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TOOL ELECTRODE WEAR AT OBTAINING EXTERNAL CYLINDRICAL SURFACES BY ELECTRICAL DISCHARGE MACHINING

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Abstract: *The electrical discharge machining is a method that could be applied to obtain cylindrical external surfaces, inclusively by using tube type tool electrodes. To diminish the shape errors due to the presence of the metallic electroconductive particles detached from the two electrodes in the work zone, a machining scheme based on the achieving of the vertical work movement by the workpiece from up to down was preferred. An experimental research in accordance with the requirements of a full factorial experiment with three independent variables at two variation levels was performed. As independent variables, the pulse on time, pulse off time and peak current were considered, while as process output parameters the tool electrode massic and linear wear were determined. Empirical mathematical models were established and they highlighted the stronger influence exerted by the peak current intensity. The correlation coefficient was calculated also for the values obtained by the two distinct ways of evaluating the tool electrode wear.*

Key words: *ram electrical discharge machining, machining scheme, tool electrode wear, massic wear, linear wear, empirical mathematical model, correlation coefficient.*

1. INTRODUCTION

The electrical discharge machining is included in the larger group of nonconventional machining technologies. Essentially, the electrical discharge machining is based on the material removal from the workpiece as a result of the initiating and developing electrical discharges between the closest asperities existing on the active surface of the tool electrode and on the surface to be machined of the workpiece. Both electrodes (tool electrode and workpiece) are connected in a direct current electrical circuit; to increase the electrical discharges energy, in the discharge circuit of the electric pulse generator, capacitors of adequate capacities are included.

The electrical discharges determine the melting and even the vaporizing of the asperities peaks found in contact with the electrical discharge columns; such a material removal is intended to be high in the case of the workpiece material, but small quantities of material are also removed from the tool electrode and this leads to a process of tool electrode wear [2, 6–8].

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As other nonconventional machining technologies, the electrical discharge machining could be applied when the mechanical properties of the workpiece material are high enough and the so-called classical machining methods could not be applied or the shape of the surface to be obtained could not be machined by classical machining method or high difficulties could appear when such machining methods (classical methods) are applied.

If it is necessary to obtain external cylindrical surfaces of small diameters (lower than 10 mm) by electrical discharge machining, essentially two machining schemes could be applied:

a) Using the wire electrical discharge machining, when a wire of small diameter (lower than 0.3 mm) found in a winding process from a wire supply wheel to a wire take up wheel is used; the rectilinear zone of the wire found between the two wheels is used to practically gradually separate a cylindrical part from a plate type workpiece. This machining scheme is able to ensure cylindrical surfaces of high accuracy and low roughness, but it is characterized by a low machining rate and needs a specialized electrical discharge machine or devices adapted on the ram electrical discharge machines;

b) Using tool electrodes that have a cylindrical hole and whose work movement could gradually detach a cylindrical part from the workpiece.

One could mention that there are also other machining schemes by electrodischarge (for example, by using a planetary motion of the tool electrode around the axis of the cylindrical surface to be obtained), but they could need more complicate machine tools or machining devices. As parameters of technological interest specific to the electrical discharge machining, one could mention the material removal rate, tool electrode wear, roughness and the accuracy of the machined surface, thickness of the layer affected by the machining process etc.

Since the tool electrode wear is able to affect the accuracy of the machined surfaces, over the years the researchers developed theoretical and experimental investigations concerning the evolution of the tool electrode wear, to find possibilities of minimization of the consequences of such an unwanted process.

Thus, Flaño et al. took into consideration the influence exerted by the tool electrode wear and gap width on the dimensions of the final workpiece [3]. They proposed a methodology involving the use of some easy-to-put in practice indicators concerning the tool electrode wear and work gap. They developed also an experimental investigation and appreciated that the experimental results confirmed their considerations.

Wang et al. approached the influence exerted by the tool electrode wear on some of the machining process characteristics in the case of micro electrical discharge machining [11]. They notice that when using a tool electrode whose diameter higher than 500 μm, the relative tool electrode wear ratio could be affected by a downward trend, while when the tool electrode diameter is lower than 500 μm, there are difficulties in removing debris and the tool electrode wear increases.

Uhlmann and Domingos took into consideration the possibility to automatically dress the graphite electrode when using the electrical discharge machining [10]. They achieved a full factorial analysis prior to the integration of the dressing technology and thus they determined the optimal values of the electrical parameters. The application of this technology was investigated in the case of obtaining seal slots in turbine components.

Mathai et al. studied the tool electrode end wear and the wear ratio in the case of planetary electrical discharge machining of test samples made of the titanium alloy Ti-6Al-4V [5]. They considered that the pulse on time and the tool electrode polarity are the most important factors that influence the tool electrode wear process.

Klocke et al. noticed that the use of the graphite tool electrodes could ensure a high material removal rate and a low tool wear [4]. They experimentally examined the behavior of some kinds of graphite, determining their optimal conditions for developing the electrical discharge machining process. They appreciated that the discharge current is the main influence factor able to affect both the material removal rate and the tool electrode wear.

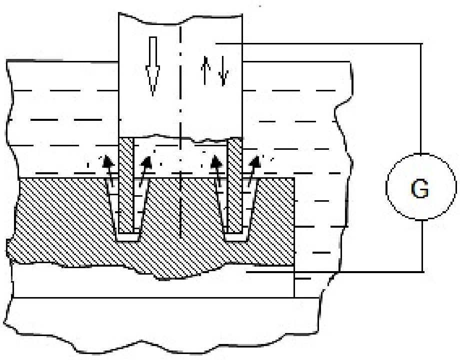
The objective of the research presented in this paper was to obtain adequate information concerning the evolution of the wearing process when a certain electrical discharge machining scheme is applied and which could be the factors able to affect the tool electrode wearing process.

2. SELECTED MACHINING SCHEME

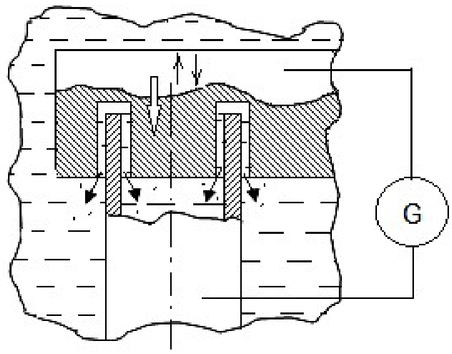
The approached problem was initially to establish a way of detaching a cylindrical test piece with a diameter of about 6 mm from a part made of a metallic material characterized by a high heat resistance. The idea was to use a tube type tool electrode attached to the work head of the ram electrical discharge machine so that as a consequence of using the common up to down vertical work movement, the desired cylindrical test piece is separated from the workpiece placed in a vice on the machine tool table (Fig. 1,*a*). After applying such a machining scheme of electrical discharge machining, one noticed high shape errors from the cylindricity of the machined surface.

These machining errors could be justified by the spurious electrical discharges generated by means of the electroconductive metallic particles detached by the electrical discharges from the two electrodes. The electroconductive metallic particles are difficulty removed from the machining zone and the spurious electrical discharges develop along trajectories including the tool electrode, the electroconductive particles and the workpiece. One could mention that additional vibration motions of low frequency and amplitude are usually applied during the electrical discharge machining process to facilitate the removal of the used dielectric liquid found in the machining zone (usually immersed in the dielectric liquid).

To diminish the shape errors generated by the above-presented machining scheme, the idea of placing the tube type tool electrode in a vice found on the machine tool table and the workpiece on the machine tool work head was tested (Fig. 1,*b*). One noticed a significant diminish-



a



b

Fig. 1. Machining schemes applied to obtain cylindrical test pieces from a plate type workpiece on a ram electrical discharge machining: *a* – vertical work movement from up to down achieved by tool electrode; *b* – vertical work movement from up to down achieved by the workpiece [6].

ing of the shape errors in this case, due to the easy removal of the electroconductive particles detached from the two electrodes just under the action of their gravity force. In this way, the electroconductive particles remain for a shorter period in the machining zone and are able to generate fewer spurious electrical discharges.

It is expected that many groups of factors could exert influence on the tool electrode wear. Thus, one could take into consideration the shape and the dimensions of the surface to be obtained, the machining scheme, the tool electrode shape, the chemical composition of the workpiece and tool electrode materials, the type and the characteristics of the dielectric liquid, the way of dielectric liquid circulation, the pulse characteristics etc. [6].

In order to develop an experimental investigation, one took into consideration only three process input factors: the pulse time t_p, the pulse off time t_b and the pulse peak current intensity I_p. In accordance with the results obtained previously by other researchers, one noticed that the influence exerted by the pulse on time and pulse off time on the material removal rate presents usually maximums. On the other hand, when the peak current intensity increases, it is expected an increase of the material removal rate.

One knows that distinct polarities are considered in order to ensure the most convenient values of the output parameters. In such conditions, one could consider that the remarks valid in the case of the material removal rate could remain valid at least in a certain extent also in the case of the tool electrode wear, since the material removal develops also in such a situation.

The tool electrode massic wear W_m could be determined as the difference between the tool electrode mass before and after each experiment:

$$W_m = m_i - m_f, \quad (1)$$

where m_i is the initial mass of the tool electrode and m_f is the final mass of the tool electrode.

A similar relation could be written when evaluating the linear tool electrode wear:

$$W_l = l_i - l_f, \quad (2)$$

l_i being the initial length of the tube type tool electrode and l_f – its final length.

3. EXPERIMENTAL CONDITIONS

In order to develop an experimental research aiming to highlight the influence exerted by the electrical discharge machining process input factors on the tool electrode wear, a Sodick AD3L type electrical discharge machine was used.

Segments of tubes made of copper and that had an external diameter d_{ext} = 6.2 mm, an internal diameter d_{int} = 5 mm and a length $l \approx 45$ mm were taken into consideration as tool electrodes. These tool electrodes were positioned and clamped in chucks placed in a vice found on the machine tool table.

The test pieces were parallelipipedic parts made of the hardened high speed steel HSS 18-1-1-0 (chemical composition: 0.659 % carbon, 17.7 % tungsten, 4.04 chromium, 1.19 % vanadium, 1.28 % molybdenum, 0.158 % nickel). The test pieces were positioned and clamped in an Erowa type device, usually used for clamping the tool electrodes.

The tool electrodes were weighted before and after each experiment by means of a type Partner Radwag AS20 analytical balance. Their lengths were also measured by means of a digital caliper.

To ensure the possibility of processing the experimental results and a certain accuracy of this action, one proposed and applied the requirements specific to a full factorial programmed experiment with three independent variables at two levels of variation. As the independent variables (process input factors), the pulse on time t_p [µs], pulse off time t_b [µs] and the value of the peak current I_p [A] were considered.

One opted only for two levels of process input factor variation considering that for the investigated experimental interval, the output parameter (output variable, tool electrode wear) will have a monotone variation when changing the values of the process input factors. As proper values of the process input factors, the followings were used: $t_{p\ min}$ = 110 µs, $t_{p\ max}$ = 140 µs, $t_{b\ min}$ = 30 µs, $t_{b\ max}$ = 40 µs, $I_{p\ min}$ = 15.3 A, $I_{p\ max}$=19.2 A.

The initial values of the process input parameters were established by considering the recommendations formulated by the software of the electrical discharge machine; the other values of these process input parameters were established taking into consideration a difference of about 25 % in comparison with the values recommended by the machine tool software.

For each experiment, a depth of penetration of 9.5 mm was considered, by taking into consideration the workpiece thickness (10 mm). The duration of each experiment was inscribed in the column no. 11 from Table 1.

The values of the process input factors and output parameters were included in the columns nos. 2, 3 and 4 from table 1, while the results of distinct measurements were mentioned in the columns nos. 5, 6, 8 and 9. Three measurements were made in the case of each experiment and only the average value was inscribed in the columns no. 7 and 10 from the Table 1.

There are various ways of evaluating the tool electrode wear. For example, such a way could take into consideration the quantity of material removed from tool electrode as a consequence of the electrical discharges. In other situations, the diminishing of certain tool electrode dimensions (also as a consequence of the electrical discharges) could be used as an indicator of the tool electrode wear.

Sometimes, relative values are considered as more adequate to estimate the evolution of the tool electrode wear. For example, one could take into consideration the ratio of the tool electrode wear to the quantity of material removed from the workpiece or the ratio of the tool electrode massic or linear wear to the experiment duration.

Table 1

Experimental conditions and results

Column no. 1	Values of the process input factors			Values of the process output parameters						
				Tool electrode massic wear			Tool electrode linear wear			Machining process duration, min
	Pulse on time t_p, µs	Pulse of time t_b, µs	Peak current, I, A	Tool electrode mass before experiment, m_i, g	Tool electrode mass after experiment, m_f, g	Diminishing of the tool electrode mass W_m, g	Length of tool electrode before exeperiment, l_i, mm	Length of tool electrode after experiment, l_f, mm	Diminishing of tool electrode length, W_l, mm	
Column no. 1	2	3	4	5	6	7	8	9	10	11
1	110	30	15.3	4.5310	4.5262	0.0048	44.89	44.80	0.09	66
2	140	40	15.3	4.7050	4.6988	0.0061	45.45	45.39	0.06	110.44
3	140	30	19.3	4.6234	4.6190	0.0044	46.27	46.15	0.12	49.54
4	110	40	19.3	4.6473	4.6360	0.0113	45.07	44.96	0.12	36.31
5	110	30	19.3	4.5246	4.5133	0.0113	44.81	44.69	0.12	27.26
6	110	40	15.3	4.6982	4.6933	0.0050	45.40	45.33	0.07	59.26
7	140	30	15.3	4.6174	4.6102	0.0072	46.11	46.04	0.07	112.02
8	140	40	19.3	4.6360	4.6283	0.0077	46.91	44.81	2.10	47.19

4. ANALYSIS OF THE EXPERIMENTAL RESULTS

The experimental results presented in Table 1 were mathematically processed by means of a specialized software based on the method of least squares [1]. The software allows association to the experimental results of five types of empirical mathematical models (polynomial of first and second degree, power, exponential and hyperbolic type functions.

The selection of the adequate empirical mathematical mode could be made by considering the so-called Gauss's criterion. This criterion takes into consideration the sum of the squares of the differences of the function values estimated by means of the proposed empirical mathematical model and the experimental results. The lower the sum is, the adequate is a certain empirical mathematical model.

However, in the machine manufacturing process, frequently the power type empirical models are preferred, due to the fact that they offer a direct image about the influence exerted by the independent variables on the dependent variable, the last being represented in this case by the process output parameters.

By means of the above mentioned software, the following mathematical models were determined;

- In the case of tool electrode massic wear:

$$W_m = 0.0008723 t_p^{-0.748} t_b^{0.377} I_p^{1.520}, \quad (3)$$

  in this case the Gauss's criterion having the value $S_G = 4.700901 \cdot 10^{-6}$;
- In the case of the tool electrode linear wear, the examination of the values included in the column no. 10 from table 1 showed that the value corresponding to the last experiment (no. 8) is very different from the other values of the set: for this reason, one removed this value when determining the empirical mathematical model and used only the other 7 values. In this way, the following power type empirical mathematical model was determined:

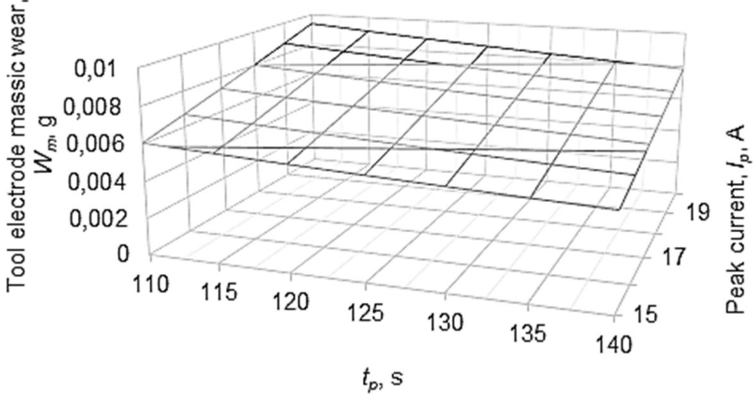


Fig. 2. Influence exerted by the pulse on time t_p and peak current intensity I_p on the tool electrode massic wear (pulse off time t_b = 35 µs).

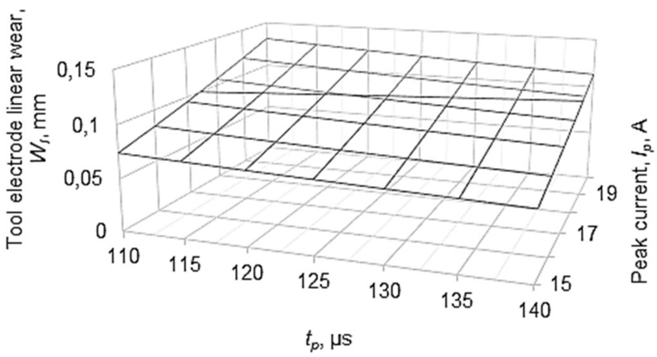


Fig. 3. Influence exerted by the pulse on time tp and peak current intensity I_p on the tool electrode linear wear (pulse off time $t_b = 35$ µs).

$$W_l = 0.0418 t_p^{-0.630} t_b^{-0.528} I_p^{1.998}, \quad (4)$$

for which the Gauss's criterion has the value $S_G = 5.697642 \cdot 10^{-5}$.

On the base of the mathematical relations (3) and (4), the graphical representations from Figs. 2 and 3 were elaborated; one took into consideration the factors that have the maximum influence on the tool electrode wear, namely the pulse on time t_p and the peak current intensity I_p, respectively.

The analysis of the mathematical relations (3) and (4) shows that the maximum influence is exerted on both the tool electrode massic and linear wear by the peak current intensity, since in the both relations the exponent attached to the I_p size has the maximum value compared with the values of the exponents attached to the pulse on time t_p and pulse off time t_b. On the second place, in the both mathematical relations, the pulse on time t_p could be considered, if the absolute values of the exponents are evaluated.

One notices also that if the increase of peak current intensity determines an increase of the tool electrode massic and linear wear, the increase of the pulse of time has as a result a diminishing of the tool electrode wear, since the exponents attached to the size t_p have a negative value in the both cases.

A contradiction could be noticed if one examines the signs of the exponents attached to the pulse off time t_b; one observes that the exponent has a positive value in the case of the tool electrode massic wear and a negative value in the case of tool electrode linear wear. This situation could be partially explained by the distinct evolution of the tool electrode wear in the two situation. Thus, one notice that when measuring the length of the tool electrode after the experiment, one does not take into consideration the existence of the tool electrode lateral wear, which however affects the integrity of the tool electrode and without being considered when measuring only the length of the worn tool electrode (Fig. 2).

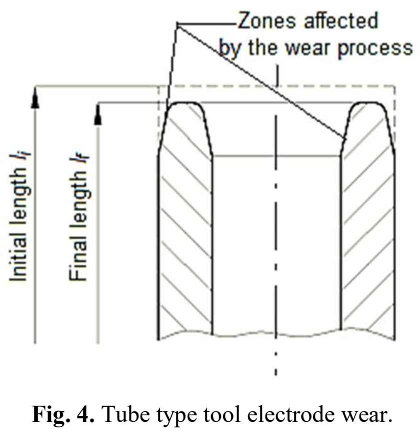


Fig. 4. Tube type tool electrode wear.

Another aspect that could be taken into consideration when analyzing the two distinct ways of tool electrode wear evaluation could be the possible correlation between the set of experimental results corresponding to the measurement of the tool electrode massic and linear wear. It is expected that since the same process (wear process) is taken into consideration in the both situation, certain correlation could exist.

In order to evaluate the correlation between two sets of experimental results, usually the so-called Pearson's coefficient could be used [9]:

$$r_{xy} = \frac{n\sum x_i y_i - \sum x_i \sum y_i}{\sqrt{n\sum x_i^2 - \left(\sum x_i\right)^2}\sqrt{n\sum y_i^2 - \left(\sum y_i\right)^2}}, \quad (5)$$

where n is the number of measurements included in each of the two series of measured values x_i and y_i and $i = 1, 2, \ldots, n$.

One accepts that a good correlation exists when the values of the Pearson's coefficient are close to the values +1 or −1. The higher the difference between these values and the Pearson's coefficient is, one could appreciate that the lower the correlation is.

The values of the Pearson's coefficient when considering the set of the experimental results corresponding to the tool electrode massic and linear wear could be determined by means of the function COREL from the software Excel; in this way, one could notice that $r_{xy} = 0.498$.

Additionally, the values of the Pearson's coefficient were calculated taken into consideration the above mentioned process results (massic wear and linear wear) and the experiments durations, included in the column no. 11 from Table 1. One noticed that this coefficient has the value $r_{xy} = -0.446$ when the values of the tool electrode massic wear and the experiments durations are considered and $r_{xy} = -0.858$ when the values of the tool electrode linear wear and the experiments durations were taken into consideration. One could conclude that a good

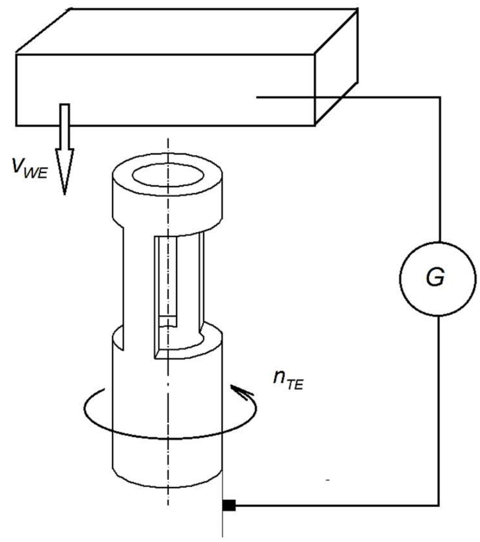


Fig. 5. Machining scheme proposed to improve the tool electrode behavior when consider its wear.

correlation exists between the tool electrode linear wear and the machining processes durations.

One could consider that the proposed machining scheme (based on the performing the work movements by the workpiece from up to down to the tool electrode placed on the machine tool table could contribute to the increase of the machining accuracy by diminishing of the period when the debris find in the machining zone. Another increase of the machining accuracy could be obtained by the use of a rotating tool electrode with an adequate rotation speed n_{TE} (Fig. 5), to avoid the copying of the tool electrode shape errors by the machined surface. In this case, the both electrodes are connected in the circuit of the pulse generator *G* and the workpiece will achieve the linear work movement v_{WE}.

One appreciates that the presence of the zones where there are some slots in the tube type tool electrode could contribute to the diminishing of the number of the spurious electrical discharges and, in this way, to the increase of the machining accuracy.

5. CONCLUSIONS

The electrical discharge machining is a machining method that could be applied to obtain cylindrical external surfaces using tube type tool electrodes. The performing of some preliminary experiments showed that a diminishing of the shape errors is possible by using a machining scheme in which the workpiece performs the work vertical movement from up to down to the tube type tool electrode placed on the machine tool table. To investigate the evolution of the tool electrode wear process in such a situation, a full factorial experiment with three independent variables at two variation levels was used. As process input factors, one considered the pulse on time, the pulse of time and the peak current intensity. The process output parameters were the tool electrode massic wear and the linear wear, respectively. The experimental results were mathematically processed by means of a specialized software and power type empirical mathematical relations were determined. One noticed that the maximum influence is exerted by the peak current intensity and the second influence factor is the pulse on time. To diminish the shape errors of the machined surface and when there is a low tool electrode wear, a rotating tube type tool electrode that have some slots could be used. In the future, there is the intention to build and experiment such a type of tool electrode and to extend the experimental research.

REFERENCES

[1] G. Crețu, *Bazele cercetărilor experimentale. Indrumar de laborato*r [Fundamentals of the experimental research. Laboratory handbook], Technical University "Gheorghe Asachi", Iași, 1992.

[2] O. Dodun, L. Slătineanu, M., Coteaţă, *Prelucrări neconvenţionale cu scule materializate. Îndrumar de laborator* [Nonconventional machining with materialized tools], Editura Tehnica – Info, Chişinău, 2005.

[3] O. Flaño, I. Ayesta, B. Izquierdo, J.A. Sánchez, J.M. Ramos, *Experimental study on the influence of electrode geometry and electrode path on wear pattern in EDM*, Procedia CIRP, vol. 68, 2018, pp. 405 – 410.

[4] F. Klocke, M. Schwade, A. Klink, D. Veselovac, *Analysis of material removal rate and electrode wear in sinking EDM roughing strategies using different graphite grades*, Procedia CIRP, Vol. 6, 2013, pp. 163 – 167.

[5] V. J. Mathai, H. K. Dave, and K. P. Desai, *Study on Effect of Process Parameters on End Wear of Tool Electrode during Planetary EDM of Ti-6Al-4V*, International Journal of Materials, Mechanics and Manufacturing, Vol. 5, No. 3, 2017, pp. 159-163.

[6] L. Slătineanu, C. Mircescu, M. Coteaţă, O. Dodun, I. Beşliu, M. Radovanovic, *Characteristics of obtaining external cylindrical surfaces by ram electrodischarge machining*, 2014 International Conference on Production Research - Europe, Africa and Middle East 3rd International Conference on Quality and Innovation in Engineering and Management, July 1-5, 2014, Cluj-Napoca, pp. 457-462.

[7] L. Slătineanu, G. Nagîţ, O. Dodun, M. Coteaţă, F. Chinesta, A. Gonçalves-Coelho, J. Pamies Teixeira, M. San Juan, L. Santo, F. Santos, *Non-traditional manufacturing processes*, Editura Tehnica Info, Chişinău, 2004.

[8] L. Slătineanu, H. P. Schulze, O. Dodun, M. Coteaţă, L. Gherman, *Electrode tool wear at electrical discharge machining,* Key Engineering Materials, Vol. 504, 2012, pp. 1189-1194.

[9] *Statistics How To,* 2018 available at: `http://www.statisticshowto.com/probability-and-statistics/correlation-coefficient-formula/`, accessed: 2018-02-28.

[10] E. Uhlmann, D. C. Domingos, *Automated dressing of graphite electrodes for electrical discharge machining (EDM) of seal slots in turbine components*, Procedia Manufacturing, Vol. 6, 2016, pp. 45 – 52.

[11] K. Wang, Q. Zhang, G. Zhu, Y. Huang, J. Zhang, *Influence of tool size on machining characteristics of micro-EDM*, Procedia CIRP, Vol. 68, 2018, pp. 604–609.