Investigation and Optimization of EDM Milling and its Comparison with Die Sink EDM

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Abstract: In this study EDM milling process parameters of AISI H13, have been investigated by using Response Surface Methodology (RSM). Current (16-32A), pulse-on time (100-700 µs) and depth of cut (1-3mm) were considered as independent variables, while surface roughness, tool wear ratio (TWR), and material removal rate (MRR) as process output responses. Results reveal that increases in the current and decreases in pulse-on time cause more MRR and more TWR and depth of cutting has no significant effect on them. Minimum surface roughness, minimum TWR and maximum MRR were considered as optimization criteria. Verification experiments were carried out in order to analyze the results via software. Optimized settings were used for EDM Milling and die sink EDM experiments to compare the results. The results indicate that using EDM milling has considerable economic savings than die sink EDM, better surface roughness, and higher MRR.

Keywords: Die sink EDM, Electro discharge milling, Optimization, Response surface methodology

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1 INTRODUCTION

Computer Numerical Control (CNC) systems have made EDM more useful and have provided requirements to make it as popular as mechanical milling systems. Standard cylindrical electrodes are used in this process. Complex-shaped cavities are created by the movement of a rotary electrode in a predefined path [1]. In addition to compensation of tool radius, a few other requirements such as compensations of spark and tool wear should be considered to use tool path which is applicable to mechanical milling for EDM Milling. Bleys et. al., [2] devised a method for compensation of tool wear in EDM Milling. Tool wear is calculated according to estimation of the discharged electro pulse and is submitted to machine's software simultaneously with machining. As a result, tool would compensate itself according to its actual wear.

Liu et. al., [3] Studied the effect of technological parameter on the insulating Al_2O_3 ceramic by electro discharge milling. In their research, Liu et al. utilize a copper auxiliary electrode that is placed between tool electrode and ceramic. The spark takes place between tool electrode and the auxiliary one. These sparks are transferred to surface of the ceramic and cause machining of the ceramic. Bairamoghlo et. al., [4] experimented EDM milling by setting parameters such as voltage, pulse-off time, pulse-on time, rotational speed of tool, cut depth, and tool diameter in different levels as input process on two specimens of high carbon and low carbon steels. They reported that pulse energy and well-flushing of dielectric parameters have significant effect on material removal rate, tool wear rate, and surface quality. Fojohan et. al., [5], set high rotating velocity to pipe-shaped tool in EDM milling and compared it with die sink EDM. They reported that material removal rate, tool wear, and surface quality resulting from milling outperform die sink EDM's ones because of fast motion of electro sparks, elimination of pulse-off time, infinite pulse-on time, and continuity of machining operation. Using design of experiments (DOE) in various applications has recently gained prevalence [6], [10]. Assarzadeh et. al., [11] statistically investigated the effects of electro-discharge machining parameters on WC/6%Co composite. They studied the influence of input parameters, current, gap voltage, pulse-on time, and duty cycle on the responses (MRR, TWR, and Ra); and finally optimized the process via using a desirability function. Karthikeyan et. al., [12] conducted an experiment on the effect of tool rotation with micro EDM milling of EN 24 using tungsten electrode. They reported that the rotation of the tool reduces the amount of tool material deposited on the workpiece surface. Jafferson et. al., [13] investigated the effect of non-electrical parameters on micro EDM milling of stainless steel. Their study revealed that thickness of the layer and rotational speed of the tool along with horizontal feed rate of the electrode significantly influences the performance of EDM milling. Experiments of high-throughput electrical discharge milling of WC–8%Co with tubular graphite electrode were conducted by Yang Shen et. [14].

Purpose of the present study is an investigation and optimization of the EDM milling process parameters, current, pulse-on time, and depth of cut on the surface roughness, tool wear ratio, and material removal rate of AISI H13 steel by using Response Surface Methodology (RSM). To validate the results of optimization, an experiment was carried out at optimum settings and compared with the optimization results. Experiments of multiple optimized EDM Milling and die sink EDM were performed and the results were compared with each other. Better surface roughness, lower electrode cost, elimination of manufacturing electrode, and higher material removal rate are the advantages of EDM milling in comparison to die sink EDM. It is demonstrated that using electro discharge milling has considerable economic savings compared to employing die sink EDM.

2 METHODOLOGY

2.1. Response Surface Methodology (RSM)

Response Surface Methodology (RSM), one of the optimizing techniques, is widely used in describing different processes and suggestion of optimum setting [6], [15]. Response Surface Methodology (RSM) is a set of statistical and mathematical technics which are used for modeling and predicting results, affected by input parameters [8], [9]. When all independent variable parameters during experiment are measurable and controllable, the response surface will be represented by Eq. (1).

$$Y= f(x_1, x_2, x_3, \ldots, x_k) \quad (1)$$

Where, k is number of independent input variables. It is necessary to find a logical function to attribute the response to the input variables. Thus, a second order polynomial function, as shown in Eq. (2), is usually used in Response Surface Methodology (RSM) [16], [17].

$$y = \beta 0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \sum_{i} \sum_{j} \beta_{ij} X_i X_j + \epsilon \quad (2)$$

Where β0 is a constant value, βi are linear coefficients, βii are second order coefficients, βij are interaction coefficients and ε is random error.

2.2. Desirability approach

Many response surface problems include the analysis of several responses. Simultaneous consideration of multiple responses contains first building of an appropriate response surface model for each response and then trying to find a set of operating condition that in some sense optimizes all responses or at least keeps them in desired ranges. The desirability method is suggested because of its simplicity, availability in the software and provides flexibility in weighting and giving importance for individual response. Desirability method is a simultaneous optimization technique which was promoted by Drringer and Suich in 1980 [7], [16]. Solving such multiple response optimization problems employing this technique involves using a technique for combining multiple responses into a dimensionless measure of performance named the overall desirability function [17]. The general approach is to first convert each response Yi into a unit with less utility bounded by 0<di<1, where a higher di value indicates that response value Yi is more desirable, and if the response is outside an acceptable region, di=0. Then the design variables are selected to maximize the overall desirability [16]:

$$D=(d_1.d_2\ldots.d_m)^{1/m} \tag{3}$$

Where, m is the number of responses. In the current study, the individual desirability of each response, di, was calculated using Eqs. (4-6). Shape of the desirability function depends on the weight field ‘r’. Weights are used to emphasize the target value. When the weight value is equal to 1, this will make the desirability function in linear mode. Selecting r>1 places more importance on being close to the target value, and choosing 0<r<1 makes this less important [15]. If the target T for the response y is a maximum value, the desirability will be defined by Eq. (4).

$$d=\begin{cases}0 & y<L\\ \left(\frac{y-L}{T-L}\right)^r & L\le y\le T\\ 1 & y>T\end{cases} \tag{4}$$

For goal of minimum, the desirability will be defined by Eq. (5).

$$d=\begin{cases}1 & y<L\\ \left(\frac{T-y}{T-L}\right)^r & L\le y\le T\\ 0 & y>T\end{cases} \tag{5}$$

If the target is located between the lower (L) and upper (U) limits, the desirability will be defined by Eq. (6).

$$d=\begin{cases}0 & y<L\\ \left(\frac{y-L}{T-L}\right)^r & y<L\\ \left(\frac{T-y}{T-L}\right)^r & L\le y\le T\\ 0 & y>T\end{cases} \tag{6}$$

3 EXPERIMENTAL WORK

The EDM machine used in the experiments was the ROBOFORM 400 made by Swiss Char Milz Company. The machine has four rotating axes: x, y, z, c (tool rotation axis). C axis rotation enables EDM milling. This machine is equipped with CNC system and is capable of machining flat and curvature surfaces as three-axial milling. The workpiece material in this research is tool steel AISI H13. The chemical composition of the material, which is the average of three X-ray fluorescence (XRF) measurements, is presented in Table. 1. This kind of steel is one of the most important chromium based hot-work steels that is appropriate for hot-work tools under high stress, extrusion die to produce pipe and rebar, and hot extrusion tool. It is also proper to produce bolt and nut, rivet, die cast mold, casting tool of light metals alloys, forming, forging and plastic dies. Electrode material which is used in EDM milling and die sink EDM is copper with purity of 84.99% which are illustrated in Fig. 1 and Fig. 2, respectively.

Table 1 Chemical composition (wt.-%) of AISI H13

				Mn	M	P	S	
Fe	c	Si	Cr		o			V
	0.3	0.9		0.3	1.2	0.	0.0	0.95
Bal	6	5	5.23	5	5	03	3	

Fig. 1 EDM milling tool

To achieve Material Removal Rate (MRR) and Rate of Electrode Wear (REW) precise laboratory scale with accuracy of 0.001 g was used. In each experiment, ratio of workpiece weight reduction to time indicates MRR (milligram per minute) and also the ratio of electrode weight reduction to workpiece weight reduction indicates REW (percent). Surface roughness with Ra value was measured using roughness meter machine

Mitutoyo surftest 500 in order to investigate specimens' surface roughness.

Fig. 2 Die sink EDM tool

Machining profile (Fig. 3) is machined with different depths in each experiment. Figure 4 illustrates a picture of the experimental set-up. The fixed process parameters are presented in Table 2. The three parameters that were varied as the input properties of the DOE-method are current (I), Pulse-on time (T), and Depth of milling (D).

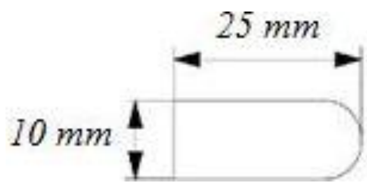

Fig. 3 Profile geometry

In the present study, the experiments were designed based on a Central Composite Design (CCD), three-level RSM design [5].

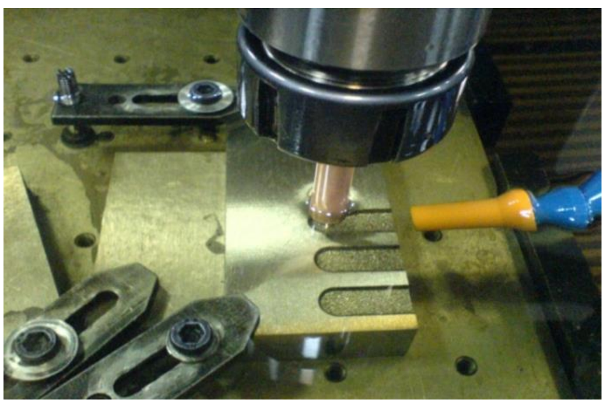

Fig. 4 Experimental set-up

The commercial DOE software code Minitab version 17 [18], is invoked. Input parameters are current I (16-32 A), pulse-on time T (100-700 μs), and depth of milling D (1-3 mm). These parameters were selected as the three process-independent input variables. Table 3 shows the process input variables and the three experimental design levels (from -1 to +1). These levels are illustrated with coded and actual values. Table 4 illustrates the designed matrix with the measured values of the responses, namely the material removal rate (MRR), rate of electrode wear (REW), and surface roughness (Ra). The experimental design is constructed from 20 experiments that include eight experiments as factorial points in the cubic vertex, six experiments as axial points and six experiments in the cubic centre as centre point experiments.

Table 2 Fixed EDM milling process parameters

Parameter	Value
Polarity	Positive
Voltage	80 volt
Pulse off time	Optimized by machine
Dielectric spraying	Jet flushing
Tool rotational speed	20 rpm

Table 3 independent process parameters and their values, related to the three design levels

Parameters	Notation	Unit	-1	0	1
Current	I	[A]	16	24	32
Pulse-on time	T	[μs]	100	400	700
Depth of cut	D	[mm]	1	2	3

4 RESULTS AND DISCUSSION

The surface roughness, relative electrode wear, and material removal rate were considered as process responses. Analysis of variance (ANOVA) was employed to investigate significant effective parameters on EDM milling process and interpretation of the results. The results show that proper responses could be achieved by the means of controlling input parameters.

4.1 Material Removal Rate (MRR)

According to analysis of variance for MRR (Table 5) the only effective parameters are current (I) and pulse-on time (T). Pulse-on time quadratic term (T2) has a significant effect on MRR. The interaction effect of current and pulse-on time (I×T) was identified as the significant term. Therefore, the final regression in terms of actual parameter values yields to Eq. (7).

$$MRR=240.842+6.57739\times I-0.657901\times T+0.00024\times T^2 +0.0127232\times I\times T \quad (7)$$

Table 4 The design matrix expressed by three input process parameters as design levels and the responses.

Experiment No	Current (A)	Pulse-on time(μs)	Depth of cut (mm)	Material Removal rate (MRR) (mg/min)	Tool Wear Rate (TWR) (%)	Surface roughness (Ra) (μm)
1	16	100	1	270	0.9	4.3
2	32	100	1	322	4.8	8.15
3	24	400	2	225	0.5	8.90
4	16	700	1	92	0.7	8.40
5	32	700	1	296	0.6	12.60
6	16	100	3	275	1	4.60
7	32	100	3	319	4.5	8.35
8	24	400	2	220	0.6	9.25
9	16	700	3	105	0.3	8.25
10	24	400	3	210	0.8	9.20
11	32	700	3	182	0.3	12.50
12	24	400	2	215	0.4	9.20
13	16	400	2	131	0.4	8.20
14	24	400	2	208	0.6	9
15	32	400	2	278	0.7	10.20
16	24	100	2	275	2.5	7.30
17	24	700	2	202	0.4	10
18	24	400	1	225	0.7	9.30
19	24	400	2	212	0.4	9.20
20	24	400	2	196	0.4	9.15

Figure 5 illustrate the response surface of MRR in terms of current (I) and pulse-on time (T). Non-significant parameter values, i.e. depth of milling in the Fig. 6, was kept at fixed level of 3mm. The results show that decreasing pulse-on time and increasing current lead to an increase of the MRR. As the current increases, discharge energy increases and in turn, it leads to an increase in melted and evaporated material volume; so the MRR increases. Meanwhile low pulse-on time causes reduction in radius channel plasma, more energy density is produced that leads to an increase in MRR. Pulse-on time and current have an interaction effect on MRR so that reduction of pulse-on time and increase of current causes more discharge energy and higher MRR occurs.

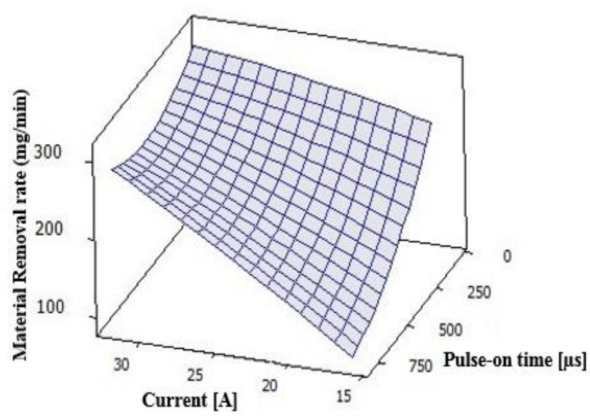

Fig. 5 Response surface of MRR in terms of current and pulse-on time

4.2. Surface roughness (Ra)

ANOVA results reveal that current (I), pulse-on time (T), quadratic effect of current (I2), and quadratic effect of pulse-on time (T2) were identified as the most significant affecting parameters on surface roughness, Table 6. From the DOE analysis the Minitab software elaborated the following regression formula in un-coded units for the surface roughness:

$$Ra = -3.32 + 0.543\ I + 0.00804\ T - 0.00630\ I^2 - 0.000003\ T^2 \quad (8)$$

Table 5 Revised analysis of variance of MRR

Source of variation	Sum of squares	Degree of freedom	Mean squares	T value	F value	P value
Regression	77572.5	4	19393.1	-	168.02	0.000
I	62.4	1	0.05	18.367	-	0.991
T	-48.4	1	-206.19	-14.246	-	0.000
T×T	31.8	1	93.93	6.619	-	0.000
I×T	35.62	1	55.33	9.379	-	0.000
Residual Error	1731.3	15	115.4			
Pure Error	858.4	11	78.0			
Lack-of-Fit	872.9	14	218.2	-	2.80	0.10
Total	79303.8	19				
R-Sq = %97.82			R-Sq (adj) = %97.23			

Figure 6 illustrate the response surface of "surface roughness" in terms of current and pulse-on time. Non-significant parameter value, i.e. depth of milling in the Fig. 6, was kept fixed at 3 mm. The results show that reduction of pulse-on time and current lead to decrease of the MRR. An increase of current results in an increase of discharged energy which enables the surface roughness to raise that in turn, leads to an elevation of width and melted Crater volume. Reduction of pulse-on time, i.e. increase of spark frequency, leads to increase of the energy to be generated by more number of sparks in a period of time.

4.3. Tool wear ratio (TWR)

The effective terms on the Tool wear ratio (TWR) are current (I), pulse-on time (T), quadratic effect of pulse-on time (T2) and interaction effects of current and pulse-on time (I×T). The revised ANOVA in accordance with effective terms is presented in Table 7. The final regression equation including actual values of effective parameters is presented in Eq. (9).

$$TWR = -2.602 + 0.2647\ I - 0.002936\ T + 0.000009\ T2 - 0.000335 I\times T \quad (9)$$

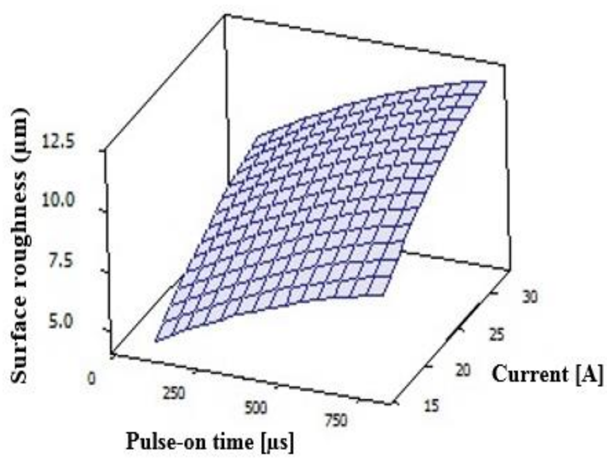

Fig. 6 Response surface of surface roughness in terms of current and pulse-on time

Table 6 Revised analysis of variance of surface roughness

Source of variation	Sum of squares	Degree of freedom	Mean squares	T value	F value	P value
Regression	77572.5	4	19393.1	-	168.02	0.000
I	37.0563	1	37.0563	18.367	397.11	0.991
T	36.2903	1	36.2903	-14.246	388.90	0.000
T×T	0.52	1	0.52	6.619	5.57	0.032
I×T	0.399	1	0.399	9.379	4.28	0.056
Residual error	1.3997	15	0.09333			
Pure error	0.0933	5	0.0187			
Lack-of-fit	1.3064	10	0.13064	-	7.00	0.150
Total	77.0364	19				
R-Sq = %98.18			R-Sq (adj) = % 97.70			

The TWR response surface with regard to current (I) and pulse-on time (T) has been depicted in Fig. 8 while the value of depth of milling was kept fixed at 3 mm. The results show that Increase of pulse-on time leads to reduction of tool wear ratio. In the beginning of electro discharge, light electrons start moving toward a node and bombard it because of electrical field. Prolonged pulse duration will give more chance to much heavier positive ions for reaching to the target cathode workpiece; thus, occupying most of the plasma channel path does not let the excited electrons to attack the anode tool [19]. Increasing current resulting from discharged energy rise leads to more tool wear ratio. Fig. 6 illustrates the effects of tool wear on workpiece and tool.

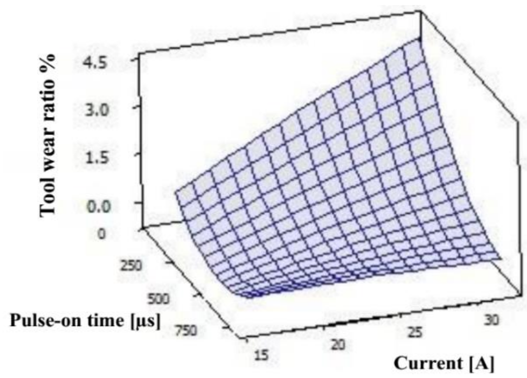

Fig. 7 Response surface of tool wear ratio in terms of current and pulse-on time

Table 7 Revised analysis of variance of tool wear ratio

Source of variation	Sum of squares	Degree of freedom	Mean squares	T value	F value	P value
Regression	31.5885	4	7.8971	-	249.48	0.000
I	6.6612	1	6.6612	18.367	210.44	0.000
T	12.9960	1	12.9960	-14.246	410.57	0.000
T×T	4.9000	1	4.9000	6.619	154.80	0.000
I×T	7.0312	1	7.0312	9.379	222.13	0.000
Residual error	0.4115	13	0.0317			
Pure error	0.0483	5	0.0097			
Lack-of-fit	0.3632	8	0.0454	-	4.7	0.098
Total	32.000	17				
R-Sq = %98.71			R-Sq (adj) = %98.32			

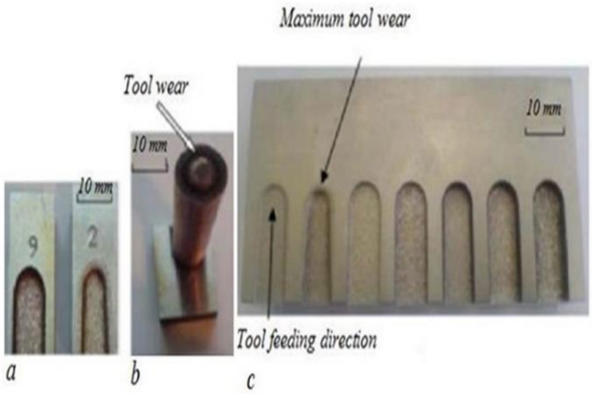

Fig. 8 a) tool wear effect on samples 2 and 9 b) tool wear effect on the electrode c) Tool wear comparison between samples

Table 8 Constraints and criteria of input parameters and responses

Parameter/Response	Goal	Lower limit	Upper limit
Current (A)	Is in range	16	32
Pulse-on time (µs)	Is in range	100	700
Depth of cut (mm)	Is in range	1	3
Material removal rate MRR (mg/min)	Maximize	92	322
Tool wear ratio TWR (%)	Minimize	0.3	4.8
Surface roughness Ra (µm)	Minimize	4.3	12.6

5 OPTIMIZATION

By statistical analysis of experimental data, regression's equations explain the relations between input variables and the responses. The response optimizer in the DOE module of Minitab statistical software package 17, has been used to optimize input parametric based on the desirability function as mentioned in section 2.2. Table. 8 summarizes the criteria for optimizing process parameters. Maximum MRR, minimum TWR and minimum surface roughness are the criteria of the optimization.

In the optimization condition presented in Table. 8, the weight value of all three responses are the same (r=1). Fig. 9 illustrates the visual representation of the optimization results. Verification experiment was performed at the obtained optimal input parametric setting to enable comparison of the actual MRR, TWR, and Ra with those yielded optimal responses. Table 9 presents the optimization results along with experimentally obtained responses and their percentage relative verification errors. Clearly, the error percentage of the study is efficient for engineering applications.

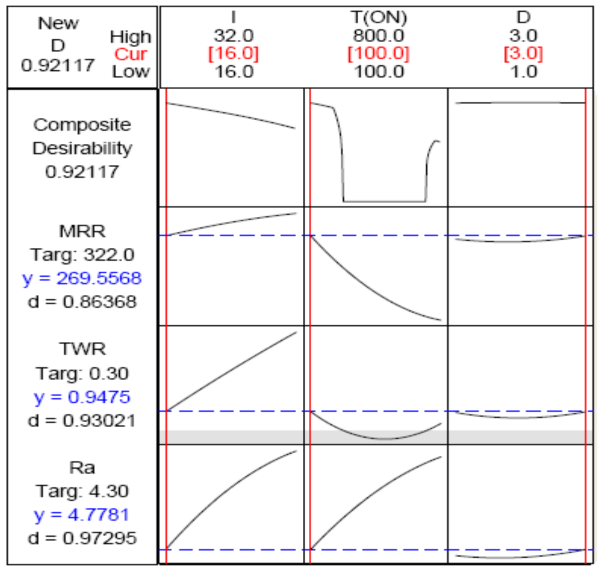

Fig. 9 Optimization results

Table 9 Optimum prediction results and experimental validation

Optimum input setting			MRR (mg/min)			TWR (%)			Ra (µm)		
I (A)	T(µs)	D (mm)	Predicted	Experimental	error(%)	Predicted	Experimental	error(%)	Predicted	Experimental	error(%)
16	100	3	269	280	3.73	0.947	1	5.25	4.78	4.4	8.59

6 COMPARISON BETWEEN EDM MILLING AND DIE SINK EDM

After optimization of the EDM milling process parameters, a comparison between EDM milling and die sink EDM was performed in the optimum condition. Output responses, MRR, TWR, and surface roughness were measured for each process. Table 10 shows the output parameters of die sink EDM vs. EDM milling results. Based on the results portrayed in Table 10, MRR of EDM milling is partially more than that of die sink EDM due to well-flushing which results from rotation of EDM milling electrode. In deep cutting depth, die sink EDM has deficiency in washing the waste material. So, the MRR will decrease in comparison with EDM milling.

Table 10 Output parameters of die sink EDM and EDM milling results

Experiment No	EDM milling	Die sink EDM
Current (A)	16	16
Pulse-on time (µs)	100	100
Depth of cut (mm)	3	3
Material removal rate MRR (mg/min)	280	260
Tool wear ratio TWR (%)	1	0.2
Surface roughness Ra (µm)	4.4	8

Table 4 indicates that tool wear ratio in EDM milling is more than that in die sink EDM because of the difference in electrode current density in two processes so that electrode current density in EDM milling is more than that in die sink EDM. Further, better and more washing of dielectric in EDM milling will cause more tool wear in EDM milling. However, TWR is not important in EDM milling because standard small cylindrical electrode is used in EDM milling and it is easy to produce and replace it while TWR is very important in die sink EDM. More TWR in die sink EDM results in more machining time, more material cost, and remanufacturing the complicated electrode. Surface roughness in EDM milling is lower than die sink EDM, Table 10; the reason is that in EDM milling the front surface of tool in primary surface were main sparks occurrence and groove surface (the surface in front of tool forehead) is secondary surface where secondary sparks take place; so crater depths in the front surface of tool will be more than that for groove surface while in die sink EDM, this situation is reversed because of the direction of tool movement.

Selecting EDM milling or die sink EDM depends on their economic assessment. Economic assessment is the total of EDM machining and tool costs. EDM cost consists of programming and tool set-up, roughing operation and finish operation, and tool cost includes costs of tool material, machining programming, and tool fabrication. Table 11 indicates a comparison of economic assessments between EDM milling and die sink EDM according to experimental work in this study.

Table 11 Economic assessment comparison between EDM milling and die sink EDM

Process	Tool weight (copper)	time-consuming of preparation and programming of tool fabrication	time-consuming of CNC tool machining
EDM milling	40g	0	0
Die sink EDM	200g	40 min	2 hours

Table 11 indicates that in EDM milling process, the time is not spent on preparation, programming and CNC machining. The more machining volume and more complex, the more difference between costs of the two processes would be. According to the mentioned points, Table 4 and Table 5, economic savings of EDM milling outperforms die sink EDM.

7 CONCLUSION

In the presented study an investigation of EDM milling by using DOE and comparing it with die sink EDM were done and the following conclusions can be drawn:

1. Curvatures on the developed response surfaces (3D plots) designate appropriate use of RSM. In addition, it demonstrates that the process parameter ranges have been selected correctly and the optimum setting would exist in the considered parameters space.
2. Increases in the current and decreases in pulse-on time cause more MRR and more TWR that lead to less machining accuracy.
3. Minimum surface roughness occurs in lower current and lower pulse-on time.
4. In general, depth of cutting has no significant effect on the MRR and TWR.
5. By performing process optimization, using desirability approach, the following settings can be described as the optimum settings of the EDM milling process: pulse-on time (T) = 2.5 µs, current (I) = 16 A, and depth of cut (D) = 3 mm
6. By comparing EDM milling with die sink EDM following items could be mentioned:
   - The more MRR, the more TWR, and the lower surface roughness are achieved in EDM milling (see Table 11).

- Economic savings is achieved in EDM milling by elimination of electrode fabrication and better dielectric flushing effect.

REFERENCES

[1] Ding, S., Jiang, R., "Tool Path Generation for 4-axis Contour EDM Rough Machining", Int J Mach Tool Manu, Vol. 44, No. 14, 2004, pp.1493-1502.

[2] Bleys, P., Kruth, J. P., and Lauwers, B., "Sensing and Compensation of Tool Wear in Milling EDM", J. Mater. Process. Technol, Vol. 149, No. 1-3, 2004, pp.139–146.

[3] Liu, Y. H., Li, X. P., Ji, R. J., Yu, L. L., and Zhang, H. F., "Effect of Technological Parameter on the Process Performance Electric Discharge Milling of Insulating Al_2O_3 Ceramic", J. Mater. Process. Technol, Vol. 208, No. 1-3, 2008, pp. 245-250.

[4] Bayramoglu, M., Duffill, A. W., "CNC EDM of Linear and Circular Contours using Plate Tools", J. Mater. Process. Technol, Vol. 148, No. 2, 2004, pp. 196–203

[5] Han, F., Wang, Y., and Zhou, M., "High-Speed EDM Milling with Moving Electric Arcs", INT J Mach Tool Manu, Vol. 49, No. 1, 2009, pp. 20-24

[6] Shamsborhan, M., Moradi, M., and Shokuhfar A., "Numerical Optimization of Planar Twist Channel Angular Extrusion as a novel severe plastic deformation method by DOE method", Modarres Mechanical Engineering, Vol. 16, No. 5, 2016, pp. 135-144, (in Persian).

[7] Moradi, M., Salimi, N., Ghoreishi, M., Abdollahi, H., Shamsborhan, M., Frostevarg, J., Ilar, T., and Kaplan, A. F. H., "Parameter Dependencies in Laser Hybrid Arc Welding by Design of Experiments and by a Mass Balance", J. Laser Appl, Vol. 26, No.2, 2014, pp. 1-9.

[8] Vahdati, M., Mahdavinejad, R., Amini, S., and Moradi, M., "Statistical Analysis and Optimization of Factors Affecting the Surface Roughness in UVaSPIF Process using Response Surface Methodology", Journal of Advanced Materials and Processing, Vol. 3, No. 1, 2015, pp. 15-28.

[9] Azadi, M., Azadi, S., Zahedi, F., and Moradi, M., "Multidisciplinary Optimization of a Car Component under NVH and Weight Constraints using RSM", ASME 2009 International Mechanical Engineering Congress and Exposition, Lake Buena Vista, Florida, USA, 13–19 November 2009, Vol. 15, pp. 315-319.

[10] Abdollahi, H., Mahdavinejad, R., Ghambari, M., and Moradi, M., "Investigation of Green Properties of Iron/jet-milled Grey Cast iron Compacts by Response Surface Method", Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, Vol. 228, No. 4, 2014, pp. 493-503.

[11] Assarzadeh, S., Ghoreishi, M., "Statistical Investigation into the Effects of Electro-Discharge Machining Parameters on WC/6%Co Composite-Part 2: Parametric Analysis and Optimization through Desirability Function (DF)", International Journal of Advanced Materials Manufacturing & Characterization, Vol. 3, No. 2, 2013, pp. 463-468.

[12] Karthikeyan, G., Garg, A. K., Ramkumar, J., and Dhamodaran, S., "A Microscopic Investigation of Machining Behaviour in ED-Milling Process", J. of Manuf. Process, Vol. 14, No.3, 2012, pp. 297–306.

[13] Jafferson, J. M., Hariharan, P., Kumar, J. R, "Effect of Non-electrical Parameters in μ ED Milling: an Experimental Investigation", Int J. Adv. Manuf. Technol., Vol. 95, 2016, pp. 15-22

[14] Yang Shen et al., "High-throughput Electrical Discharge Milling of WC–8%Co", Int J. Adv. Manuf. Technol., Vol. 82, No. 5, 2012, pp. 1071–1078

[15] Montgomery, D. C., "Design and Analysis of Experiments", Wiley, New York, 2005.

[16] Myers, R. H., Montgomery, D. C., "Anderson-Cook, Response Surface Methodology (RSM): Process and Product Optimization using Designed Experiments", 3rd ed., Wiley, New York, 2009.

[17] Khuri, A. I., Cornell, J. A., "Response Surfaces Design and Analysis", 2nd ed., Marcel Dekker, New York, 1996.

[18] "Minitab software", release 17, http://www.minitab.com.

[19] Chen, Y., Mahdavian, S. M., "Parametric Study into Wear in a Computer Numerical Controlled Electro-Discharge Machining Process Wear", Vol. 236, No. 1-2, 1999, pp. 350-354.