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Article

Performance Assessment and Mathematical Modeling of Process Parameters in Electrical Discharge Machining of EN-31 Tool Steel Material Using Taguchi DOE

P. N. L. Pavani[a], R. Pola Rao[b], and K. Santa Rao

Department of Mechanical Engineering, GMR Institute of Technology, Rajam-532127, Andhra Pradesh, India
E-mail: [a]pavani.pnl@gmrit.org (Corresponding author), [b]polarao.r@gmrit.org

Abstract. In non-traditional machining, electrical discharge machining (EDM) has tremendous potential on account of versatility of its applications and is successfully, commercially used in modern industries. EDM process is capable to machine geometrically complex, hard material components, tool steels, composites, super alloys, ceramics and carbides. In EDM, Material Removal Rate (MRR) and Tool wear rate (TWR) are generally analyzed to assess its performance. For this, a perfect combination of input variables is required. In the present study, machining is done on Tool steel workpiece material using a pure copper electrode. The input parameters like Pulse-ON time, Pulse-OFF time, Current and Gap voltage are selected for experimentation and Taguchi method is employed for the DOE by considering 4 factors and 3 levels. A total of 27 experiments (L_{27} orthogonal array) have been designed with a possible combination of selected input parameters. The present work mainly focuses on development of an extensive mathematical model for correlating the input and output variables using a conventional regression analysis. The adequacy of proposed model was tested with the help of some collected data through experimentation using Taguchi optimized DOE. The proposed linear multi-variable regression equation was found to be a best fitted model with 98% confidence levels.

Keywords: Electrical discharge machining (EDM), material removal rate (MRR), tool wear rate (TWR).

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1. Introduction

Electrical Discharge machining (spark machining) has found its applications in many industrial areas like die making, prototype manufacturing, profile making etc. It involves machining by providing current as an input and the material is removed due to a spark generated between the electrode & tool at regular intervals. A dielectric fluid is used as a medium for machining which determine the MRR and Surface finish of a workpiece. But, tools used in EDM process usually face high TWR for corresponding to low MRR which may lead to getting of inaccurate dimensions for product; so, this has become an important factor to be considered for the present study. Taguchi method was used to frame design of experiments by considering a standard L_{27} orthogonal array with three levels and four factors. The four important machining parameters considered for the present study are pulse-on time, pulse-off time, input current and gap voltage. In EDM, MRR is directly proportional to amount of energy applied during pulse –on time. Tzeng et al. (2007) [1] described the application of the fuzzy logic coupled with Taguchi methods to optimize the precision and accuracy of the high-speed EDM process. It has been found that pulse time, duty cycle and peak value of the discharge current are the important factors affecting the precision and accuracy of the EDM process.

Vikram Singh et al. (2014) [2] proposed a mathematical relation using response surface methodology technique by optimizing the WEDM parameters. To get maximum material removal, cutting rates and minimum surface roughness, Taguchi L_{27} orthogonal array was used to considering the optimal conditions for the machining variables. H. S. Payal et al. (2008) [3] analyzed electro discharge machined surfaces of EN-31 tool steel material by using scanning electron microscope and optical microscope to understand the mode of heat affected zone which may affect the structure of the machined surface and tool. During the study, it was found that the molten mass has been removed from surfaces as ligaments and sheets. Singaram et al. (2013) [4] presented a study on optimization of EDM parameters using response surface methodology. The EN-31 tool steel material has been machined using a 99.9% pure copper electrode and the process parameters were correlated with the responses for MRR. A second order mathematical equation has been proposed and has been validated with analysis of variance. Harpuneet Singh (2012) [5] investigated the Effect of Copper Chromium and Aluminum Electrodes on EN-31 Die Steel on Electric Discharge Machine Using Positive Polarity with copper chromium and brass electrodes. During the study it has been observed that the depth of cut and hardness was better with brass material while copper material has high MRR with low TWR. Priyesh et al. (2015) [6] studied Overcut Using EDM with a tool made of Graphite, Copper & Silver materials. Study has shown that the current was a significant parameter which affects the overcut in addition to pulse on time & pulse off time.

Selection of machining parameters is crucial in Electrical discharge machining process. Shailesh Dewangan et al. (2013) [7] studied about the selection of machining parameters in electrical discharge machining of AISI P20 tool steel material with impulse flushing system using three different electrode materials. L_{27} taguchi orthogonal array was framed with six different process parameters to observe the MRR and TWR. It was found that graphite electrode gives high MRR compared to copper and brass. The discharge current was directly proportional to both MRR and TWR where as pulse on time was inversely proportional to MRR and inversely proportional to TWR. Suraj et al. (2013) [8] analyzed MRR and SR with different electrode for SS 316 on Die-Sinking EDM using Taguchi Technique. L9 orthogonal array has been selected for the experimentation. Results have been analyzed by calculating signal-to-noise ratios to analyze the effect of input parameter more accurately. Due to the selection of less number of variables and factors, significant parameters for the output responses were not found.

Sultan et al. (2014) [9] proposed an optimized model with a Box-Behnken design involving three variables with three levels for determination of the critical experimental conditions. It has been found that surface roughness was influenced in electrically discharge machining of EN 353 steel alloy by all the three factors peak current, pulse on time, and pulse off time. The model developed was used to predict the experimental values and the error between them was comparatively less. Kibria et al. (2010) [10] made a comparative study of different dielectrics for micro-EDM performance during microhole machining of Ti-6Al-4V alloy. It has been observed that the mixing of boron carbide additive in deionized water has a great influence for enhancing the machining performance characteristics.

Tripathy et al. (2015) [11] proposed a multi-attribute optimized model of process parameters in powder mixed electro-discharge machining using Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and grey relational analysis. The proposed models predicted the results and the confirmation tests have shown an improvement 0.161689 and 0.2593 in the preference values using TOPSIS and GRA respectively. Sohani et al. (2009) [12] used the response surface methodology for analysis of effect of tool geometry in addition to the other edm parameters. The experimental results have shown that the circular shaped tool are preferable for getting high MRR and low TWR compared to the other tool profiles. M. K. Pradhan et al. (2010) [13] proposed regression and ANN models to predict the surface roughness in EDM ing of D2 steel. The models are tested with a new experimental data and the predictive nature of the proposed models has been analyzed. ANOVA technique was used to check the regression model and the statistical results have shown that the EDM parameters called input current and pulse on time have significant effect on surface roughness. Harshit Dave et al. (2016) [14] investigated the effect of different tool and work piece combinations in the analysis of MRR and TWR of an EDM process.

From the above literature, it has been identified that performance of EDM mainly depends on input parameters like pulse on time, pulse off time, current, gap voltage, work piece material and electrode material. The output parameters like MRR and TWR has been analyzed under various combinations of EDM parameters. For this, Taguchi approach has been used. Later, different techniques like ANOVA, ANN and Regression analysis are used to test and predict the experimental data. The present work aims on performance assessment and mathematical modelling of EDM parameters using taguchi DOE. A linear multi variable regression equation is found for all response variables.

2. Design of Experiments Using Taguchi Approach

While performing experimentation, one needs to vary the input parameters or the variables to observe the change in response variables. In this process, the number of experiments to be done for a reasonable response study, which usually varies with type of experimentation being conducted. For this, Statistical Design of experiments is an efficient method for obtaining valid results. DOE begins with determining the "objectives" of an experiment and selecting the "process factors" for the study. An Experimental Design is the laying out of a detailed experimental plan in advance of doing the experiment. Well-chosen experimental designs maximize the amount of "information" that can be obtained for a given amount of experimental effort. The statistical theory underlying DOE generally begins with the concept of process models. Often the experiment has to account for a number of uncontrolled factors that may be discrete, such as different machines or operators, and/or continuous such as ambient temperature or humidity.

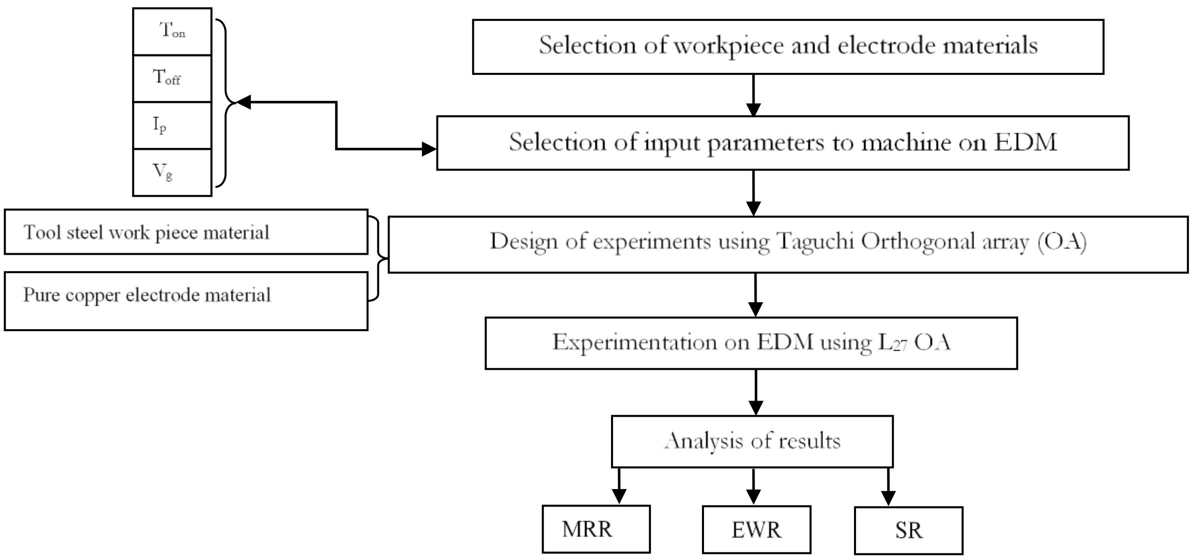

Fig. 1. Flow chart of experimentation.

Taguchi Technique for Design of experiments is framed and constructed to perform a selected number of experimentation having all the properties considered.

In the present study, experiments are designed by considering EDM process parameters like Pulse On time (T_{on}), Pulse off time (T_{off}), Input current (I_p) and Gap voltage (V_g). Taguchi approach is used to design a L_{27} orthogonal array with three levels and four factors ($3^{(4-1)}$ design) as shown in Fig. 1. The suggested orthogonal array can be used for proper selection of these machining parameters can result in a higher MRR and lower TWR as shown in Tables 1-3. The input parameter values are selected from range of values and operational limits of the EELECTRONICA smart ZNC EDM.

Table 1. Combination of machining parameters.

Factors / Levels	Pulse On time (T_{on})	Pulse off time (T_{off})	Input current (I_c)	Gap voltage (V_g)
1	1000	3	15	57
2	2000	6	30	64
3	3000	9	45	71

Table 2. Combinations of machining parameters as per L27 orthogonal array.

Run/Exp No	Pulse On time (T_{on}) (μs)	Pulse off time (T_{off}) (μs)	Input current (I_c) (amp)	Gap voltage (V_g) (V)
1	1	1	1	1
2	1	1	1	1
3	1	1	1	1
4	1	2	2	2
5	1	2	2	2
6	1	2	2	2
7	1	3	3	3
8	1	3	3	3
9	1	3	3	3
10	2	1	2	3
11	2	1	2	3
12	2	1	2	3
13	2	2	3	1
14	2	2	3	1
15	2	2	3	1
16	2	3	1	2
17	2	3	1	2
18	2	3	1	2
19	3	1	3	2
20	3	1	3	2
21	3	1	3	2
22	3	2	1	3
23	3	2	1	3
24	3	2	1	3
25	3	3	2	1
26	3	3	2	1
27	3	3	2	1

Table 3. Design of Experiments using Taguchi approach [15].

Exp. No	Pulse On time (T_{on}) (μs)	Pulse off time (T_{off}) (μs)	Input current (I_c) (amp)	Gap voltage (V_g) (V)
1	1000	3	15	57
2	1000	3	15	57
3	1000	3	15	57
4	1000	6	30	64
5	1000	6	30	64
6	1000	6	30	64
7	1000	9	45	71
8	1000	9	45	71
9	1000	9	45	71
10	2000	3	30	71
11	2000	3	30	71
12	2000	3	30	71
13	2000	6	45	57
14	2000	6	45	57
15	2000	6	45	57
16	2000	9	15	64
17	2000	9	15	64
18	2000	9	15	64
19	3000	3	45	64
20	3000	3	45	64
21	3000	3	45	64
22	3000	6	15	71
23	3000	6	15	71
24	3000	6	15	71
25	3000	9	30	57
26	3000	9	30	57
27	3000	9	30	57

3. Experimentation on EDM

The experiments on conducted on die sinking EDM of ELECTRONICA smart ZNC as shown in Fig. 2. EN 31 grade tool steel and pure copper materials are selected as work piece electrode for experimentation. The details of work piece and electrode are shown in Table 4. Workpiece and electrode materials of required dimensions (80mm x 80mm x40mm) and 40mmX φ 19mm were initially cut using a power hacksaw tool. Later the surfaces grounded using a surface grinding machine and also filed for getting a flat and smooth surface. In the current study, L_{27} OA experiments are repetitive in nature. Experiments were repeated as per the selected DOE to estimate the variability associated with the phenomena. The replication of experiments can be used to decide whether the selected process is worthful or not. In all the cases the values are close enough with minimum error.

4. Experimental Results

Based on L_{27} orthogonal array shown in Table 2, experiments were conducted on EDM. After each test run, weight loss in work piece and electrode materials was measured and output responses like material removal rate, electrode wear rate values are calculated and are tabulated in Table 4. The empirical relations used for calculation of MRR & TWR are shown in Eq. (1) and (2) [16].

In addition to MRR & TWR, surface roughness is also measured at three different places on the machined area by using a portable surface roughness tester Mitutoyo make SJ-201 make at three different places and average value is considered for analysis and then tabulated as shown in Fig. 3 and Table 5.

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Fig. 2. (a) Experimental setup (Electronica make smart ZNC die sinking machine) and (b) Electrode used.

Table 4. Details of work piece and electrode materials used for experimentation.

Work piece	
Work piece Material used & its composition	C-1.5%, Mn- 0.52%, Si- 0.22%, Cr-1.3%, S-0.05%, P- 0.05%
Dimensions of work piece	80mm x 80mm x40mm
Electrode	
Electrode Material used	Pure copper
Dimensions of Electrode	40mm X φ 19mm
Thermal conductivity of copper	380.7W/mK
Melting point	1083°C
Elastic modulus(E)	1.23×105 N/mm^2
Poisson’s ratio	0.26
Density	8.9 gm/cm^3

$$Material\ Removal\ rate\ (MRR) = \frac{Initial\ weight - Final\ Weight}{Density\ of\ material\ X\ Cycle\ time} \quad (1)$$

$$Electrode\ wear\ rate\ (EWR) = \frac{Initial\ weight - Final\ Weight}{Density\ of\ material\ X\ Cycle\ time} \quad (2)$$

5. Mathematical Modeling through Regression Analysis

Regression analysis is a statistical procedure for estimating relationships among variables. It includes many techniques for modeling and analyzing several variables, when the focus is on the relationship between a dependent variable and one or more independent variables (or 'predictors'). In order to study the performance of EDM process parameters of EN-31 tool steel material on the material removal rate, electrode wear rate and surface roughness a second order linear multi variable regression equation was developed using Minitab V17 software [17]. The proposed linear multi-variable regression equation can be used to find out the relationship between variables and a best fitted model was selected based on the Adjusted R^2 values. Adjusted R^2 is a measure to know the variation in the mean values of the proposed mathematical models.

During machining on EDM, input current & pulse- on time can be able to increase the depth of crater more because of high intensity of sparks generated. This leads to an increase in TWR, whereas with increase in Pulse-off time MRR decreases [18]. To check the variation of input variables on responses, in this study, regression equations are developed for the response variables like Material removal rate (MRR), Electrode wear rate (TWR) and Surface roughness (SR) in terms of the dependent variables like Pulse-on time, Pulse-off time, Input current and gap voltage.

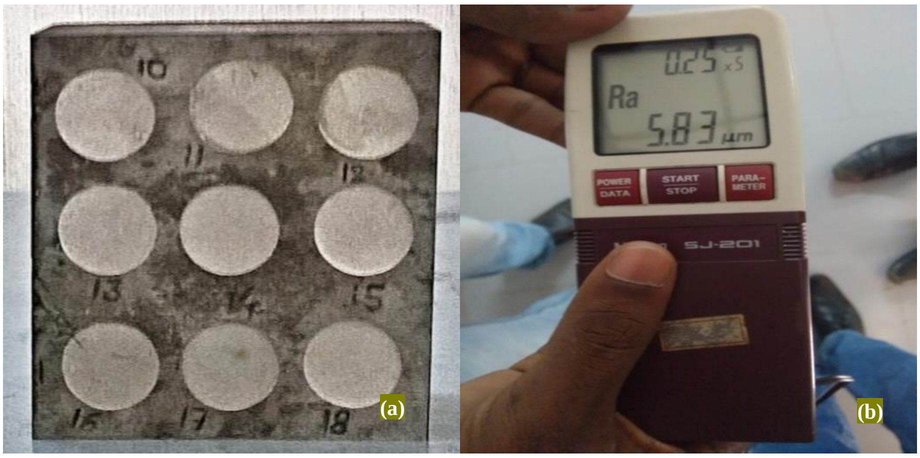

Fig. 3. (a) Work piece after machining and (b) Surface roughness measurement using roughness tester (Mitutoyo make SJ-201).

Table 5. Experimental results.

Exp. No	Material Removal Rate (MRR) (g/min)	Electrode Wear Rate TWR (g/min)	Surface Roughness SR (µm)			
			Trial 1	Trial 2	Trial 3	Average
1	2.15	1.88	2.45	3.31	2.48	2.75
2	2.15	1.88	2.11	2.59	3.08	2.6
3	2.15	1.87	2.37	2.08	2.98	2.48
4	2.09	1.84	3.22	3.35	2.87	3.15
5	2.09	1.84	3.29	2.9	3.18	3.13
6	2.08	1.84	3.3	3.12	2.9	3.11
7	3.51	4.69	3.26	2.78	2.87	2.97
8	3.51	4.68	3.1	3.03	2.56	2.9
9	3.51	4.68	3.19	2.83	2.91	2.98
10	4.72	6.21	4.79	7.31	5.79	5.97
11	4.72	6.21	5.94	4.83	6.01	5.6

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Exp. No	Material Removal Rate (MRR) (g/min)	Electrode Wear Rate TWR (g/min)	Surface Roughness SR (μm)			
			Trial 1	Trial 2	Trial 3	Average
12	4.72	6.21	6.01	5.33	4.18	5.18
13	1.99	6.96	2.54	4.98	3.83	3.79
14	1.98	6.96	3.19	3.88	2.9	3.33
15	1.98	6.96	4.96	5.02	5.18	5.06
16	1.73	1.92	3.08	4.21	4.91	4.07
17	1.73	1.52	2.99	4.01	3.53	3.51
18	1.73	1.52	4.21	3.84	3.9	3.99
19	1.65	5.77	2.75	2.62	2.55	2.64
20	1.65	5.77	2.69	2.38	3.41	2.83
21	1.65	5.77	2.9	3.53	3.58	3.34
22	1.73	1.52	3.03	3.8	2.99	3.28
23	1.73	1.52	3.26	2.78	3.19	3.08
24	1.73	1.52	2.93	3.54	3.07	3.18
25	1.77	3.17	3.58	4.02	3.98	3.86
26	1.77	3.16	2.93	3.12	2.79	2.95
27	1.77	3.17	3.69	3.13	2.85	3.23

Equations (3)–(5) shown below are the fitted regression models [18, 19] for calculating MRR, TWR and SR. Equations of MRR, TWR and SR are developed with 98% confidence levels. Validation of the suggested mathematical model is done for all output results and some of them are shown in Table 6.

$$MRR_v = -8.55384 - 0.001474*T_{on} - 1.33904*T_{off} - 0.208104*I_c + 0.295119*V_g - 0.000001*T_{on}^2 + 0.000489*T_{on}*T_{off} + 0.000087\ T_{on} * I_p + 0.016544\ T_{off}*I_c \quad (3)$$

R-sq-100%; R-sq(adj)-100%.

$$TWR = -4.924 + 0.009997*T_{on} - 0.895*T_{off} + 0.0062*I_c + 0.0096*V_g - 0.000002*T_{on}^2 - 0.000002*T_{off}^2 + 0.02186*T_{off}*I_c \quad (4)$$

R-sq-98.82%; R-sq(adj)-98.39%.

$$SR = 19.8 + 0.006027*T_{on} - 0.175*T_{off} + 0.2045*I_c - 0.780*V_g - 0.000001*T_{on}^2 + 0.0101*T_{off}^2 - 0.003353*I_c^2 + 0.00641*V_g^2 \quad (5)$$

R-sq-98.82%; R-sq(adj)-98.39%.

where T_{on} is Pulse on time (μs); T_{off} is Pulse off time (μs); I_c is Input current (Ω), and V_g is the gap Voltage (V).

Table 6. Validation of results.

Exp. No	Exp.MRR (g/min)	MRR from Regression (g/min)	Error (%)	Exp.TWR (g/min)	TWR from Regression (g/min)	Error (%)	Exp. SR (μm)	SR from Regression (μm)	Error (%)
1	2.15	2.18	1.39	1.88	2.02	7.45	2.75	3.08	12
7	3.51	3.53	0.56	4.69	4.84	3.2	2.97	3.42	15.2
9	3.51	3.53	0.56	4.68	4.84	3.42	2.98	3.42	14.8
10	4.72	4.84	2.54	6.21	7.22	16.27	5.97	7.48	25.3
15	1.98	2.09	5.55	6.96	8.43	21.13	5.06	5.95	17.6

6. Conclusions

The objective of present study is to investigate effect of EDM process variables in order to optimize MRR, TWR & Ra using Taguchi's robust design methodology and to develop a mathematical model to predict all response variables using linear multi-variable regression analysis. A standard L_{27} OA was using the selected input variables to check the variation of response variables like MRR, TWR and SR. The experimental design with replication in experiments has been used to check the variability, repeatability and accuracy of EDM performance under different machining conditions. Based on the results of experimental investigations the following conclusions are made.

- The results of the present study, machining of EN-31 Tool steel with a pure copper electrode have shown better results in increasing MRR and decreasing TWR.
- It is also observed that the surface roughness values under all machining conditions were low compared to the other electrode materials.
- Taguchi methodology was useful in identifying the best combination of tool, work piece and process variables.
- During the study, it is also seen that the total number of experiments possible with the selected combination of machining parameters is also minimized to some extent by considering a Taguchi L_{27} orthogonal array.
- Mathematical relations are developed using a linear multi-variable regression model for all response variables using Minitab v.17 software.
- The validation of proposed regression model for MRR, TWR &Ra is satisfactory with minimum error.
- So the proposed regression models can be used to get a best fit between the process and response variables.

7. Scope for future work

In future, work will be extended by performing ANOVA of the results obtained in this study and also to get the idea of microstructures through microscopic analysis. At present, authors are in the same process.

Nomenclature

MRR = Material Removal rate
TWR= Tool Wear rate
SR= Surface roughness
T_{on}= Pulse on time
T_{off}=Pulse off time
I_c= Input current
V_g= Gap voltage

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