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Influence of Input Factors on Certain Characteristics of the Electrochemical Engraving Process

Ion Surugiu[1]***, Margareta Coteață***[2]***, Laurențiu Slătineanu***[3]***, Adelina Hrițuc***[4]

Abstract: *Electrochemical engraving is a process that allows the making of various inscriptions on the surfaces of parts of electroconductive materials. The removal of material from the workpiece occurs due to chemical reactions developed between the workpiece material and an electrolyte in the presence of a direct electric current. Many factors can affect the values of the output parameters of the electrochemical engraving process. The main groups of factors capable of influencing the output parameters of the electrochemical engraving process are the nature and chemical composition of the workpiece material, the shape and arrangement of the workpiece surface to the cathode, some physical and chemical properties of the electrolyte, the shape and the arrangements of the cathode surfaces, duration of the engraving process, etc. Some functional equipment requirements intended to develop experimental research of the process were first formulated to assess the influence exerted by some of the input factors in the engraving process. A test piece and simple equipment designed to meet the functional requirements under consideration were then considered. A planned factorial experiment was designed to highlight the influence of input factors on characteristics that define the results of electrochemical engraving. Empirical mathematical models were generated by the mathematical processing of the experimental result for the modification during the electrochemical processing of some of the test piece zones. These empirical mathematical models provide information on the intensity of the electrochemical processing in different areas of the test piece. Power-type mathematical functions were used for this purpose. The electrolyte concentration, the intensity of the electric current flowing between the electrodes, and the duration of the processing were taken as independent variables.*

Keywords: *electrochemical engraving, empirical mathematical model, experimental research, input factors, output parameters*

1 INTRODUCTION

Electrochemical machining consists of controlled removal of workpiece material due to electrical charges and mass changes between the electrolyte, tool cathode, and workpiece anode when these components are included in the circuit of a direct electric current source [1, 4, 6, 9, 10].

Electrochemical machining is part of the wider group of nonconventional machining methods. It is considered that in the case of nonconventional machining, the removal of material from the workpiece is done primarily by processes other than plastic deformation, the latter being specific to classical or traditional machining. Nonconventional machining is used when it is not possible or difficult to meet the quality requirements of the part (requirements for surface accuracy and roughness) or, due to the shape or complexity of the surfaces to be machined; it is difficult or even impossible to obtain them by conventional machining methods. In order for electrochemical processing to be used, the workpiece material must be electroconductive.

During electrochemical machining, as a result of the chemical reactions between the electrolyte and the anode material, a chemical compound may appear. The presence of the chemical compound may stop the process of removing material from the workpiece or strongly reduces the intensity of this process. To the removal of the passivating layer thus occurred, there are groups of processes based on natural depassivation (electrochemical polishing, electrochemical pickling, etc.), on forced hydrodynamic depassivation (electrochemical drilling, electrochemical milling, electrochemical turning, etc.), and mechanical abrasion. (electrochemical grinding, electrochemical honing, electrochemical lapping, electrochemical superfinishing, etc.).

Electrochemical engraving can be included in processes that use natural depassivation, but there may also be electrochemical engraving processes based on forced hydrodynamic depassivation.

In principle, different inscriptions or drawings can be transferred by electrochemical engraving on the surfaces of workpieces made of electroconductive materials. Those areas of the workpiece which are not to be affected by the action of the electrolyte are usually protected by substances resistant to the erosive action of the electrolyte.

Some results published in recent decades in connection with electrochemical etching have highlighted the researchers' concerns to expand the applications of electrochemical etching, improve the equipment used for this purpose, select the values of input factors for optimal process, etc.

Thus, Glebov considered that electrochemical engraving has advantages over chemical engraving [5]. He conducted some experimental research to ensure the diminishing of the etch undercut, appreciating that some ways can be used for this purpose.

Galanin et al. addressed the electrochemical engraving of test pieces made of different steels in neutral salt solutions, with varying the size of the working gap [3]. The aim was to modify the shapes of the cavities made by an electrochemical engraving by taking into account the microstructure of the steels.

In a paper presenting the situation of electrochemical machining in 2018, Ruszaj et al.

signalizes the extension of research on a hybrid engraving process, which uses both the chemical reactions between the electrolyte and the workpiece material, as well as the effects of the electric discharges initiated between the workpiece and the tool electrode [7].

The objective of the research, the results of which are presented in this article, was to obtain more information on the influence of input factors on the values of the output parameters of the electrochemical etching process.

2 INITIAL CONSIDERATION REGARDING THE ELECTROCHEMICAL ENGRAVING PROCESS

In principle, the working scheme used in the case of electrochemical engraving involves connecting the workpiece to the positive pole of a direct current source. At the same time, the cathode will be materialized by a metal electrode found at a certain distance from the workpiece. This distance must not be too short to avoid the risk of electrical discharges, especially when using high voltage values applied to the two electrodes. At the same time, the distance between the electrodes must not be too great so as not to generate large losses of electric energy on the resistance constituted by the electrolyte found between the electrodes.

The surface of the workpiece is covered with a substance resistant to the aggressive action of the electrolyte. The layer of resistant substance will not cover those surfaces where the process of electrochemical erosion must take place. Suppose initially the layer of resistant substance completely covers the surface of the workpiece. Afterwards, it is to be removed material from the surfaces that will be affected by the erosive process using cutting or other processes. In the case of so-called *electrochemical photoengraving*, a layer of photoresist is used, which is subjected to exposure and subsequently treated with a developer, to remove the layer of substance resistant to the action of the electrolyte.

Fig. 1. Results of electrochemical engraving applied to a workpiece obtained by sintering granules of different alloy steels

Electrochemical erosion occurs according to the two laws of electrolysis, formulated almost two hundred years ago by Michael Faraday. By taking into account these two laws and some aspects of a practical nature, a formal relationship is reached [9]:

where v is the speed of the electrochemical erosion process, U - the voltage applied to the electrodes, U_{pol} - the polarization voltage of the electrodes, σ - the electrical conductivity of the electrolyte, V_{sp} - the specific volume of eroded material in the workpiece, and s - the distance between the electrodes, frequently considered as *the size of the working gap*.

The previous relation highlights the fact that for different distances between the working surface of the cathode and the processed surfaces that correspond to the profile to be obtained on the workpiece, it is expected that material removal with different speeds will occur. By taking into account some aspects of a geometric nature and starting from the previous relationship, we arrive at the following relationship corresponding to the variation of the working gap [6, 9]:

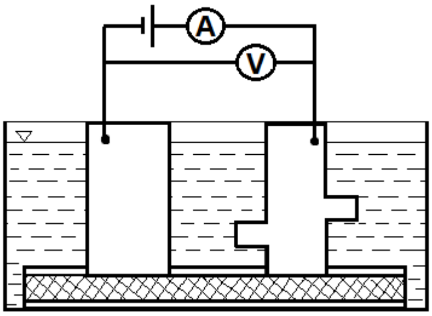
$$s = \frac{\left(U - U_{pol}\right)\sigma V_{sp}}{v_E \, sin\, \alpha + B}, \qquad (2)$$

where v_E is the speed of the working movement performed by one of the electrodes moving relative to the other electrode, α - the angle formed by the normal to the profile of the processed surface and the direction of the working movement, and B is a constant [6].

Figure 1 shows the appearance of a surface made by an electrochemical engraving by one of the authors of this article on a workpiece obtained by sintering a mass of granules from different alloy steels.

Starting from the information accumulated in this way, the problem of conducting more detailed research was formulated to highlight the influence exerted by various factors on the output parameters of the electrochemical engraving process. In this sense, the machining scheme that can be observed in figure 2 was designed.

The use of a cathode made of a material resistant to the action of the electrolyte and having a parallelepiped shape was considered. For the test piece, the aim was to ensure a shape that would allow the evaluation of the extent to which the process of electrochemical erosion occurs at greater or lesser distances to the working surface of the cathode.



(1)

Fig. 2. Proposed processing scheme and simple equipment for the experimental research of the electrochemical engraving process

At the same time, the possibility of analyzing the evolution of the electrochemical erosion process on so-called "shaded" surfaces was considered. The "shaded" surfaces could not be observed directly from the cathode direction. Still, they could reach the electric field lines generated between the two electrodes connected in a direct current source circuit. As a result of these considerations, the shape of the test piece used can be seen in Figure 3.

It can thus be seen that dimensions *a*, *b*, *c*, and *d* can be used to see to what extent those dimensions have been affected by the process of electrochemical erosion by the different distances between the active surface of the cathode and some surfaces of the workpiece parallel to the surface of the active cathode. An image of how the electrochemical process is carried out could also be provided by the dimensions *e* and *f* that define the thicknesses of some components of the workpiece by taking into account surfaces that are not parallel to the active surface of the cathode.

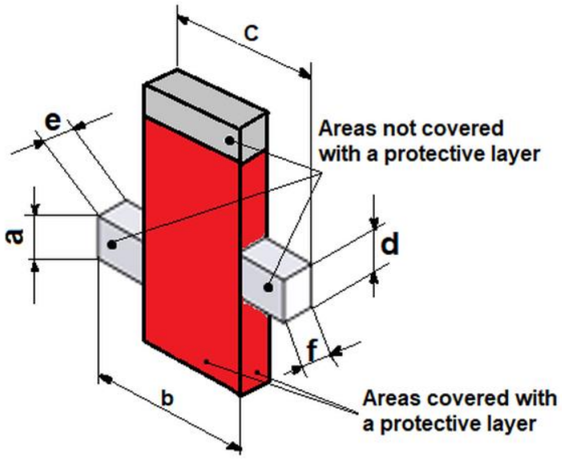


Fig. 3. Dimensions of the test piece prepared for the study of the evolution of the electrochemical erosion process

The loss of mass by the test piece could also be an output parameter of the electrochemical erosion process and the dimensions of the test piece mentioned above.

As the main groups of factors that could influence some output parameters of the electrochemical erosion process, the following could be considered:

- Nature and chemical composition of the test piece material. It is known that the volume of material removed in a certain unit of time and for a certain intensity of the electric current is dependent on the nature and chemical composition of the workpiece material, constituting the so-called *specific volume* V_{sp};

- The shape and arrangement of the surfaces of the test piece that are not covered by the electrolyte-resistant substance and on which an electrochemical etching process may occur. The shape elements of the test piece profile will also be involved in defining the size of the working gap *s*, taking into account the variation of the size of the working gap not only due to the actual distance between the cathode and the anode;

- Some physical and chemical properties of the interstitial electrolyte. As can be seen from relation (1), the material removal rate of electrochemical erosion is directly proportional to the electrical conductivity of the electrolyte, and this can vary in relation to the electrolyte concentration, the working temperature, the degree of impurity of the electrolyte, etc. The operating temperature of the electrolyte can also change due to the behavior of the electrolyte as an electrical resistance that will cause the generation of a certain amount of heat. The viscosity of the electrolyte can also become important, exerting an influence on the electrolyte's ability to penetrate into narrow spaces and respectively to be able to be recirculated, by bringing a less impure electrolyte into the working gap;

- The shape and arrangement of the active surfaces of the cathode. A certain direction of the electric field lines between the cathode and the anode can be strongly influenced by the shape and arrangement of the active surfaces of the cathode. It is accepted that the higher the density of the electric field lines that reach the uncovered surfaces of the test piece, the more intense the removal of the workpiece material will be;

- Duration of the test piece material removing process. It is expected that the intensity of the electrochemical erosion process will be higher at the beginning. If a depassivation method is not used (for example, by shaking the electrolyte in the tank in which the electrochemical erosion process takes place), the accumulation of the erosion process products may lead to the gradual appearance of a passivating layer, which will contribute to a gradual reduction in the productivity of the workpiece material removal process.

Considering that the above are hypotheses about how electrochemical engraving in particular or the process of electrochemical erosion in general, the possibility of verifying at least partial initial considerations was considered by designing and materializing experimental research.

3. FUNTIONAL REQUIREMENTS FOR SIMPLE ELECTROCHEMICAL PROCESSING EQUIPMENT

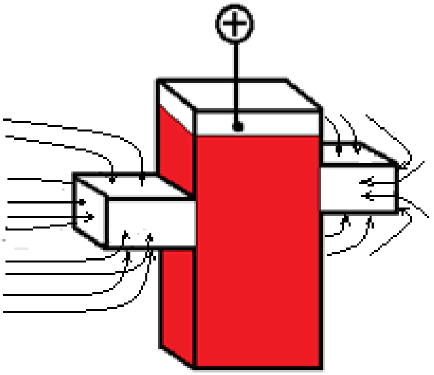


Fig. 4. The way in which the electric field lines reach the test tube and determine the removal of material by electrochemical erosion

Based on the above, the problem of designing simple electrochemical processing equipment was formulated. The principles of using the first axiom in axiomatic design have been considered in formulating the requirements that this equipment must meet [8, 11].

We remind that according to this first axiom, the functional requirements of an object or process whose design is required must be independent. Following the functional requirements, the alternatives for materializing each of the requirements will be established later. Ensuring the independence of functional requirements could allow any of the design parameters to be changed without affecting the validity of other design parameters in any way.

The zero-order functional requirement can thus be formulated first:

*FR*0: design electrochemical erosion processing equipment that is simple enough and provides conditions for detecting the influence exerted by some of the input factors in the electrochemical erosion process on some of the output parameters of the process.

As functional requirements of the first order, the following could be considered:

*FR*1: ensure the existence of adequate space for the development of an electrochemical engraving/erosion process with natural depassivation;

*FR*2: ensure the existence of a direct current source with the possibility of voltage change and strong enough to allow a process of electrochemical erosion processing;

*FR*3: ensure the existence of a cathode part that can be connected to the direct current source;

*FR*4: ensure the existence of a test piece of a shape suitable for carrying out experimental research and which can be connected in the circuit of a direct current source;

*FR*5: ensure the presence of devices that allow the location and clamping of the cathode and the test piece at different distances from each other;

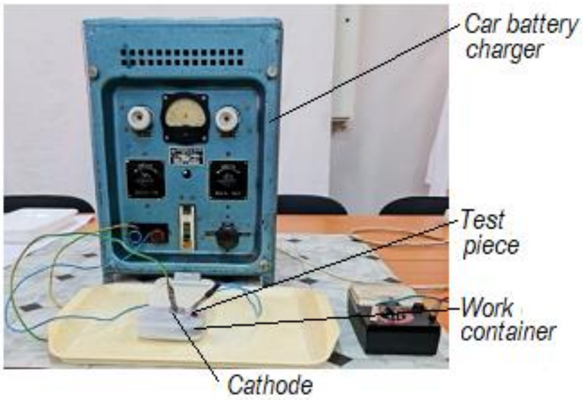


Fig. 5. View of the equipment used for experimental research on some aspects of electrochemical engraving

*FR*6: provide possibilities for electrolytes with different chemical compositions and concentrations.

Concerning these functional requirements and by analyzing, the different alternatives for their materialization (as design parameters *DP*, according to the requirements of axiomatic design), equipment corresponding to the machining scheme in Figure 2 has been designed and whose aspect can be observed in figure 5.

4. EXPERIMENTAL CONDITIONS

It can be seen that the analysis highlights a large number of factors capable of influencing the values of the output parameters of the electrochemical erosion processing. In the experimental research, only three of the input factors were taken into account, namely, the concentration c [%,] of the electrolyte, the intensity of the electric current i [A] passing through the electrolyte, and the duration t (min) of the process of electrochemical erosion. The dimensions a, d, e, and f of the test piece (Figure 3) were considered output parameters from the investigated process. They have distinct values before and after the application of electrochemical processing. It was estimated that there could be a monotonous variation of the values of the output parameters to the variation of the input factors sizes.

In this way, it became possible to use monotonous functions as empirical models, such as, for example, the first-degree polynomial, the exponential function, the power type function, etc.

Power-type functions are frequently used in machine manufacturing (for example, in assessing the influence of input factors on the size of the cutting force components, the size of the roughness parameter *Ra*, the cutting tool life, etc.). and in the case of the present experimental research the power-type functions were preferred.

To reduce the number of experimental tests, the experimental planning method was used, i.e., a planned full factorial experiment of type *L*8 was used, with three independent variables at two levels of variation [8]. According to the principles of using this type of fully planned factorial experiment, $2^3 = 8$ experimental tests will be required. As such, two levels of concentration ($c_{min} = 10\%$, $c_{max} = 20\%$), intensity ($i_{min} = 1$ A, $i_{max} = 2$ A) and duration of the electrochemical erosion process ($t_{min} = 5$ min, $t_{max} = 10$ min) were taken into account. The values of the input factors mentioned above were established starting, in principle, from the values recommended in the literature. The minimum s_{min} distance between the two electrodes was 5 mm in all 8 experimental tests.

As a source of direct current, the equipment used to charge car batteries has been considered. It can provide working voltages up to 48 V. As this equipment has a stepped voltage adjustment, and the intensity of the electric current is dependent of the voltage applied to the two electrodes and the electrical resistance of the components involved in the electrochemical erosion process, it was found that the values initially proposed for the electric current cannot be used. This does not constitute an impediment since, in the case of using the least-squares method to determine an empirical

Table 1. Experimental conditions and results

Exp. no.	Input factors, coded value/real value			Output parameters			
	c, %	*i*, A	*t*, min	*Δa*, mm	*Δd*, mm	*Δe*, mm	*Δf*, mm
1	1/10	1/1.0	1/5	0.12	0.10	0.14	0.02
2	2/20	1/1.3	1/5	0.44	0.07	0.37	0.17
3	1/10	2/2.0	1/5	0.07	0.27	0.16	0.15
4	2/20	2/2.9	1/5	0.40	0.16	0.26	0.31
5	1/10	1/1.0	2/10	0.38	0.09	0.35	0.04
6	2/20	1/1.0	2/10	0.37	0.15	0.56	0.09
7	1/10	2/2.0	2/10	0.45	0.39	0.81	0.36
8	2/20	2/2.9	2/10	1.0	0.20	1.11	0.55

mathematical model, it is not necessary to use strictly specified values of the input factors in the investigated process.

As an electrolyte, an aqueous solution of sodium chloride with two concentrations was used.

The values of the input factors used in the experimental tests were mentioned in the first columns of Table 1, both in coded form (according to the principles of a planned full factorial experiment) and as real values. In the last columns of table 1, the values of some dimensions that characterized the processed surfaces were entered (Fig. 3). These linear dimensions were measured using a digital caliper.

5. PROCESSING OF EXPERIMENTAL RESULTS

The experimental results were processed using specialized software based on the use of the least-squares method [2]. This software allows the identification of five categories of empirical mathematical models (first- and second-degree polynomial functions, power type function, exponential function, hyperbolic function).

The selection of the most appropriate mathematical model from the five available can be made using Gauss's criteria. In our case, as mentioned, it was preferred to use a mathematical model of the power type function. The value of the Gauss's criterion also provides an image of the extent to which the empirical mathematical model adopted is appropriate to the set of values experimentally determined for the output parameter used.

Through the mathematical processing of the experimental results, the following empirical mathematical models of power function type were identified:

- For the size of *a*:

the value of Gauss's criterion being S_G=0.02439823;

- For the size of *d*:

the value of Gauss's criterion being S_G=0.002667467;

- For the size of *e*:

the value of Gauss's criterion being S_G=0.01681628;

- For the size of *f*:

$$\Delta f = 0.00169 c^{0.763} i^{1.972} t^{0.729}, \quad (6)$$

$$\Delta a = 0.000637 c^{1.260} i^{0.317} t^{1.384}, \quad (3)$$

$$\Delta d = 0.0855 c^{-0{,}560} i^{1.204} t^{0.813}, \quad (4)$$

$$\Delta e = 0.00222 c^{0.655} i^{0.422} t^{1.628}, \quad (5)$$

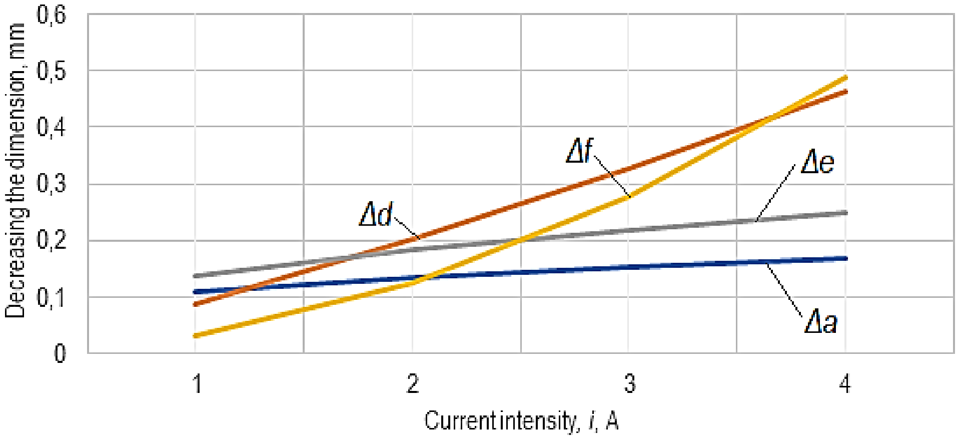


Fig. 6. Influence of the intensity of the electric current i on the decrease of the dimensions a, d, e and f (c = 10%, t = 10 min)

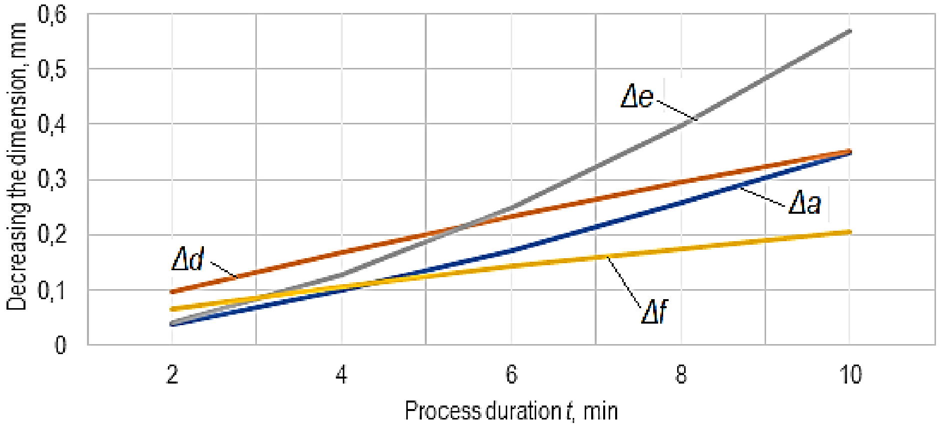


Fig. 7. Influence of the process duration t on the decrease of the dimensions a, d, e and f (c = 10%, i = 2 A)

the value of Gauss's criterion is S_G=0.01342071.

Starting from the determined empirical mathematical models, the graphical representations from figures 6 and 7 were elaborated.

The analysis of the mathematical models and the graphic representations elaborated on their basis allowed some observations regarding the investigated process. Some of these observations are presented below.

Except for the mathematical model established for dimension *d*, the values of the exponents attached to the input factors are positive in all other cases. This confirms the expectation that the increase of the concentration *c* (at least between certain values), of the intensity *i* of the electric current and of the duration *t* of the electrochemical erosion process determines a more intense removal of material from the test piece and, therefore a more pronounced decrease of the considered dimensions.

At the same time, it cannot be said that a certain input factor exerts the greatest influence. For example, in the mathematical model corresponding to the variation of dimension *a*, the strongest influence is exerted by the duration *t* of the process (which is assigned the highest value of the exponent in the empirical mathematical model), while in the case of dimension *d*, the influence higher seems to be exerted by the intensity *i* of the electric current.

A possible explanation for this situation could take into account the measurement errors generated, for example, by the fact that the resulting surfaces were no longer parallel to the initial surface position after processing, but they showed a certain inclination and a rounding of the thighs, respectively.

At the same time, the negative value of the exponent attached to concentration *c* in the mathematical model valid for dimension *d* may be justified by the fact that for high values of concentration *c*, a certain decrease in material removal rate of the electrochemical erosion process is noticed.

6. CONCLUSIONS

Electrochemical machining is a nonconventional processing method that involves the removal of material from the workpiece as a result of chemical reactions between the workpiece material and the electrolyte under the conditions of connecting the workpiece and the tool electrode in a direct current electrical circuit. The tool electrode and the workpiece are immersed in the electrolyte. Both in the case of electrochemical processing in general and in the case of electrochemical engraving in particular, there are a number of input process factors that influence the values of the output parameters. In the case of research whose results have been presented in this article, it was proposed to develop empirical mathematical models to highlight the influence of electrolyte concentration, electric current intensity, and duration of the processing on dimensions of test pieces used. Based on the experimental results, empirical mathematical models of power type function were determined. In principle, these models show an intensification of the removal of material from the workpiece when increasing the electrolyte concentration, the intensity of the electric current and the duration of the process. In the future, it is intended to identify a form of the test piece that will provide more edifying results on how the values of the process input factors influence the values of the output parameters of the electrochemical machining process. It will also highlight the influence exerted by other input factors on the values of the output parameters of the process.

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Authors addresses

[1]*Ion Surugiu, Ph.D. Student, "Gheorghe Asachi" Technical University of Iași, Blvd. D. Mangeron, 59A, 700050 Iași, Romania, phone 0747368457, e-mail: ion.surugiu@student.tuiasi.ro*

[2]*Margareta Coteață, Associate Professor, "Gheorghe Asachi" Technical University of Iași, Blvd. D. Mangeron, 59A, 700050 Iași, Romania, phone 0752141598, e-mail: mcoteata@tcm.tuiasi.ro*

[3]*Laurențiu Slătineanu, Professor, "Gheorghe Asachi" Technical University of Iași, Blvd. D. Mangeron, 59A, 700050 Iași, Romania, phone 0723718675, e-mail: slati@tcm.tuiasi.ro*

[4]*Adelina Hrițuc, Ph.D. Student, "Gheorghe Asachi" Technical University of Iași, Blvd. D. Mangeron, 59A, 700050 Iași, Romania, phone 0747368457, e-mail: adelina.hrituc@student.tuiasi.ro*

Contact person

[*]*Adelina Hrițuc, Ph.D.Student, "Gheorghe Asachi" Technical University of Iași, Blvd. D. Mangeron, 59A, 700050 Iași, Romania, phone 0747368457, e-mail: adelina.hrituc@student.tuiasi.ro*