Comparison of optimal machining parameters of sinking EDM and micro EDM processes

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Abstract

Electrical discharge machining (EDM) is a process where the material removal of the workpiece is achieved through high frequency sparks between the tool (electrode) and the workpiece immersed into the dielectric. The material removal rate (MRR), electrode wear and surface integrity are the important output parameters of EDM process. The machining parameters that achieve the highest MRR strongly depend on the size of the machining surface i.e. the engaged electrode and workpiece surface. In the case of the sinking electrical discharge machining (SEDM), the machining surface size is at least several times greater than the machining surface size when the micro electrical discharge machining (MEDM) is employed. Thus, the machining parameters that achieve the highest MRR are different for both processes. To compare these two processes, the optimal machining parameters were found using Taguchi method for three electrodes of different diameters. Results show a significant difference in the optimal machining parameters when the machining surface is drastically reduced.

Keywords: EDM**,** optimal machining, robust design, design of experiments (DOE), analysis of variance (ANOVA)

1. Introduction

EDM process takes place between the electrode, usually made of copper, graphite or tungsten, and workpiece, usually made of conductive material. During the machining, both are submerged in the electrically resistant dielectric oil. Sparks in the gap between the electrode and the workpiece are caused by the electric pulses generated by the pulse generator. The sparks melt and remove material from electrode and the workpiece. In the case of SEDM, the gap width between the workpiece and the electrode is from 10 to 100 µm. The material removal rate is around 100 times higher on the workpiece than on the electrode, thus the negative shape of the electrode is transferred into the workpiece. SEDM is well established material removal process, which is mainly used in toolmaking to produce dies and moulds.

Due to the new trends (smaller, cheaper, better), machines should consume less power, should be smaller and more accurate. Following the trends, the MEDM process emerged, which can produce cavities even smaller than 20 µm in diameter which is already in the field of micro machining; the micro products have at least one dimension smaller than 1 mm [1].

Since MEDM is relatively new machining process, an extensive research is performed recently focusing on factors affecting the machining accuracy [2,3]. To improve the machining accuracy, the electrode wear has to be under control [4]. Analytical models of the SEDM are known from the literature [5-8], but the models for MEDM are still in developing stages [9]. The research on MEDM is focused also on the machining processes for electrode production [10].

In the case of rough machining by SEDM process or milling MEDM, the electrode wear should be under control, but the wear rate is far less important than MRR. Thus, the machining parameters that achieve the highest MRR are considered as the optimal machining parameters. They strongly depend on the machining surface size and the electrode and workpiece material. To find the optimal machining parameters is of a great importance especially in the batch production [11].

To compare the SEDM and MEDM processes, the significant and the optimal machining parameters were found experimentally for various sizes of electrodes. To reduce the number of experiments, the Taguchi method was used. The calculated optimal machining parameters were experimentally proved.

The paper is organised as follows. The introduction was given in the first section. In the second section, the Taguchi method of design of experiments and method for analysing of results are introduced. Experimental arrangement is given in the third section and results and discussion is given in the fourth section. Finally, the conclusions are drawn in the last, fifth section.

2. Taguchi method

Design of experiments (DOE) is a statistical technique that made it possible to analyse the effect of more than one factor at the same time. Taguchi method or Taguchi approach is a DOE technique with new experimental strategy where the quality is defined in general terms. The method could be used not only to improve quality, but also to quantify the improvements made in terms of saving money. The experimental design and analyse of the results can be done with less effort and expenses by using the Taguchi approach. Since the method enormously reduces the number of experiments, quality loss of results must be taken into account.

The first step of Taguchi method requires the knowledge about the domain that is examined, since the main function, side effects and failure modes have to be identified. A wrong decision in this step makes all other steps useless.

The second step is to find control factors and their levels. To reduce the number of experiments, only the most important factors should be considered. Two or

Table 1
Electrodes size and the values of the machining parameters on all three levels

d (mm)	A (mm^2)	i_d (A)			i_e (A)			U_r (V)			t_e (µs)			t_o (µs)			time (min)
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	
0.3	0.07	1	2	3	2	3.3	4.6	25	35	45	38	41	45	72	90	113	3
8.7	60	2	5	8	2	3.3	4.6	25	35	45	72	117	162	14	23	32	5
13.8	150	19	29	39	2	3.3	4.6	25	35	45	540	720	910	41	72	112	7

three factor levels can be chosen. In the latter case, the levels should be evenly distributed. The factor levels should be placed very carefully, since the Taguchi method defines the significant and optimal parameters only within the levels. *In the case of wide range of factor levels, the optimal factors (parameters) are roughly defined. On the other hand, when the factor levels are to close the factor can not be significant since its influence to the main function is less than the calculated noise.*

The orthogonal array that defines the experiments is selected in the third step. The fourth step is to perform the experiments. In the fifth step, the results are analyzed with analysis of variance (ANOVA) and F-test to verify the experiments and to determine the significant factors for the main function. Optimal factors are predicted in the sixth step. And in the last step of Taguchi method optimal parameters should be tested to confirm or reject optimal parameters found by Taguchi method.

3. Experimental arrangement

The experiments were done on an IT E 200M-E machine with isoenergetic generator. The workpiece material was hardened steel X210Cr12 (according to DIN standard) with hardness 60 HRc. The electrode material was electrolytic copper and the dielectric was Erozol 25 which is suitable for both, rough and fine machining.

The aim of experimentation is to find the significant machining parameters for the material removal rate (MRR) and to predict and verify the optimal machining parameters. In terms of Taguchi method, the machining parameters were factors and the main function was dependence of the MRR on machining parameters.

Machining parameters that are described as follows were taken into consideration. Working current i_d and ignition current i_e are defining the discharge current and the slope of the rising of the current at the beginning of the discharge, reference voltage U_r defines the gap distance, frequency of discharges is strongly influenced by discharge duration t_e and pause time t_o. The flushing of the gap was constant in all experiments and it enabled stable machining. The ignition voltage was constant in all experiments and it was set to 280 V.

Three electrodes of various diameters were used in experiments. Table 1 shows the levels of the machining parameters for each tested electrode. The electrodes have different machining surface sizes, thus the levels of the machining parameters and duration of the experiment varied, too. The machining depth and hole diameter were used to calculate the material removal rate (MRR), which is used as a quantitative measure for the rough machining process performance.

The factor levels, in our case the machining parameters levels, were chosen as close as possible to the optimal value by taken into account the preliminary experimental results, which are not presented in this paper.

To find out the optimal combination of the machining parameters given in Table 1, each electrode was treated separately and L_{18} orthogonal array was used to reduce the number of experiments. The combinations of machining parameters given in Table 2 were used for each electrode and each experiment was repeated three times.

Table 2
Standard L_{18} orthogonal array ($2^1 \times 3^7$)

Nr.	Em-pty	i_d (A)	i_e (A)	U_r (V)	t_e (µs)	t_o (µs)	Em-pty	Em-pty
1	1	1	1	1	1	1	1	1
2	1	1	2	2	2	2	2	2
3	1	1	3	3	3	3	3	3
4	1	2	1	1	2	2	3	3
5	1	2	2	2	3	3	1	1
6	1	2	3	3	1	1	2	2
7	1	3	1	2	1	3	2	3
8	1	3	2	3	2	1	3	1
9	1	3	3	1	3	2	1	2
10	2	1	1	3	3	2	2	1
11	2	1	2	1	1	3	3	2
12	2	1	3	2	2	1	1	3
13	2	2	1	2	3	1	3	2
14	2	2	2	3	1	2	1	3
15	2	2	3	1	2	3	2	1
16	2	3	1	3	2	3	1	2
17	2	3	2	1	3	1	2	3
18	2	3	3	2	1	2	3	1

According to the given orthogonal array 7 parameters can be used on 3 levels and one parameter on 2 levels. In our case only 5 machining parameters are considered, thus the first and the last two columns are left empty. According to the L_{18} orthogonal array, the design of experiments requires 18 experiments. Each experiment is repeated three times. Thus, 54 experiments were performed by one electrode.

4. Results and discussion

After the experiments, the MRR was measured and it was used for process evaluation by the Taguchi method. The experimental results were treated separately for each electrode; the significant and the optimal machining parameters for each electrode were calculated. Further on, the optimal combination of the machining parameters was tested experimentally.

Based on the Taguchi method, the analysis of variance (ANOVA) describes statistically the relationship between the machining parameters and MRR. By comparing signal-to-noise ratio (S/N) of the

MRR the optimal combination of the machining parameters was determined. Since MRR should be as high as possible, the S/N calculation was decided as “the higher the better”:

$$\eta = -10 \cdot \log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{MRR_i^2}\right)[dB], \qquad (1)$$

where n is the number of times each experiment is repeated, in our case $n = 3$ and η denotes the S/N ratio calculated for every experiment. The S/N is calculated for every machining parameter level. The S/N ratio for the first level of the working current $i_{d,1}$ is calculated according to the Eq. 2. As clearly seen, only the S/N of the experiments where working current i_d was set to the value of the first level (Table 2) are included in the given equation.

$$\eta_{i_{d,1}} = \frac{1}{6}\cdot(\eta_1 + \eta_2 + \eta_3 + \eta_{10} + \eta_{11} + \eta_{12}) \qquad (2)$$

Overall mean value m is calculated according to the Eq. 3.

$$m = \frac{1}{18}\sum_{i=1}^{18}\eta_i \qquad (3)$$

ANOVA is well described in the literature, e.g. in [12] and thus it will not be described here.The method uses F-test to find the significance of the factors, in our case the significance of the various machining parameters to the MRR. The calculated statistic F_0 of every machining parameter is compared to the critical value derived from the Snedecor distribution [13]. In our case, the critical value is equal for all machining parameters and all electrode sizes: $F_{0.05;2,9}$=4.26.

For each electrode, the ANOVA was performed and the results are given in Table 3. Comparing the calculated statistic F_0 with the critical value $F_{0.05;2,9}$ the significance of each machining parameter can be determined. The machining parameters having F_0 greater than $F_{0.05;2,9}$ are significant to the MRR and are marked by * in Table 3.

Table 3
Statistic F_0 calculated by analysis of variance for every machining parameter and electrode size

Statistic	Electrode surface (mm^2)			$F_{0.05;2,9}$
	0.07	60	150	
F_0 (i_d)	7.06*	114*	23.07*	4.26
F_0 (i_e)	5.06*	25.3*	4.86*	4.26
F_0 (U_r)	0.95	3.57	0.39	4.26
F_0 (t_e)	0.20	14.8*	55.37*	4.26
F_0 (t_o)	0.15	1.04	6.38*	4.26

It is well known that electric current is the most significant parameter when machining with EDM. As shown in table 3, both currents i_d *and* i_e are significant for all tested electrode sizes.

Reference voltage U_r is not significant since the levels of reference voltage were chosen in the area of stable machining and very close to the optimal values.

Discharge duration t_e is significant when machining with 60 and 150 mm^2 electrodes, since the discharge duration levels were chosen widely apart. On the other hand, the discharge duration t_e is not significant when machining with 0.07 mm^2 electrode since its levels were chosen close to the optimal level to precisely define the optimal discharge duration. According to the preliminary results not shown in this paper, the optimal discharge duration for machining with electrode 0.07 mm^2 was expected around 45 µs.

Pause time t_o is significant within the range of levels when machining with 150 mm^2 electrode. For other electrode sizes the pause time t_o is not significant within the selected levels.

To find the optimal machining parameters for each electrode size, the S/N of each machining parameter (Eq. 2) level must be considered. The S/N values for electrode size 0.07, 60 and 150 mm^2 are presented in Fig. 1, Fig. 2 and Fig.3 respectively.

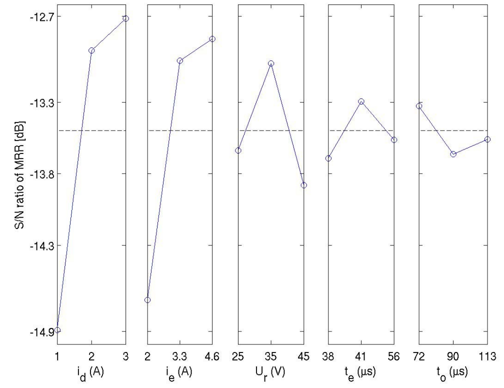

Fig. 1. S/N for electrode size 0.07 mm^2

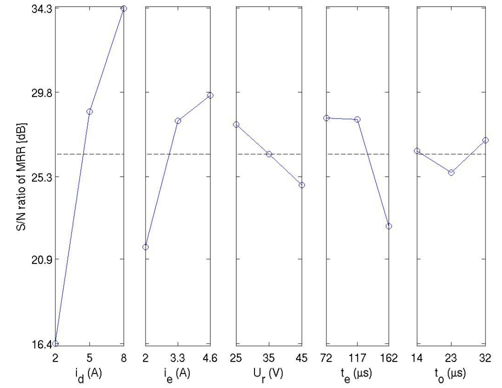

Fig. 2. S/N for electrode size 60 mm^2

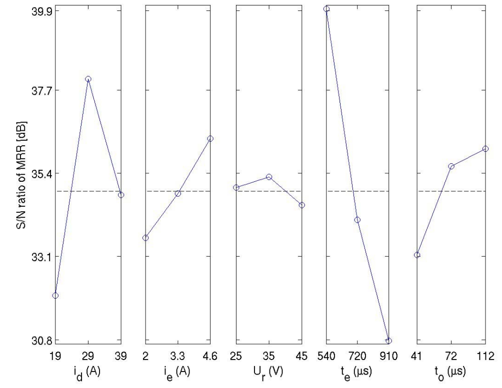

Fig. 3. S/N for electrode size 150 mm^2

Since higher MRR is desired “the higher the better” S/N calculation was used (Eq. 1). The highest S/N of the observed machining parameter levels (Fig. 1, Fig. 2 and Fig.3) indicate the optimal machining parameter values, which are gathered in Table 4 together with the MRR. In the table, the MRR achieved by the optimal machining parameters and the highest MRR achieved by the best combination of the machining parameters defined in the orthogonal array are compared.

Table 4
Comparison of MRR with best machining parameters according to table L_{18} and optimal machining parameters

El. size (mm^2)		i_d (A)	i_e (A)	U_r (V)	t_e (μs)	t_o (μs)	MRR
0.07	L_{18}	3	3.3	25	41	72	0.093
	opt.	3	4.6	35	41	72	0.098
60	L_{18}	8	4.6	25	162	23	13.43
	opt.	8	4.6	25	72	32	14.78
150	L_{18}	29	3	45	540	72	24.06
	opt.	29	4.6	35	540	112	28.15

According to the Fig. 1, Fig. 2 and Fig. 3, the highest levels of the working current i_d and ignition current i_e are found as the optimal values which indicate that greater values of the levels of working and ignition current could be chosen to find real optimal values. The exception is the working current when 150 mm^2 electrode is used (Fig. 3). The optimal working current is 29 A.

According to Table 3, the reference voltage U_r is not significant and thus the optimal values are between 25 and 45 V for all electrode sizes.

When machining with electrode 0.07mm^2 (domain of MEDM) the discharge duration t_e and pause time t_o are not significant (Table 3), thus the optimal values are between 38 and 56 μs and 72 and 113 μs respectively (Fig. 1). In the case of larger electrodes (domain of SEDM), the discharge duration t_e is significant and the optimal values are 117 μs for 60 mm^2 electrode and 540 μs for 150 mm^2 electrode. In the latter case, the optimal discharge duration could be even less since the lowest discharge duration level is found as the optimal one.

The pause time t_o is not significant within the chosen levels for 0.07 and 60 mm^2 electrode. Thus, the optimal values are between 72 and 113 μs and between 14 and 23 μs respectively (Fig. 1 and Fig. 2). For 150 mm^2 electrode, the pause time is significant within the chosen levels and the optimal value is 112 μs, but it could be even greater since the highest level is found to be the optimal one.

Additional experiments were performed to establish the MRR achieved by the optimal machining parameters. The MRR of the optimal machining parameters are compared to the highest MRR achieved in experiments defined in the orthogonal array (Table 4). MRR of the predicted optimal machining parameters is higher than the highest MRR achieved in experiments defined in the orthogonal array.

5. Conclusions

According to the experimental results, the following conclusions can be drawn:

- The working and ignition currents are significant for the MRR for all electrode sizes, i.e. in the case of SEDM and MEDM. The optimal value of the current depends on the electrode size: greater the electrode higher the working and ignition current.

- The reference voltage U_r has no significant influence to the MRR as long as the machining process is stable.

- Greater the electrode longer the discharge duration t_e. Since the discharge voltage is independent of the electrode size and machining parameters, the discharge current (i_d + i_e) and discharge duration t_e define the discharge energy, which can be higher in the case of grater electrode.

- In SEDM, greater the electrode longer the pause duration t_o. But reducing the electrode size down to micro domain, the optimal pause duration increases.

- Taguchi method turn out to be a suitable method for design of experiments and analysis of experiments. MRR of the predicted optimal machining parameters is higher than the highest MRR achieved in experiments defined in the orthogonal array.

References

[1] Madou MJ. Fundamentals of micro fabrication, the science of miniaturization (2nd edn), CRC press LCC, Florida, 2002.

[2] Pham DT, Dimov SS, Bigot S, Ivanov A and Popov K. Micro-EDM—recent developments and research issues, J. of Materials Processing Technology, 149 (1-3), 2004, pp 50-57.

[3] Pham DT, Dimov SS, Bigot S, Ivanov A and Popov K. A study of the accuracy of the micro electrical discharge machining drilling process. 5th international conference on integrated design and manufacturing mechanical engineering, University of Bath, 2004.

[4] Tsai YY and Masuzawa T. An index to evaluate wear resistance of the electrode in micro-EDM. Journal of Materials Processing Technology, Elsevier, pp 304-309, 2004.

[5] DiBitonto DD, Phillip TE, Mukund RP and Maria AB. Theoretical models of the electrical discharge machining process. I. A simple cathode erosion model. J. Appl. Phys., 1989.

[6] Mukund RP, Maria AB, Phillip TE and Daryl DD. Theoretical models of the electrical discharge machining process. II. The anode erosion model. J. Appl. Phys., 1989.

[7] Phillip TE, Mukund RP and Maria AB. Theoretical models of the electrical discharge machining process. III. The variable mass, cylindrical plasma model. J. Appl. Phys., 1993

[8] Van D. Physico-mathematical analysis of the electro discharge machining process. Ph. D. thesis, Katholieke universiteit te Leuven, 1971.

[9] Katz Z and Tibbles CJ. Analysis of micro-scale EDM process. Int. J. Adv. Manuf. Technol., Springer-Verlag, London, 2004.

[10] Weng FT, Shyu RF and Hsu CS. Fabrication of micro-electrodes by multi-EDM grinding process. Journal of Materials Processing Technology, Elsevier, 2003, pp 332-334.

[11] Weng FT and Her MG. Study of the batch production of micro parts using the EDM process. Int. J. Adv. Manuf. Technol., Springer- Verlag, London, 2002, pp 226-270.

[12] Phadke MS. Quality engineering using robust design. Prentice-Hall International, Inc. 1989.

[13] Montgomery DC. Design and Analysis of Experiments. New York: John Wiley & Sons, Inc., 2001.