STATISTIC ANALYSIS OF THE EXPERIMENTAL RESULTS OBTAINED AT SINGLE DISCHARGE ELECTROEROSION

Lorelei Gherman[1], Ionuț Palaghia[2], Oana Dodun[1], Laurențiu Slătineanu[1]

[1]"Gheorghe Asachi" Technical University of Iaşi, Department of Machine Manufacturing Technology
Blvd. D. Mangeron, no. 39, code 700050, Iaşi, Romania
[2]"Gheorghe Asachi" Technical University of Iaşi, Faculty of Civil Engineering and Building Services,
Blvd. D. Mangeron, no. 1, code 700050, Iaşi, Romania

Corresponding author: Lorelei Gherman, lo_drey@yahoo.com

Abstract: Electrical discharge machining is widely used when complicated shaped parts are wanted. While machining using electric sparks, the tool could be influenced by the electric effects as well. Machinability-wise, a lower tool wear is desired. But at brass electroerosion by single discharge machining, problems occur when tool electrodes made of copper are used. By performing tests under the same working conditions, the discharge craters of the workpiece can be measured and productivity can be determined. The measurement of the tool wear can illustrate some indicators important for the producer and ways to improve processing parameters. An experimental set-up was designed, using a constant electric capacity of 1000 μF and a single discharge equipment. 50 experiments were conducted under the same processing factors and experimental results were analyzed by means of statistical analysis. The results demonstrate the electric energy influence on the overall material removal rate.

Key words: single electrical discharge, systemic analysis, control chart, statistic analysis, histogram.

1. INTRODUCTION

Nonconventional methods of materials processing are used as an alternative to the so-called "traditional" methods of part manufacturing, such as material cutting or plastic deformation. The main principle for the nonconventional methods is material forming or deformation using the processing effect of energy in a range of varieties: ion beam machining (using the energy of the ions), plasma beam machining (with the effect of the thermal energy), laser processing (by means of the energy of photons), electrical discharge machining (using the thermal effect of the electric discharges) etc.

Some specialists classify these technologies in relation with the phenomena developing during processing: electrical discharge technologies, ultrasonic are technologies, beam technologies (plasma, laser, electrons), chemical and electro-chemical technologies (or other hybrid technologies, which are combinations of two or more processing types). Such manufacturing methods are mainly based on *the mechanical, electrical* and *chemical* phenomena (based on the type of energy).

The nonconventional or non-traditional methods of processing can be classified by the tool materialization criterion: technologies with materialized tools (such as electrochemical or electrical discharge machining) and technologies that use concentrated energies, when the tool is created as fascicles of energy carrying particles which are produced in the shape beams (laser, plasma).

If the working environment is taken into consideration, the nonconventional methods can be classified in two types: *dry* environment erosion and *liquid* environment erosion.

As a non-traditional manufacturing technology, electrical discharge machining or EDM is a dimensional processing method based on the integrity fracture and material processing by means of electrical discharges (Dodun, 2001). EDM is a practice widely used at machining of complex shaped parts or of difficult to process materials. It provides many benefits considering productivity, surface roughness, tool wear in the case of some materials. It is based on the effects of the electric discharge, which can be *magnetic, dielectric, thermal* (heating by the Joule effect).

Electrical discharge machining uses the electric voltage given by a generator, connecting a tool electrode and the workpiece material at the positive and the negative pole of a direct current generator. At a certain distance between tool and test piece material, an electric spark occurs. The effects are of vaporizing the surface level of test piece material, melting the material left under the newly formed crater and producing thermal changes in the nearby layers of workpiece material. The vaporized particles are usually displaced using a dielectric fluid acting as a resistor in the electric scheme. The tool electrode can be made of copper or copper alloys, graphite etc.

EDM provides accurate results regarding the geometry obtained at machine parts, which is highly favourable for the industrial producer. Also, it offers very good results concerning the surface roughness obtained at processing, which is one of the most important quality parameters in manufacturing.

When talking about the processability of a material, certain factors must be taken into consideration. The main objective in a technological research is to improve certain parameters that are characterizing it. A good processability is indicated by a good surface roughness, by a low tool wear, by a high material removal rate (MRR or productivity), by a low energy and supplies consumption etc.

At EDM, the tool wear and mainly MRR are the focus parameters. It was showed (Slătineanu, 2011) in prior researches that electrode tools made of copper have a higher wear when machining workpiece made of copper or copper alloys than when machining aluminium or some carbon steel types. This is a reason to further investigate the interaction between a copper tool electrode and a copper alloy test piece. In order to obtain a good processability, a low tool wear and a high material removal rate are desired. Many researchers have conducted studies on EDM, based on preset types of analysis or design of experiments.

A study of the wire electrical discharge machining process parameters was made in order to obtain the best results concerning machining performance (Mukherjee et al., 2012). The input factors they studied were the electric ones (pulse frequency and duration, wire tension, peak current), the dielectric fluid flow rate and the duty factor. Their approach was to apply six non-traditional methods of statistical analysis, such as the artificial bee colony, biogeography-based optimization or the sheep flock algorithm, in order to achieve improved results. The output factors, the measured data, consisted in surface roughness parameters, material removal rate and cutting width. The analysis consisted in performance optimization by single and then multiple objectives, taking into account the six algorithms. The best individual algorithm proved to be biogeography-based optimization, although enhanced results occurred at the six algorithms combination.

Taguchi method, as a design of experiments (DOE) technique, was used by Sivapirakasam et al. (Sivapirakasam et al., 2012) in the research of the machining factors influence on the breathing zone concentration of the aerosol generated at EDM. Some process factors (pulse time, peak current, flushing pressure) were considered in the study of aerosol components with inductively coupled plasma, mass spectrometry, scanning electron microscopy and X-ray diffraction. A risk analysis and safety measures were made based on the results obtained after testing the metallic and gas components of the aerosol. The best results concerning the processability were achieved at the highest levels of peak current and pulse duration, these two factors being the most influencing. The statistical analysis used the Signal to Noise ratio at three levels of process parameters to determine the optimal EDM factors.

Chen et al. (Chen, 2012) pursued the analysis, prediction and compensation of processing errors at parts with complex geometries manufacturing. A high processability was obtained by means of spatial statistical analysis, based on the measurement values by probe inspection system and their association in a bicubic B-spline surface. The probe dimensions were measured and then processed by regression analysis using a CMM (coordinate measuring machine). The researchers proposed a model of prediction and compensation of errors based on the spatial statistical analysis and verified it by experiments in order to confirm the increased processability results.

The MSPM technique or multi-variate statistical process monitoring was used by researchers (Chen and Sun, 2009). For two case studies, of slurry fed ceramic melter and of an industrial propylene polymerization process, they applied the probabilistic principal component analysis and its combination models. A statistical technique based on a missing variable model was proposed. The contribution analysis used in combination with the first two techniques provided better results concerning the process monitoring.

An experimental analysis on the Monel 400 alloy processing (Selvakumar, 2009) was performed by wire electrical discharge machining with an Electra Supercut 734 series 2000 CNC Wirecut-EDM machine. Some process input factors were considered, such as pulse frequency, peak current, pulse time and test piece thickness. The control parameters were subjected to five different levels and test results were studied with a digital micrometer type Mitutoyo. The output factor determined was the material removal rate. Mathematical and statistical methods were combined in the response surface methodology when the individual and combined input factors were evaluated.

Appreciating that the electric parameter has one of the highest importances in this type of processing, one may consider choosing a certain value for an electric power (capacity, voltage etc.) and maintaining it constant during machining, in order to emphasize the influence of the other parameters on the processability by EDM.

2. MATERIAL REMOVAL RATE AT EDM

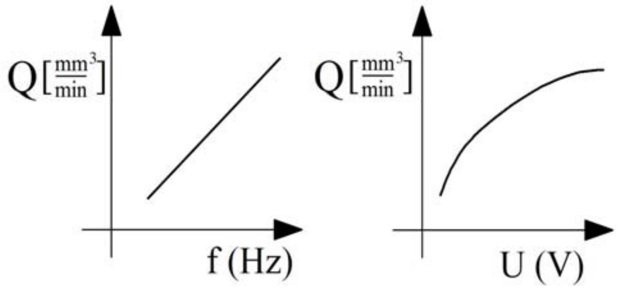
The process productivity Q or the material removal rate MRR is defined as the volume V of material removed during processing in a certain period of time t (Dodun, 2001):

$$Q = \frac{V}{t} \quad \left[mm^3/\min\right] \tag{1}$$

$$V_p = V_{ip} \cdot f_n \cdot t \quad \left[mm^3\right] \tag{2}$$

where V_p stands for volume of material dispatched, V_{ip} is the mean volume of elementary craters and F_n is the frequency of normal impulses.

The influence of the electric pulse and of the electric voltage on the productivity by single discharge is represented in figure 1.



a b

Fig. 1. Graphical representations of the influence on the productivity exerted by: a- pulse frequency; b- voltage (Dodun, 2001)

Some processing factors appear to have a different influence than others on the material removal rate. Also, by their increase, the volume of material may be larger as well. In order to better comprehend the parameters that affect a regular EDM process, a systemic analysis was performed and schematically represented in figure 2.

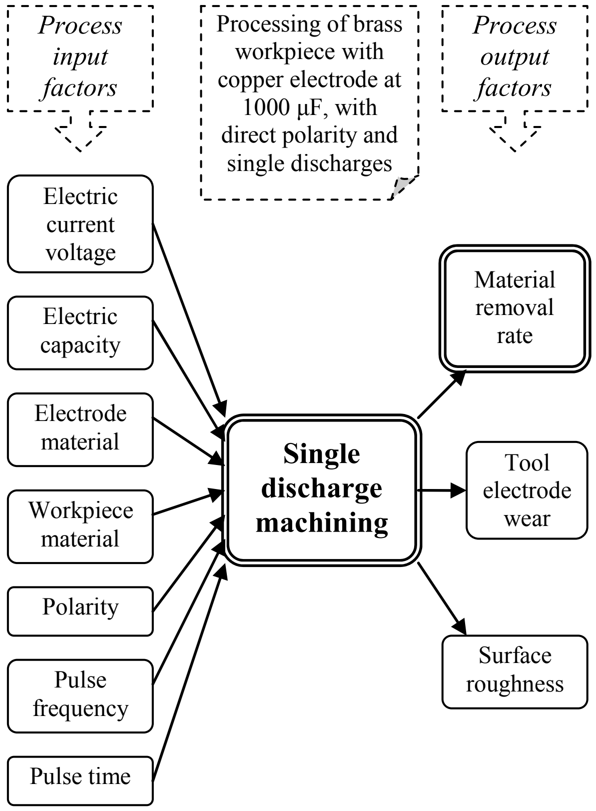


Fig. 2. Systemic analysis of a single EDM process

Some of the input factors represented could be varied in order to determine which values give a higher material removal rate.

On the other hand, MRR can be achieved at EDM if discharge craters would be measured by various means. One would be a mass determination prior and after machining; the mass difference divided by the specific density of the workpiece represents the required MRR value.

Another method would be to measure the discharge crater dimensions: the diameter, the length, the width etc. which are themselves indicators for the materials removal rate, but also offer an image on the volume of material processed. The higher the values obtained for such crater dimensions is, the higher the MRR is.

Since a high productivity is the most desired outcome at mass production, a design of experiments can be applied to the process and some types of statistical analysis can be performed on the results.

3. STATISTICAL ANALYSIS

Statistics is the science that deals with quantitative and qualitative analysis of mass phenomena, based on obtaining necessary data for such analysis from a representative sample.

Statistical analysis is a secure inspection of the data gathered in experimental stages where the processed results are shown as a graphical representation highlighting the best values for easier use and better understanding of the analysed phenomenon. This is why statistical analysis is applied in certain steps, such as obtaining or collecting process values, organizing them, then studying the data and explaining the results (Coman, 2007).

Statistical analysis is widely used in any field of science, research etc. Its main use is to study the gathered data and then to provide a clear visual map of the results from which the most favourable and most disadvantageous values can be easily discovered, thus indicating a precise view of the desired outcomes or future development paths.

By performing statistical analysis on a set of experiments (acting as a model) we can subsequently compare it to the default or optimal results and notice what changes can be done to improve the process, enhance the results, thus obtaining good machinability parameters.

In production, histograms are realised in order to allow the distribution normality inspection of parts obtained at mass production on automatic machine-tools. When the distribution is normal, a large number of factors act on the pursued dimension, but without having a dominant influence from any of them. Potential deviations from the regular form of the distribution might allow recognition of the significant or dominant process factors. On the other hand, the so-called statistical control files (charts) allow the manufacturing control even during the time of processing. It is possible, for example, to track the dimension development in series or mass manufacturing of certain parts categories. Statistical control files permit taking action when the tendency to obtain dimensions outside the limits of the prescribed tolerance field appears. Charts for statistical control are useful in obtaining an image of the dynamic stability of a technological process.

When making frequency diagrams, the procedure is to order the values obtained at dimension measuring so that, by means of the extreme values difference one may acquire the size of the amplitude. Subsequently, a number of intervals is established in order to divide the field scattering by means of specific relations. Knowing the amplitude and the number of intervals, one may determine the limits of each interval. Obtaining a number of dimension values that exist in each interval, a schematic representation such as a histogram can be built, which could offer a first perspective on the normality distribution by comparing it to a graphic representation of the continuous Gauss type distribution (Picoş et al., 1981).

For the statistic control charts, the measured dimensions are written in tables in the exact order in which they were taken from the manufacturing flow and they are used to establish the various types of means. The further step is to apply graphical representations based on such means and formulating conclusions referring to the means fit between the previous calculated limits at a certain confidence level.

3.1 Conditions regarding MRR for the statistical analysis of experimental results

An experimental set-up was designed, proposed and executed. In order to understand the influence of each discharge on the processability indicators, single electrical discharge were considered as machining elements. Many experiments taking place in the same environment, under the same processing parameter values bring a clear perspective on that experiment.

A preset number of 50 experiments were considered to take place under the same machining conditions: a constant electric capacity, the same material sheet for the copper tool electrode and the brass workpiece, on the same single discharge equipment. Such equipment is shown in figure 3.

The copper tool electrode is first fixed with a device between two electrically non-conductive pieces. The tool is moved vertically by means of a device that has both a top-down fine distance movement and the possibility to move on the front plane in order to achieve certain inclination angles for the fixed part. The fixing device is attached to a larger arm, which also offers the option of top-down movement.

The workpiece material can be fixed in a chuck placed on the equipment table. The table can move horizontally in two perpendicular directions, in order to move the test piece under the tool electrode.

An electric generator provides the electric power that materializes the electrical discharges. This particular generator provides the alternative of 8 different electric capacities by means of using 8 capacitors; the one used was of 1000 μF.

The electric generator is connected to the tool electrode and to the test piece by means of using two fasteners. The fastener linked to the tool is the one corresponding to the positive pole and the one linked to the workpiece corresponds to the negative pole.

The outcome factor pursued was the material removal rate, for which determinations of the diameter, the crater length and width were made.

The electric voltage was measured before and after each experiment, because after each discharge a

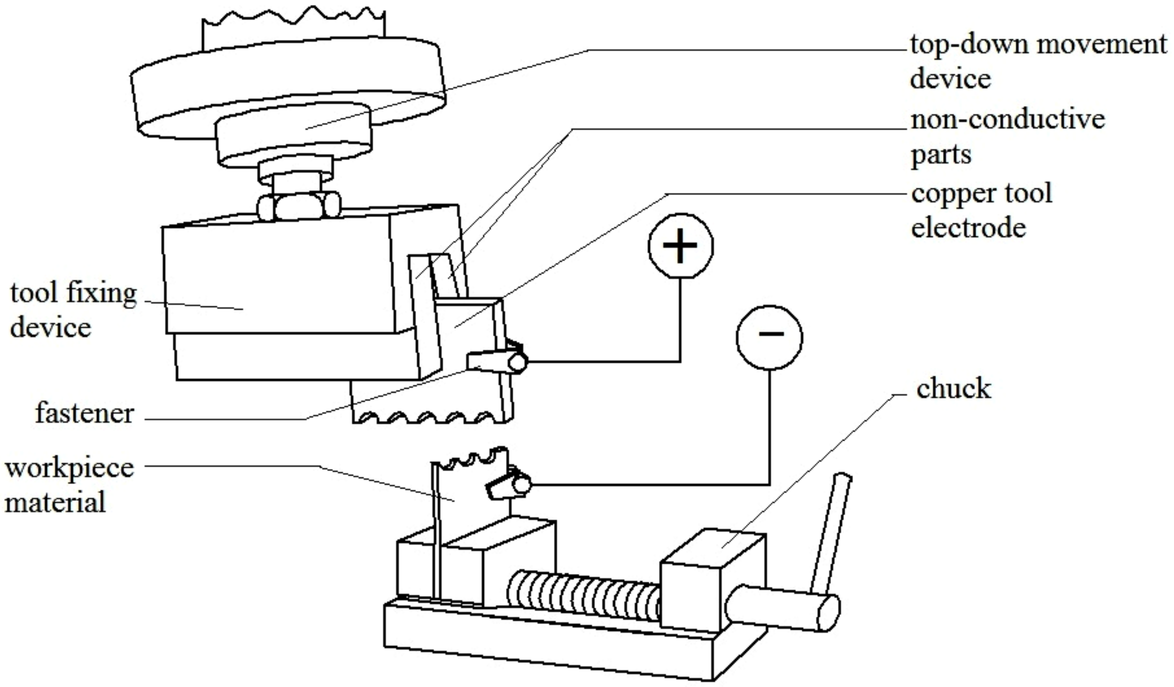


Fig. 3. Single discharge equipment

certain amount of energy still remains in the electric circuit. Based on Equation 3, one can obtain the electric energy W value and relate it to the crater dimensions that were obtained at each of the 50 trials.

$$W = \frac{1}{2}(U_i^2 - U_f^2)C \qquad (3)$$

where U_i is the initial voltage, U_f is the voltage measured after the electrical discharge and C is the electric capacity set from the generator.

With higher energies, it is expected that the dimensions would increase as well.

DOE or design of experiments stands for controlled testing with certain variables of various chemical formulas, structures, materials, processes etc. DOE is used to obstruct negative process factors and avoid risks and defects, to reproduce the sample experimental results in good conditions for the producer and randomize the outcome.

4. EXPERIMENTAL RESULTS

The experimental results obtained were the 50 discharge craters occurred on the four margins of the workpiece sheet of 20 x 35 x 0,1 mm^3. The craters obtained were measured by means of a digital microscope and the 50 values for diameter, length and width of the craters were noted down. Also, the electric energy was calculated based on the measurement of the voltage before and after each discharge. The experimental results are shown in table 1.

The variation of the three types of crater dimension and of the electric energy can be studied if a graphical representation of them would be made. In order to connect the electric energy with the crater dimension, the energy could be divided by 1000 so that the same order of units would be used. A chart following the evolution of the four series of values is shown in image 4.

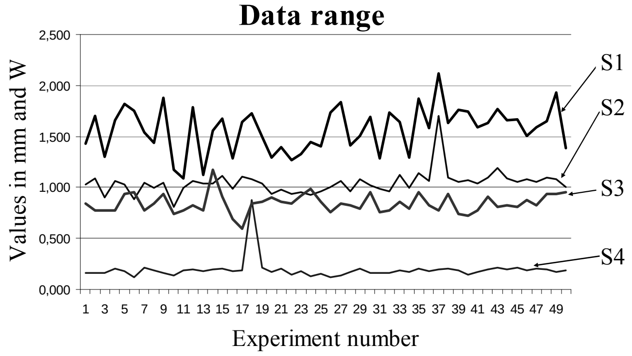


Fig. 4. Comparative image of the factors variation, where *S1* is the diameter, *S2*- length of the crater, *S3*- discharge energy divided by 1000 and *S4*- crater depth

Table 1. Experimental results

No.	Dia-meter, mm	Length, mm	Height, mm	Initial vol-tage U_i, V	Final vol-tage U_f, V	Electric energy W, J
0	*1*	*2*	*3*	*4*	*5*	*6*
1	1,425	1,026	0,159	52	32	840
2	1,702	1,085	0,163	52	34	774
3	1,304	0,901	0,161	52	34	774
4	1,654	1,061	0,200	52	34	774
5	1,821	1,028	0,176	55	34	934,5
6	1,754	0,882	0,122	56	35	955,5
7	1,539	1,049	0,209	52	34	774
8	1,434	0,993	0,185	54	35	845,5
9	1,880	1,045	0,159	55	34	934,5
10	1,171	0,806	0,139	52	35	739,5
11	1,089	0,992	0,190	52	34	774
12	1,784	1,064	0,192	53	34	826,5
13	1,122	1,034	0,175	52	34	774
14	1,556	1,038	0,199	58	32	1170
15	1,677	1,112	0,203	54	33	913,5
16	1,287	0,984	0,176	51	35	688
17	1,639	1,105	0,184	52	39	591,5
18	1,729	1,079	0,173	54	35	845,5
19	1,495	1,038	0,211	53	33	860
20	1,296	0,939	0,169	55	35	900
21	1,395	0,976	0,201	53	33	860
22	1,270	0,935	0,142	54	35	845,5
23	1,323	0,956	0,175	56	36	920
24	1,447	0,927	0,128	56	34	990
25	1,407	0,965	0,151	53	33	860
26	1,732	1,003	0,119	51	33	756
27	1,836	1,067	0,139	54	35	845,5
28	1,415	0,963	0,168	53	34	826,5
29	1,506	1,077	0,204	53	35	792
30	1,694	1,018	0,160	56	35	955,5
31	1,285	0,986	0,165	53	36	756,5
32	1,731	0,964	0,165	52	34	774
33	1,640	1,122	0,191	53	33	860
34	1,292	0,996	0,172	53	35	792
35	1,868	1,136	0,202	56	35	955,5
36	1,585	1,062	0,181	53	34	826,5
37	2,119	1,070	0,195	52	34	774
38	1,631	1,095	0,200	55	34	934,5
39	1,763	1,055	0,183	54	38	736
40	1,747	1,070	0,141	51	34	722,5
41	1,589	1,041	0,166	52	34	774
42	1,636	1,099	0,197	54	33	913,5
43	1,770	1,188	0,214	54	36	810
44	1,662	1,087	0,192	53	34	826,5
45	1,667	1,058	0,216	54	36	810
46	1,506	1,080	0,191	54	34	880
47	1,586	1,056	0,200	53	34	826,5
48	1,653	1,100	0,198	55	34	934,5
49	1,930	1,082	0,167	55	34	934,5
50	1,390	1,000	0,188	56	35	955,5

One may notice that the discharge energy seems to be constant, and shows a comparable evolution with those corresponding to the diameter, the width and the length development. Some deviations appear on each of the represented series, in *S1* and *S2* at the 38th experiment, in *S3* at the 15th experiment and in *S4* at the 18th experiment. Also, the width series *S4* appears to have the highest abnormality, while the diameter series *S1* has the most alternating aspect.

Based on the results given in table 1, one may apply the control chart of *stability analysis*. The control chart helps detect the abnormalities and the segments of the series where the results indicate errors. This is helpful because, after applying the method, one may eliminate the mistakes from the sample and then use the accurate results. The control chart of the diameter data is given in figure 5 and was designed by means of macros software in Microsoft Office.

The range *R* chart estimates that there are two points outside of the control limits (upper class limit *UCL* and lower class limit *LCL*), namely points no. 37 and no. 38. These will be removed from the series. The dimension *X* chart also indicates that point no. 37 is outside of the control limits and should be removed for better further analysis.

Based on the combination of charts, one may perform an *stability analysis*. Segments from point 19 to 26 and 42 to 49 turned red after the software analysis. That happened to segments from point 3 to 7, from 15 to 33 and from 37 to 38. The *XmR* chart can help evaluate a process when there is one variable. The red areas don't influence the additional statistical analysis, although difficulties may appear at further processing this data.

After removing the two points outside the control limits, *statistical analysis* can be performed by means of verifying the *distribution normality*. A regular set of trials would indicate a symmetrical, Gaussian distribution. This is why a histogram for the diameter values was developed. In order to better reveal the electric energy influence on the diameter values, a histogram for the energy rate was also developed.

When analyzing the histograms, one should take

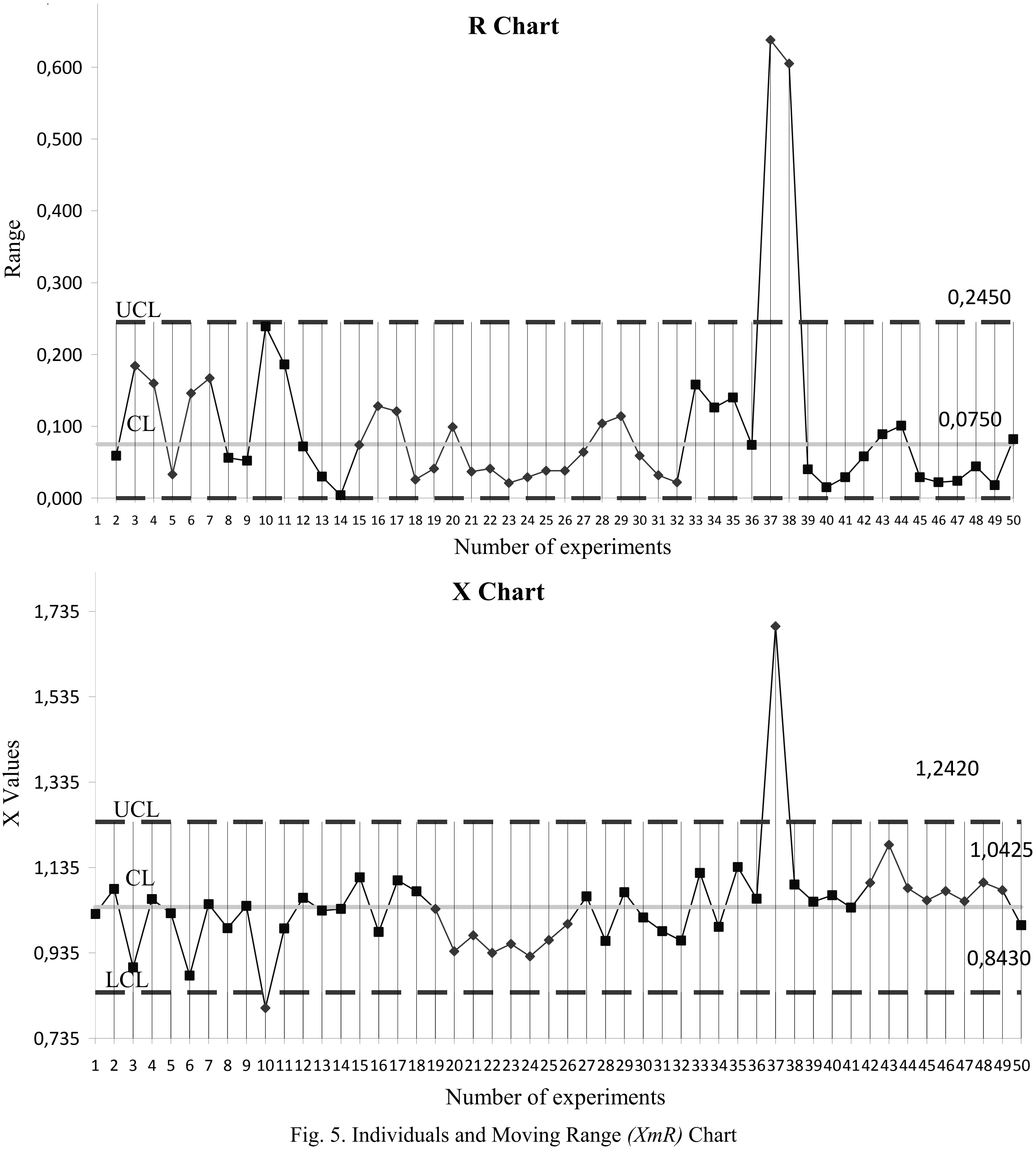


Fig. 5. Individuals and Moving Range *(XmR)* Chart

notice of the factors calculated. The most relevant factor is the *capability index p*. This parameter measures at a what extent the data fits between the classes limits. The larger the value of *p* is, the better the fit between the upper and lower limit is. A process is called a *capable process* if it meets the producer's and the client's requirements at 100%. The class specification limits (upper *USL* and lower *LSL*) indicate the exact requirements of the examined processed data. Also, the data should coincide with these requests and should fit between the limits. If it fits, the process is stable and meets the conditions.

Two indicators are used to evaluate the process capability: *Cp* and *Cpk*. In table 2, the values of *Cp* and *Cpk* are connected to the *Six Sigma* factor.

Table 2. Values for *Cp* and *Cpk*

No.	Value of factors *Cp* and *Cpk*	*Six-Sigma*	Used specific tolerance	Type of result
1	1.0	3 σ	100 %	very good process
2	1.33	4 σ	75 %	good, average process
3	1.66	5 σ	60 %	satisfactory process
4	2.0	6 σ	50 %	process needing of improve

Cp is the capability indicator and it evaluates if the experimental results fit between the upper and lower specification limits. The higher the value of *Cp* is, the better the fit between the limits is. *Cpk* stands for centering capability indicator and it estimates how well the results are centered regarding the *USL* and *LSL*. The higher the value of *Cpk*, the more centered the results appear.

In figure 6, the histogram for the diameter experimental results was plotted and represented using the same Microsoft Office QI Macro. In figure 7, the discharge energy data obtained was used in a histogram. One may notice that they have an almost symmetrical appearance, although both have portions outside the control limits. In table 3 some factor values are presented and are obtained when calculating the histograms.

Table 3. Factors resulting from the histogram analysis

Factor no.	Factor name	Values for diameter histogram	Values for electric power histogram
1.	*Cp*	0.795	0.77
2.	*Cpk*	0.741	0.42
3.	*ZTarget/ΔZ*	0.159	1.10
4.	*Pp*	0.772	0.79
5.	*Ppk*	0.719	0.43
6.	*Skewness*	-0.135	0.54
7.	*ZBench*	2.085	1.24
8.	*% Defects*	0.0%	4.0%
9.	*Sigma*	3.590	3.25

Pp is the performance indicator and *Ppk* is the performance centering factor. Both are used to the standard deviation in estimation of *Six Sigma*. Prescriptions are that *Cp* and *Cpk* should be close in value to *Pp* and *Ppk*, which they are. The *skewness* is a distribution symmetry size around its mean. *Z scores* can approximate the non-conforming parts per million (defects reported to %). *ZBench* is the Z score for the expected parts per million and one may

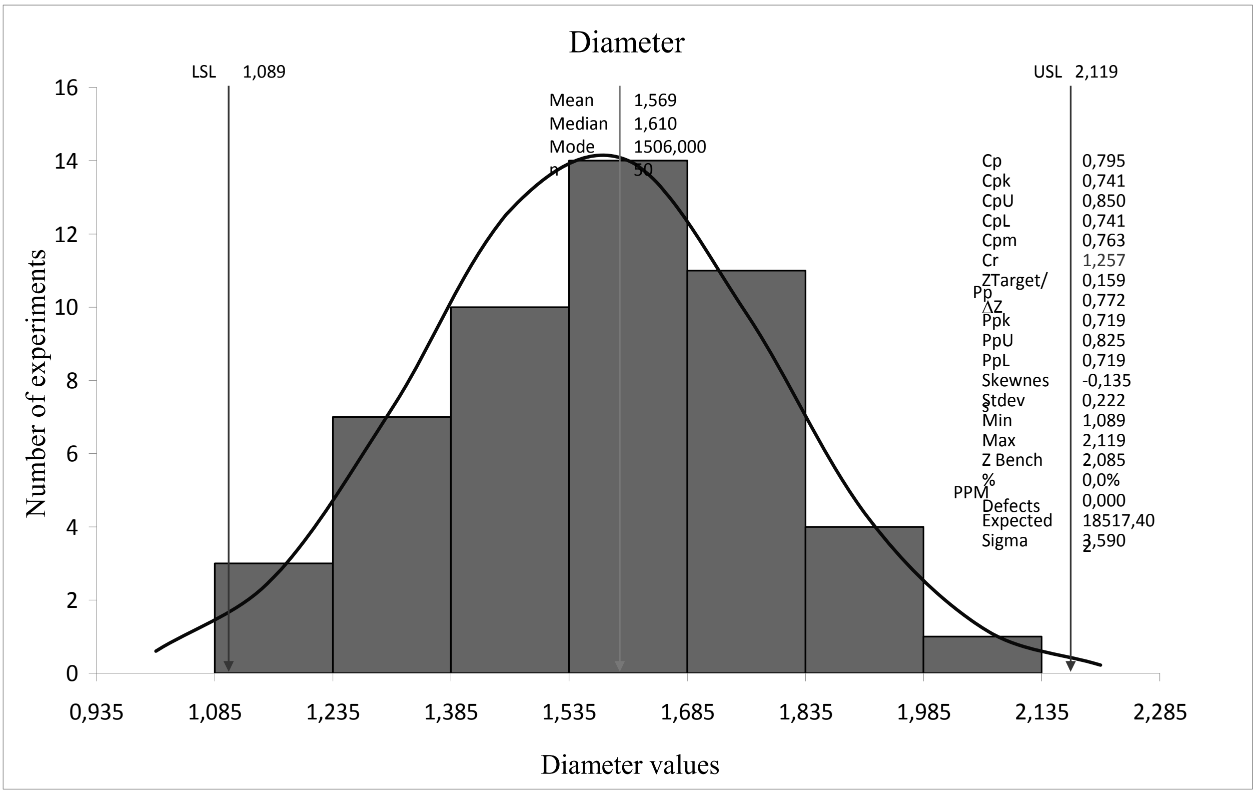


Fig. 6. Histogram for the diameter values

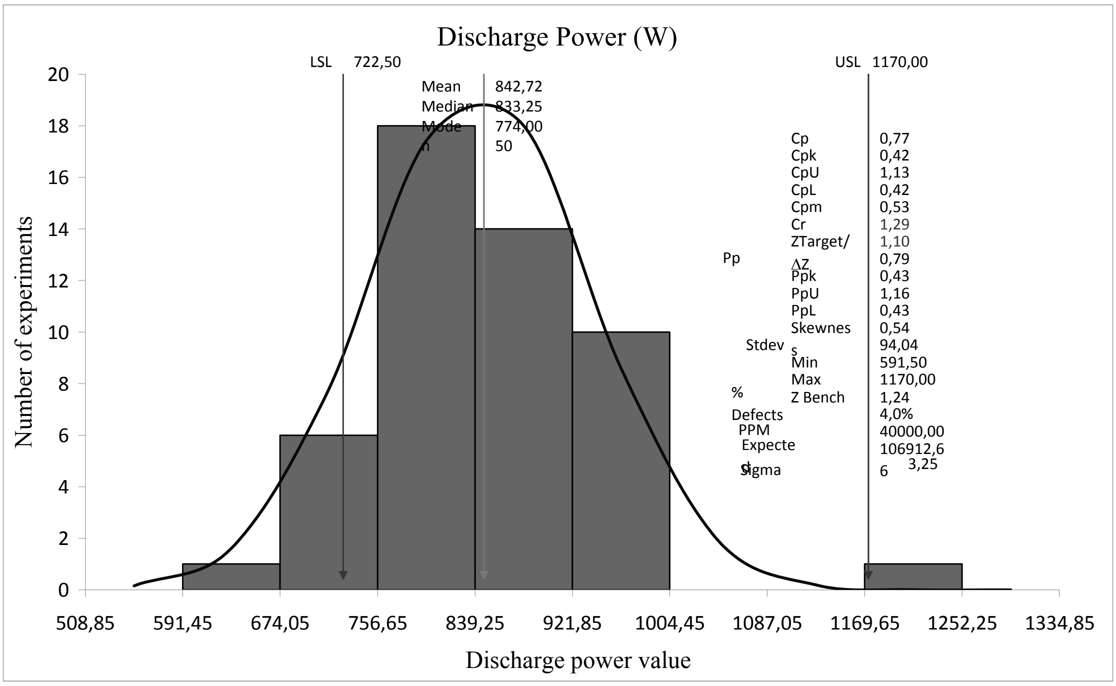


Fig. 7. Histogram for the discharge energy values

observe that it is close in value to the stipulated *ZTarget* value.

The histograms outcome indicates that the process requires improving. It is situated mainly between control limits and it looks like a regular distribution, but it obtained a low value of *Six Sigma* so it has some normality deviations. If a larger amount of points would be removed after using the control chart or correcting the red-marked parts of the series, the histograms might have a normal distribution.

5. CONCLUSIONS

Statistical analysis provides methods and tools for the authentication of a normal distribution in experimental sets of data. Such confirmation was required for a single discharge machining process. A Gaussian technique was applied for a range of 50 trials. Three dimension outcomes and one electric energy parameter were measured and stability analysis was conducted to observe if the data is in the control limits. In the future, there is the intention to deeply investigate information provided by the statistical parameters about the results of experimental researches.

6. REFERENCES

1. Chen, T., Sun, Y., (2009). *Probabilistic contribution analysis for statistical process monitoring: A missing variable approach*, Control Engineering Practice, Vol. 17, pp. 469–477.
2. Chen, Y., Gao, J., Deng, H., Zheng, D., Chen, X., Kelly, R., (2013). *Spatial statistical analysis and compensation of machining errors for complex surfaces,* Precision Engineering, Vol. 37, pp. 203–212.
3. Coman, G., (2007). *Statistics (theory and applications*) (in Romanian), pp. 77-92, PIM (Iaşi).
4. Dodun, O., (2001). *Nonconventional technologies. Machining with materialized tools* (in Romanian), pp. 9-51, Technica Info Chişinău Publishing House (Chişinău).
5. Mukherjee, R., Chakraborty, S., Samanta, S., (2012). *Selection of wire electrical discharge machining process parameters using non-traditional optimization algorithms*, Applied Soft Computing, Vol. 12, pp. 2506–2516.
6. Picoş, C., Slătineanu, L., Grămescu, T., Chirilă, V., (1981). *Machine manufacturing technology. Laboratory handbook* (in Romanian), Politechnic Institute of Iaşi, Romania, pp. 54-62.
7. Selvakumar, G., Sarkar, S., Mitra, S., (2012). *Experimental analysis of WEDM of Monel 400 alloys in a range of thickness*, International Journal of Modern Manufacturing Technologies, Vol. IV, No. 1, pp. 113-120.
8. Sivapirakasam, S.P., Mathew, J., Surianarayanan, M., (2011). *Constituent analysis of aerosol generated from die sinking electrical discharge machining process,* Process Safety and Environmental Protection, Vol. 89, pp. 141–150.
9. Slătineanu, L., Schulze, H.P., Dodun, O., Coteaţă, M., Gherman, L., Grigoraş, I., (2012). *Electrode tool wear at electrical discharge machining*, Key Engineering Materials, Vol. 504-506, pp. 1189-1194.

Received: September 10, 2012 / Accepted: December 5, 2012 / Paper available online: December 8, 2012 © International Journal of Modern Manufacturing Technologies.