dizolvare electrochimică. Problema de cercetare abordată în această lucrare a fost aceea a investigării influenței exercitate de către unii factori de intrare ai procesului asupra uzurii masice a electrodului sculă, în cazul găuririi prin eroziune complexă, electrică și electrochimică. Prin prelucrarea matematică a rezultatelor experimentale, au fost determinate două modele matematice empirice. Aceste modele evidențiază influența exercitată de către diametrul electrodului sculă, de tensiunea aplicată celor doi electrozi, de capacitatea condensatoarelor incluse în circuitul electric de descărcare și de densitatea electrolitului asupra uzurii masice a electrodului sculă.