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THE INFLUENCE OF SOME WORKING CONDITIONS ON ROUGHNESS IN ELECTROCHEMICAL MACHINING OF SOME CARBON STEEL WORKPIECES

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ABSTRACT: Electrochemical machining is a machining method that uses electrochemical reactions to remove material from a workpiece. The method involves using an electrolyte and an electric current for material removal to occur in a controlled manner. The machining method is also used in the case of workpieces made of hard materials or difficult to process by other methods. The experimental research whose results were included in the paper sought a deeper understanding of the mechanisms of the machining process and the interactions between the workpiece material and the electrolyte. The experimental research involved the configuration of a machining system, the preparation of the samples, the performance of the experimental tests resorting to the variation of some input factors such as the voltage applied to the electrodes, the size of the gap between the electrodes, the composition of the electrolyte. The experimental test planning method was used. The mathematical processing of the experimental results was carried out using specialized software, which is based on the least squares method. Empirical mathematical models were thus established, highlighting the intensity of the influence exerted by the input factors on the magnitude of the roughness parameter *Ra*. It was found that, among the input factors considered, the strongest influence is exerted by the gap size, followed by the voltage applied to the electrodes.
KEYWORDS: electrochemical machining, voltage applied to the electrodes, gap size, electrolyte concentration, surface roughness, empirical mathematical model.

1. INTRODUCTION

Electrochemical machining is a method for processing workpieces made of electrically conductive materials, in which the material is removed from the workpiece through electrochemical reactions. The process involves passing a direct electric current through a conductive medium (called *an electrolyte*) to allow anodic oxidation of the workpiece material, which leads to the gradual removal of the material from the workpiece [1-13].

The electrochemical machining process is used in various situations where removing the material from a workpiece of electroconductive material is necessary to obtain complex shapes and parts with high precision or special finishes of the resulting surfaces [5]. The electrochemical machining method is preferred in certain cases due to specific advantages such as the ability to process hard, brittle, or difficult-to-process materials by other methods. Some areas where electrochemical machining is used are as follows [2-13]:

- *The aeronautical and space industry*: electrochemical machining is used to process components made of special alloys, for example, titanium or titanium alloys, which are considered necessary to ensure the high performance of aircraft and space vehicles. The method can be used for making cooling channels in turbines, for manufacturing components of the structure of air or space vehicles, or for other applications that require high precision;

- *Manufacturing of dies and molds*: electrochemical machining is frequently used in producing dies and molds in the metalworking industry. The method allows the generation of complex channels, with accurate depths and fine details, in molds for extrusion, pressing, etc.;

- *Medicine*: in the medical field, electrochemical machining can be used to manufacture surgical instruments, some implants, or other medical components characterized by complex shapes or high-quality finishes;

- *Jewelry manufacturing*: electrochemical machining can be applied in generating fine details and decorative machining on precious metal materials workpieces for jewelry, luxury watches, etc.;

- *Energy industry*: the method can be used for the machining of components from refractory metal materials used in thermal or nuclear power plants;

- *Repair and reconditioning of parts*: electrochemical machining can be used to repair or recondition parts that have suffered damage or to restore accurate dimensions of worn parts.

Based on the principle underlying electrochemical machining, several machining processes have been developed, such as *electrochemical grinding*, *electrochemical polishing*, *electrochemical milling*, *electrochemical turning*, *electrochemical drilling*, *electrochemical pickling*, *electrochemical etching*, *electrochemical deburring*, etc. [1-13].

The key factors that influence the performance of the electrochemical machining process and the values of the parameters of technological interest are [1-14];

- *Nature of the material of the workpiece*: different types of materials conduct electricity differently and react distinctly with the electrolyte;

- *The shape and geometry of the part to be obtained*: the complexity of the geometries and contours of the parts can influence how the electrolyte and current flows are distributed on the surface of the workpiece, which can affect the uniformity of the machining process;

- *The nature of the electrolyte*: the electrolyte is the medium that allows the transport of ions and electrons during the machining process. The nature of the electrolyte can influence the machining speed, surface quality, and process efficiency;

- *The distance between the cathode electrode and the part to be made*, i.e., *the size of the gap*: the accurate distance between the electrode and the workpiece has a significant impact on some of the output parameters of the machining process;

- *The intensity of the electric current*: this factor significantly influences the amount of material removed from the workpiece in a certain time interval. A too-high intensity of the electric current can lead to excessive heating of the electrolyte, to its vaporization and, possibly, to a negative impact on the results of the machining process;

- *Duration of machining*: the time during which the electric current passes through the electrolyte has a direct impact on the amount of material removed and on the quality of the surface obtained;

- *The concentration and composition of the electrolyte*: these elements can influence the process material removal rate and the characteristics of the machined surface;

- *Temperature*: the temperature of the electrolyte can affect the speed of electrochemical reactions and, therefore, can change the speed of material removal from the workpiece.

In the Electrochemical Machining (ECM) process, the following *output parameters* are used to evaluate process performance and quality:

- *The amount of material removed from the workpiece in unit time*. This is a key parameter which provides information on machining productivity;

- *Surface quality* refers to the surface finish of the workpiece after machining. A good surface quality means a smooth surface without defects or large asperities;

- *The roughness of the machined surface,* evaluated using the *Ra* parameter: This parameter evaluates how uniform the material removal is on the surface affected by the machining process.

The roughness of a surface refers to the characteristics of the texture or asperities of that surface. It provides information on the height variations of the surface profile, i.e., the differences between the heights of the asperities and the depths of the voids between the asperities.

Roughness is often expressed in terms of deviations of the actual profile from an ideal profile (usually, a straight line).

In the electrochemical machining process, several input factors can influence the values of the roughness parameters of the machined surfaces. These factors can significantly impact the quality and characteristics of the surfaces obtained.

Some of these factors (some of them being previously mentioned as factors that exert influence on the values of the output parameters of the electrochemical machining process) are the intensity of the electric current, the duration of the machining, the nature, concentration, and temperature of the electrolyte, the size of the working gap, the shape and geometry of the tool electrode, some characteristics of the workpiece material (such as chemical composition, electrical conductivity, crystal structure), etc.

The roughness profile is a graphical representation of the height variations of the points belonging to the surface profile in a certain section and along a certain length. This profile provides a visual image of the texture and asperities of a surface, highlighting the height fluctuations of the surface asperities depending on the position considered.

Essentially, the roughness profile is a graph that shows how the surface level varies along a reference line, which is usually the mean line. The height of each point on the graph is measured from the reference line and represents the actual height of the surface at that point.

Although some aspects of electrochemical machining have been known for a relatively long time, researchers are still concerned with investigating some aspects of this machining method.

Thus, Xu and Wang [15] took into account the technological advances that affected the values of the output parameters of the electrochemical machining process, such as the characteristics of the electrochemical dissolution process of some of the new materials, which are difficult to process by classical methods and which are used in aeronautics engines. Other aspects analyzed by the two researchers referred to the numerical simulation of the electrochemical machining process, the design of complex structures of the tool electrode, the simulation of the electrolyte flow field to ensure, as far as possible, a uniform flow of electrolyte, to the innovation of electrochemical machining or hybrid machining that also involves electrochemical machining processes.

The research objectives, whose results are presented in this article, aimed at developing experimental research to identify some empirical mathematical models that would provide additional information regarding the development of electrochemical machining processes.

The article contains an introductory part regarding the general aspects of electrochemical machining, some hypotheses regarding the influence of several factors on the surface roughness resulting from electrochemical machining, the conditions for conducting experimental research, and the way of processing and analyzing the experimental results.

2. HYPOTHESES REGARDING THE INFLUENCE OF SOME FACTORS ON THE ROUGHNESS OF THE SURFACE RESULTING FROM THE ELECTROCHEMICAL MACHINING

Roughness assessment parameters can be grouped into several categories based on what they measure and how they describe the surface texture and asperities. Currently, to characterize the roughness profile in a certain section through the investigated surface, the following groups of parameters are used:

a) *Amplitude parameters,* which take into account aspects related to prominence and gaps (maximum height of prominence of the *Rp* profile, maximum height of the *Rz* profile, etc.);

b) *Amplitude parameters* referring to the average of the ordinates of the profile points (arithmetic mean deviation *Ra*, mean square deviation *Rq*, profile asymmetry factor *Rsk*, profile flattening factor *Rku*, etc.);

c) *Pitch parameters* (e.g., average width *Rsm* of profile elements);

d) *Hybrid parameters* (for example, the mean square slope *RΔq* of the evaluated profile);

e) *Curves and parameters associated with curves*, such as the bearing curve of the profile, the relative bearing length of the profile *Rmr*(*c*), etc.

The *Ra* parameter is mainly used to evaluate the roughness of a machined surface. This parameter is defined as an arithmetic mean of the absolute values of the *Z*(*x*) ordinates within the limits of the so-called base length *l*, using the relation:

$$R_a = \frac{1}{l}\int_0^l |z(x)|\,dx \ \ [\mu\text{m}]. \tag{1}$$

The values of the roughness parameter *Ra* can be determined using roughness meters; in some cases, such devices can also highlight the profile of the investigated surface in a certain section.

For the development of experimental research on the influence of different factors on the value of the roughness parameter *Ra* corresponding to a surface made by electrochemical machining, the machining scheme shown in Figure 1 was taken into account.

It can be seen that the placement of the test sample above the tool electrode has been provided at a distance corresponding to the size of the gap *S*. If the test sample and the tool electrode are connected in the

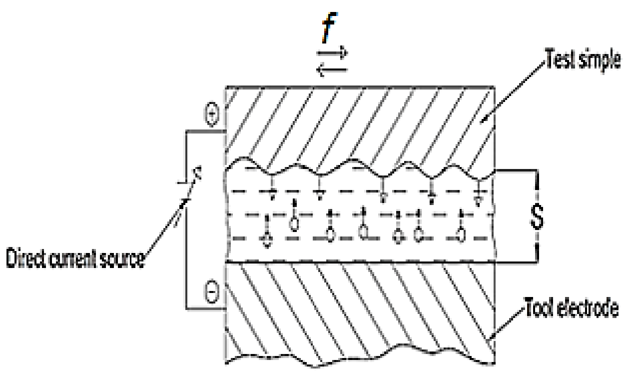


Figure 1. Adopted machining scheme

circuit of a direct current electrical source and these two components are immersed in an electrolyte, it is expected that ions from the test sample material pass into the electrolyte, thus developing a process of material removal from the test sample at the level of its lower surface.

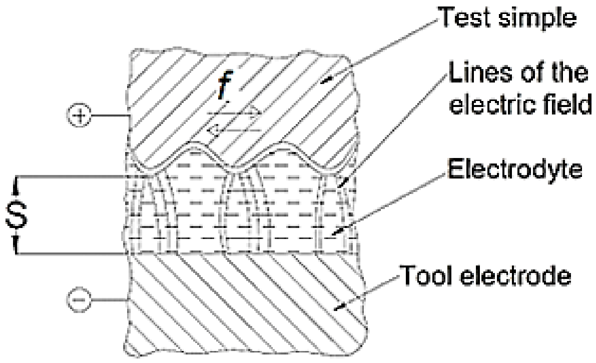


Figure 2. The removal of material mainly from the peaks of surface asperities

It is expected that the tips of the asperities of the test sample surface, located at a smaller distance from the active surface of the tool electrode, will be more intensively affected by the process of removing material from the test sample. A removal mainly by electrochemical erosion of the material from the tips of the asperities on the surface of the test sample will also be possible due to a greater concentration of the electric field lines on the tips of the asperities, compared to the removal of material from the bottoms of the voids between the asperities of the test sample surface (Fig. 2).

It was intended to use a direct current source with variable voltage to follow the influence of the electric current intensity on the change in the value of the *Ra* parameter.

The machining equipment will also have to allow controlled modification of the size *S* of the gap between the test sample and the tool electrode connected to the negative pole of the direct current source (Fig. 3).

Following those mentioned above, a process of natural depassivation will develop. The release of hydrogen bubbles on the upper flat surface of the electrode and the movement of these bubbles towards the surface of the electrolyte liquid will contribute to a certain agitation of the electrolyte and to the removal from the lower surface of the test sample of a possible passivation layer, generated as a result of the chemical reaction between the material of the test sample and electrolyte when the electric current passes.

To intensify the process of removing the passivation layer, an oscillatory movement performed by the test sample in the horizontal plane, with relatively low values of the oscillation frequency and the amplitude of the oscillation movement, was considered.

For the adopted machining scheme, a decrease in the asperity heights on the test sample surface is expected due to more intense material removal from the asperity tips. It can, therefore, assume a reduction in time of the value of the roughness parameter *Ra*. Also, considering a higher value of the intensity of the electric current, an increase in roughness will be reached due to an uncontrolled intensification of sampling material from the test sample. The oscillatory movement of the test sample in a plane

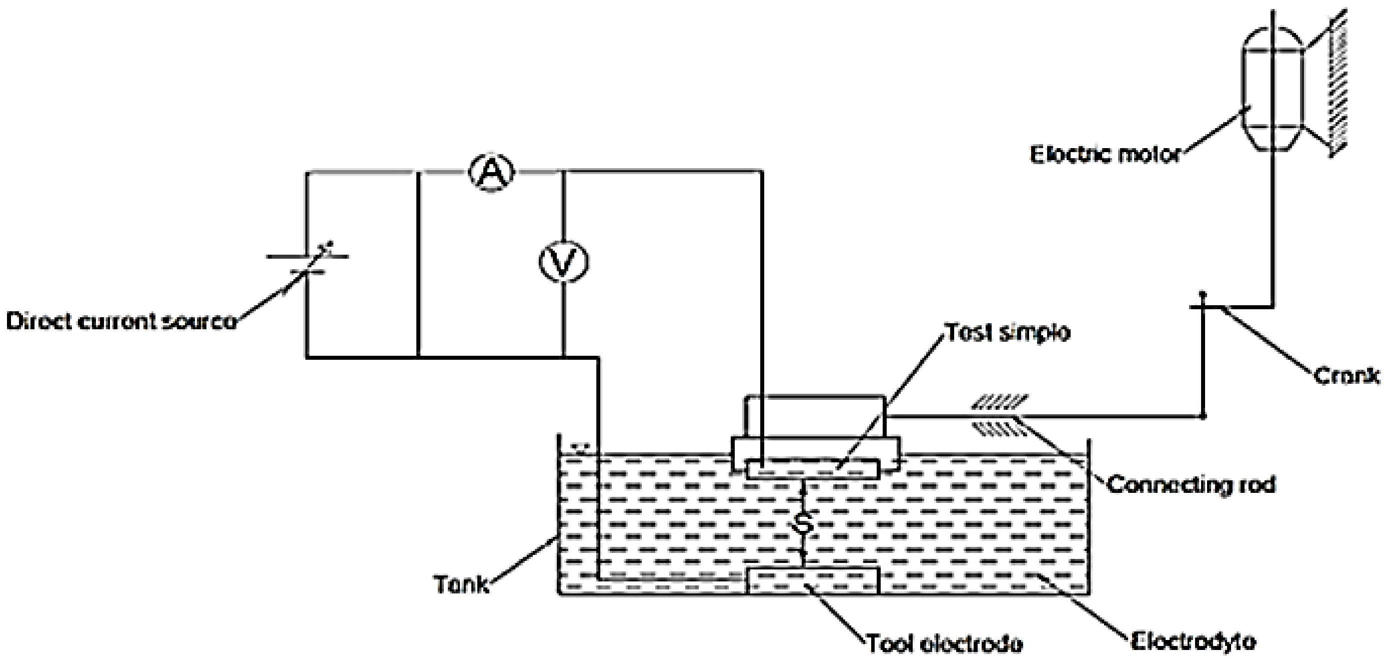


Figure 3. Schematic representation of the electrochemical machining equipment

parallel to the upper flat surface of the tool electrode will contribute to a faster depassivation of the surface of the test sample affected by the machining process, thus increasing the rate of material removal from the workpiece, but without exerting an effect decisive on the intensity of the surface roughness modification process resulting from the electrochemical machining.

Increasing the concentration of the aqueous solution corresponding to the electrolyte could cause an intensification of the material removal process from the test sample and, therefore, an increase in the roughness of the machined surface. Such a process could occur until a certain value of the electrolyte concentration is reached, after which the material removal process would be less intense, which could mean a decrease in the surface roughness, evaluated by the roughness parameter *Ra*.

The increase in the size *S* of the gap could cause an increase in the electric resistance generated by the electrolyte, a decrease in the intensity of the electric current passing through the electrolyte, and therefore a decrease in the asperity heights, which would lead to a decrease in the value of the roughness parameter *Ra*.

The increase in the size *S* of the gap could cause an increase in the electric resistance generated by the electrolyte, a decrease in the intensity of the electric current passing through the electrolyte and therefore a decrease in the asperity heights, which would lead to a decrease in the value of the roughness parameter *Ra*.

3. EXPERIMENTAL CONDITIONS

To verify the validity of some of the previously presented hypotheses, an experimental research program was designed to highlight the influence of some of the input factors in the electrochemical machining process on the change in the value of the roughness parameter *Ra*.

In this sense, the machining equipment, whose schematic representation can be seen in Figure 3, was used.

The equipment uses an electric motor that contributes to driving a crank-rod mechanism. One end of the connecting rod is solidarized with the support subsystem of the test sample, causing it to be driven in a reciprocating rectilinear movement. The amplitude of the oscillatory movement of the test sample can be varied by changing the length of the active zone of the crank rod. In turn, the frequency of the oscillating motion of the test sample can be changed between certain limits by changing the supply voltage of the DC electric motor used to drive one end of the crank rod into rotational motion.

The test sample and tool electrode are immersed in an electrolyte inside a container of electrically insulating material. For the power supply of the electric circuit in which the test sample and the tool electrode were included, a direct current source was used, fed from the usual electric current network, using a subsystem containing a voltage step-down transformer and a rectifier. The electric transformer provides conditions for obtaining several values of the voltage of the electric current. An ammeter and a voltmeter allow the monitoring of the voltage values and the intensity of the electric current used to develop the chemical machining process.

The test samples were made of low-carbon steel (0.15 % C).

Aqueous sodium chloride solutions were used as electrolytes, with two concentrations (13% and 23%).

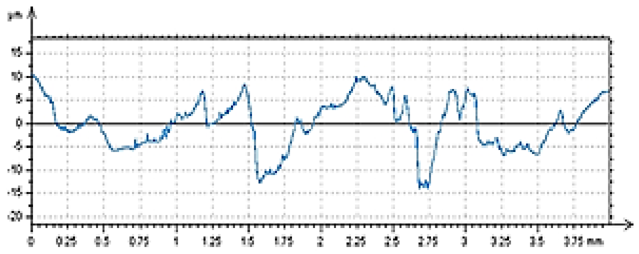
Table 1. Test conditions and experimental results obtained during the electrochemical machining of carbon steel test samples (duration of the experimental test: 3 min)

Exp. no.	Input factors						Output parameter
	Voltage *U* (V)		Concentration *C* (%)		Gap *S* (mm)		*Ra* (μm)
	Coded value	Real value	Coded value	Real value	Coded value	Real value	
1	-1	5	-1	13	-1	2,5	1.50
2	-1	5	-1	13	+1	4	1.02
3	-1	5	+1	23	-1	2,5	0.658
4	-1	5	+1	23	+1	4	1.22
5	+1	10	-1	13	-1	2,5	1.54
6	+1	10	-1	13	+1	4	1.07
7	+1	10	+1	23	-1	2,5	3.17
8	+1	10	+1	23	+1	4	1.05

The determination of the values of the roughness parameter *Ra* was carried out using a Taylor Hobson Surtronic 25 roughness meter.

A factorial experiment of type *L*8 was used to plan the experimental tests, with three independent variables (voltage *U* supplying the electric circuit, concentration *C* of the electrolyte, and size *S* of the gap), at two levels of variation.

The values of the independent variables (of the input factors in the electrochemical machining process) and the experimental results were included in Table 1.



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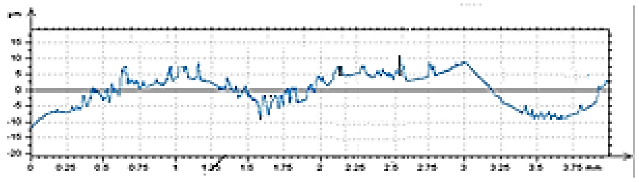

b

Figure 4. The reduction of the asperity heights shown by the surface profile before the electrochemical machining (a) and respectively after the electrochemical machining (b) (profiles made using the Taylor-Hobson Surtronic 25 roughness meter

In Figure 4, the asperity heights change after applying the electrochemical machining to the asperity heights corresponding to the initial surface can be seen.

4. PROCESSING AND ANALYSIS OF EXPERIMENTAL RESULTS

The experimental results were processed with the help of specialized software based on the least squares method [16-18].

The program allows the selection of the most appropriate empirical mathematical model for the experimental results using the Gauss criterion. Since empirical mathematical models of the power-type function are used in many situations in manufacturing engineering, determining such empirical mathematical models was preferred in the present case. It should be noted that the values of the exponents attached to the independent variables in the empirical mathematical models of the power-type function provide a direct image of the intensity of the influence that each input factor in the investigated process exerts on the value of the output parameter, in this case, the output parameter being the arithmetic mean deviation *Ra*.

Through the mathematical processing of the experimental results with the help of the specialized software, the following empirical mathematical model was determined:

$$Ra=0.876U^{0.539}C^{0.025}S^{-0.658}\ , \qquad (1)$$

where *U* is the supply voltage of the electrical circuit corresponding to electrochemical machining (in V), *C* is the concentration of the electrolyte (in %), and *S* is the size of the gap (in mm).

The diagrams in Figures 5 and 6 were developed by considering the power-type function mathematical model.

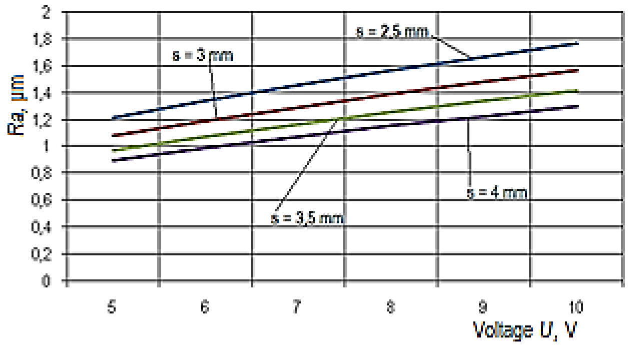

Figure 5. The influence of voltage *U* on the value of the roughness parameter *Ra* for different values of the size *S* of the gap between the test sample and the tool electrode of the electrolyte (*C*= 13 %, *t*=3 min)

The analysis of the empirical mathematical model constituted by equation (1) and the graphic representations in Figures 5 and 6 allowed the formulation of the following observations.

It is thus found that, for the experimental conditions in which the tests were carried out, the factor with the

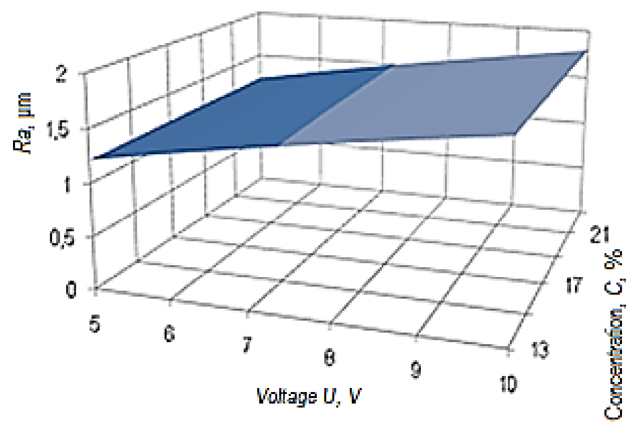

Figure 6. The influence of the voltage *U* applied to the electrodes and the concentration *C* of the electrolyte, in the case of the electrochemical machining of some steel test samples (*S*=2.5 mm, *t*=3 min)

greatest influence on the values of the roughness parameter *Ra* is the size *S* of the gap between the electrodes, since in the empirical mathematical model constituted by equation (1), this size has attached the highest absolute value of the exponent (-0.658), to the values of the exponents attached to the other two input factors.

Increasing the value of the gap *S* will lead to a decrease in the intensity of the electric current due to the increase in the electric resistance generated by a thicker layer of electrolyte and, finally, to a reduction in the size of the roughness parameter *Ra*, since the value of the exponent attached to the factor *S* is negative.

In the second place, from the point of view of the influence exerted on the magnitude of the roughness parameter *Ra* is the voltage *U* between the two electrodes immersed in the electrolyte. The value of the exponent attached to this input factor is positive, which means that an increase in the voltage *U* will lead to an increase in the magnitude of the roughness parameter *Ra*. This is due to the increase in the intensity of the electric current passing through the electrolyte when the voltage *U* increases.

A smaller and practically insignificant influence on the size of the roughness parameter *Ra* is exerted by the size *S* of the gap, to which the exponent with the lowest value (0.025) is attached to the values of the exponents corresponding to the other input factors in the investigated process.

5. CONCLUSIONS

Electrochemical machining is a technological process that uses electrochemical reactions to remove material from a part under conditions of immersing the part and the tool electrode in an electrolyte and connecting the two electrodes in the circuit of a direct current source. The study of specialized literature in recent years has shown that research on electrochemical machining has focused on developing new machining methods, including in the case of new materials, improving the efficiency and accuracy of the process, and developing new applications.

As output parameters of an electrochemical machining process, the rate of material removal from the workpiece (machining productivity), the parameters characterizing the roughness of the machined surface, the thickness of the layer of the workpiece affected by the machining, the wear of the tool electrode (in different ways compared to the wear specific to other machining methods), the degree of damage to the electrolyte, the level of environmental pollution by the materials used, etc. can be mentioned.

There are several parameters for characterizing the roughness of a surface, but currently, the most used parameter is the arithmetic mean deviation *Ra* of the evaluated profile.

In the case of electrochemical machining, the main factors capable of exerting influence on the size of the roughness parameter *Ra* are the intensity of the electric current (or the voltage between the electrodes), the nature and concentration of the electrolyte, the method of depassivation, the size S of the gap between the electrodes, the nature and chemical composition of the material of the workpiece, etc.

Through the research, the results of which are presented in the present paper, the experimental determination of an empirical mathematical model was aimed at highlighting the intensity of the influence exerted by some input factors in the electrochemical machining process on the magnitude of the *Ra* parameter, used to characterize the surface roughness results of electrochemical machining. The experimental results were processed with the help of specialized software, and a power-type function mathematical model was determined. According to this mathematical model, the most intense influence on the value of the roughness parameter *Ra* is exerted by the voltage between the two electrodes, in second place being the value of the concentration of the electrolyte. A practically insignificant influence seems to be exerted by the size of the gap between the electrodes. In the future, it is intended to continue the experimental research, taking into account other materials for the test samples and other factors capable of influencing the values of the output parameters of the electrochemical machining process.

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