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APPLICATION OF RESPONSE SURFACE METHOD FOR MODELLING OF STATISTICAL ROUGHNESS PARAMETERS ON ELECTRIC DISCHARGE MACHINING

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ABSTRACT

The prediction of optimal machining conditions for good surface finish plays a very important role in process planning. The objective of this paper is to study the influence of machining parameters of EDM for machining of tungsten carbide (WC) using electrolyte copper of negative polarity on machining characteristics. The second order mathematical models in terms of machining parameters were developed for surface roughness prediction using response surface methodology (RSM) on the basis of experimental results. All the experiments are conducted on the basis of design of experiments having faced centered central composite designs. RSM is used to determine the cause and effect relationship between mean responses and input control variables. The model selected for optimization has been validated with F-test. The adequacy of the models on response parameters have been established with Analysis of Variance (ANOVA).An attempt has been taken to optimize process parameters using RSM optimization.

Key words: EDM, ANOVA, Response Surface Methodology (RSM)

1. INTRODUCTION

Electrical Discharge Machining is a non-traditional machining technique, which is widely used to produce finish parts through the action of an electrical discharge of short duration and high current density between the tool and workpiece. The tool and the workpiece are free from the physical contact with each other. Generally, the EDM is used for machining of electrical conductive materials in the presence of a dielectric fluid.

Since EDM was developed, much theoretical and experimental work has been done to identify optimum process parameters. Even though many research developments have been carried out in EDM process which is classified into four broad categories; workpiece related, electrode performance related, EDM methods related and optimization of the EDM process based on performance parameters. A good number of studies [1-7] have considered the machinability for different workpiece materials while some studies [8-9], have concentrated on the performance of different electrode materials. A few studies [10-15] have been devoted to the variation of the EDM process. The evaluation of the performance characteristics and optimization of machining parameters have received maximum research attention [16-19]. This is because proper selection of the machining parameters can yield the best performance with a particular machining setup. It is in general observed that out of the three main performance characteristics, MRR and EWR have traditionally received greater research attention in comparison to surface roughness even though EDM is largely used for its high precision quality. Moreover, an extensive review of literature on roughness studies of EDMed surfaces reveals the fact that the centerline average roughness (R_a) has been the focus of most of the investigations. However, a surface generated by machining is composed of a large number of length scales of superimposed roughness and generally characterized by three different types of parameters, viz., amplitude parameters, spacing parameters and hybrid parameters. Amplitude parameters are measures of the vertical characteristics of the surface deviations and examples of such parameters are centre line average roughness, root mean square roughness, skewness, kurtosis, peak-to-valley height etc. Spacing parameters are the measures of the horizontal characteristics of the surface deviations and examples of such parameters are mean line peak spacing, high spot count, peak count etc. On the other hand, hybrid parameters are a combination of both the vertical and horizontal characteristics of surface deviations and example of such parameters are root mean square slope of profile, root mean square wavelength, core roughness depth, reduced peak height, valley depth, peak area, valley area etc. Thus consideration of only one parameter like centre line average roughness is not sufficient to describe the surface quality though it is the most commonly used roughness parameter. The present study aims at consideration of three different roughness parameters, viz., centre line average roughness (R_a), root mean square roughness (R_q), and mean line peak spacing (R_{sm}) for the surface texture generated in EDM of tungsten carbide. A face-centered central composite (FCC) experimental design is used in the present investigation. In addition to the direct evaluation of the variables involved in the process, this design allows the study of the interactions among them and the modeling of multifactorial response surfaces, thus providing a great deal of information about the behaviour of the system with the help of a rather small number of experiments [20]. Statistical models have been developed using response surface methodology based on experimental results considering the machining parameters, viz., pulse current (I, amp), pulse-on time (t_i, μ s) and pulse-off time (t_o, μ s) as independent variables. Finally, an attempt has been made to obtain optimum machining conditions with respect to each of the roughness parameters considered in the present study with the help of response optimization technique.

2. RESPONSE SURFACE METHODOLOGY

Response Surface Method (RSM) adopts both mathematical and statistical techniques which are useful for the modeling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize the response. RSM helps in analyzing the influence of the independent variables on a specific dependent variable (response) by quantifying the relationships amongst one or more measured responses and the vital input factors. The mathematical models thus developed relating the machining responses and their factors facilitate the optimization of the machining process. In most of the RSM problems, the form of the relationship between the response and the independent variables is unknown. Thus the first step in RSM is to find a suitable approximation for the true functional relationship between response of interest 'y' and a set of controllable variables $\{x_1, x_2, \ldots\ldots x_n\}$. Usually when the response function is not known or non-linear, a second order model is utilized [20] in the form:

$$y = b_0 + \sum_{i=1}^{n} b_i x_i + \sum_{i<j}^{n} b_{ij} x_i x_j + \sum_{i=1}^{n} b_{ii} x_{ii}^2 + \varepsilon \qquad (1)$$

where, ε represents the noise or error observed in the response y such that the expected response is (y - ε) and b's are the regression coefficients to be estimated. The least square technique is being used to fit a model equation containing the input variables by minimizing the residual error measured by the sum of square deviations between the actual and estimated responses. The calculated coefficients or the model equations however need to be tested for statistical significance and thus the following test is performed.

2.1 Significance Test Of The Regression Model

Analysis of Variance (ANOVA) is used to check the adequacy of the model for the responses in the experimentation. ANOVA calculates the F-ratio, which is the ratio between the regression mean square and the mean square error. The F-ratio, also called the variance ratio, is the ratio of variance due to the effect of a factor (the model) and variance due to the error term. This ratio is used to measure the significance of the model under investigation with respect to the variance of all the terms included in the error term at the desired significance level, α . If the calculated value of F-ratio is higher than the tabulated value of F-ratio for roughness, then the model is adequate at desired α level to represent the relationship between machining response and the machining parameters.

3. EXPERIMENTAL DETAILS

3.1 Design of Experiment

The design of experiments technique is a very powerful tool, which permits us to carry out the modeling and analysis of the influence of process variables on the response variables. The response variable is an unknown function of the process variables, which are known as design factors. There are a large number of factors that can be considered for machining of a particular material in EDM. However, the review of literature shows that the following three machining parameters are the most widespread among the researchers and machinists to control the EDM process: pulse current (I, amp), pulse-on time (t_i, μ s) and pulse-off time (t_o, μ s). In the present study these are selected as design factors while other parameters have been assumed to be constant over the experimental domain. A face-centered central composite (FCC) design is used with three levels of each of the three design factors. A k factor 3-level FCC experimental design requires 2^k+2k+C experiments, where 2^k points are in the corners of the cube representing the experimental domain, $2k$ points are in the center of each face of the cube and C points are the replicates in the center of the cube that are necessary to estimate the variability of the experimental measurements, it is to say the repeatability of the phenomenon. Therefore considering three factors and six replicates at the center point, the present design contains 20 experiments, which were performed in a random order. The upper and lower limits of a factor are coded as +1 and -1 respectively, the coded value being calculated from the following relationships:

$$x_i = \frac{[2x - (x_{\max} + x_{\min})]}{(x_{\max} - x_{\min})} \qquad (2)$$

where x_i is the required coded value of a variable x. The process variables / design factors with their values on different levels are listed in Table 1. The selection of the values of the variables is limited by the capacity of the machine used in the experimentation as well as the recommended specifications for different workpiece - tool material combinations. Table 2 shows the experimental matrix of the FCC design employed in the present study.

Table 1: Variable levels used in the experimentation

Levels	***Current*** ***(I, amp)***	***Pulse on time*** ***(t_i, μ s)***	***Pulse off time*** ***(t_o, μ s)***
-1	3.125	50	50
0	6.250	100	75
1	9.375	150	100

Table 2: Face Center Composite Design Matrix

Std. Order	***Run order***	R_a	R_q	R_{sm}
1	7	-1	-1	-1
2	5	1	-1	-1
3	9	-1	1	-1
4	3	1	1	-1
5	2	-1	-1	1
6	18	1	-1	1
7	14	-1	1	1
8	19	1	1	1
9	6	-1	0	0
10	11	1	0	0
11	1	0	-1	0
12	16	0	1	0
13	13	0	0	-1
14	17	0	0	1
15	4	0	0	0
16	20	0	0	0
17	10	0	0	0
18	8	0	0	0
19	15	0	0	0
20	12	0	0	0

3.2 Response Variables Selected

The response variables used to accomplish the present study on surface roughness are the following:

(i) Centre line average roughness (R_a):

It is defined as the arithmetic mean deviation of the surface height from the mean line through the profile while the mean line is defined so as to have equal areas of the profile above and below it. R_a may be expressed in the form:

$$R_a = \frac{1}{L}\int_0^L |Z(x)|\,dx \tag{3}$$

where *Z(x)* is the ordinate of the profile curve, *x* is the profile direction and *L* is the sampling length. The unit of R_a is μ m.

(ii) Root mean square roughness (R_q):

It represents the standard deviation of the distribution of surface heights. Its unit is also μ m. It is defined as the root mean square deviation of the profile from the mean line and is expressed as:

$$R_q = \sqrt{\frac{1}{L}\int_0^L [Z(x)]^2\,dx} \tag{4}$$

(iii) Mean line peak spacing (R_{sm}):

It is defined as the mean spacing between peaks, with a peak defined relative to the mean line (a peak must cross above the mean line and then back below it). This parameter may be expressed in the form:

$$R_{sm} = \frac{1}{m}\sum_{n=1}^{m} S_n \tag{5}$$

where *m* is the number of peak spacing and *S* is the spacing between two consecutive peaks. Its unit is *mm*.

3.3 Equipment Used

The machine used for machining is a 'Toolcraft A25' EDM machine having the stepped drive servo system and filtration flushing capability. It is capable of generating maximum pulse current of 25 ampere, pulse on time of 2000 μ s and pulse off time of 2000 μ s.

3.4 Tool electrode used

Electrolytic copper having 99.9% copper in composition and density 8904 kg/m^3 was used as tool electrode since it worked better in combination with the workpiece materials considered in the present study. The tool electrode was in the form of cylinder of diameter 15.9 mm and mounted axially in line with workpiece. The tool electrode was given negative polarity. Kerosene was used as dielectric because of its high flash point, good dielectric strength, transparent characteristics and low viscosity and specific gravity.

3.5 Work Piece Materials

The present study was carried out with tungsten carbide (WC). The Electrical resistivity is 6 x 10^{-5} ohm-cm, Thermal conductivity: 84 W/m-K and melting point: 2850^0 C. All the specimens were in the form of 20 mm x 20 mm x 4 mm blocks.

3.6 Roughness Measurement

Roughness measurement was done using a portable stylus-type profilometer, *Talysurf* (Taylor Hobson, Surtronic 3+). The profilometer was set to a cut-off length of 0.8 mm, filter 2CR, traverse speed 1 mm/sec and 4 mm traverse length. Roughness measurements, in the transverse direction, on the work pieces were repeated four times and average of four measurements of surface roughness parameter values was recorded. The measured profile was digitized and processed through the dedicated advanced surface finish analysis software *Talyprofile* for evaluation of the roughness parameters.

Table 3: Observed Responses of surface parameters.

Std. Order	***Run order***	R_a***(μ m)***	R_q***(μ m)***	R_{sm}***(mm)***
1	7	1.2966	1.8033	0.0356
2	5	3.9300	4.8233	0.1183
3	9	3.2166	3.9900	0.0815
4	3	5.8933	7.3033	0.1450
5	2	2.4733	2.9700	0.0802
6	18	4.2833	5.2033	0.1370
7	14	4.5133	5.4433	0.1002
8	19	6.7933	8.3900	0.1770
9	6	2.7163	3.3063	0.0778
10	11	6.6600	8.0933	0.1546
11	1	4.3500	5.2466	0.1276
12	16	7.5266	8.8600	0.1630
13	13	5.0200	5.9933	0.1310
14	17	4.1430	5.5033	0.0763
15	4	6.8866	8.0833	0.1823
16	20	4.5633	5.5333	0.1204
17	10	5.6666	6.6933	0.1373
18	8	4.0700	4.9133	0.1129
19	15	4.2100	5.1400	0.1230
20	12	6.0166	7.1033	0.1580

4. RESULTS AND DISCUSSION

The influences of the electrical discharge machining parameters (current, pulse on- time and pulse off time) on the response variables selected have been assessed for tungsten carbide. The second order model was postulated in obtaining the relationship between the surface roughness parameters and the machining variables. The analysis of variance (ANOVA) was used to check the adequacy of the second order model. The second order response surface equations have been fitted using the equations can be given in terms of the coded values of the independent variables as the following:

$$\begin{aligned} R_a &= 5.34 + 1.33I + 1.16t_i + 0.285t_o \\ &+ 0.064It_i - 0.153It_o + 0.083t_it_o \\ &- 0.797I^2 + 0.453t_i^2 - 0.904t_o^2 \end{aligned} \tag{6}$$

$$\begin{aligned} R_q &= 6.39 + 1.63I + 1.39t_i + 0.36t_o \\ &+ 0.126It_i - 0.144It_o + 0.124t_it_o \\ &- 0.916I^2 + 0.437t_i^2 - 0.868t_o^2 \end{aligned} \tag{7}$$

$$\begin{aligned} R_{sm} &= 0.136 + 0.0357I + 0.0168t_i \\ &+ 0.0059t_o + 0.0001It_i - 0.0016It_o \\ &- 0.0016t_it_0 - 0.0147I^2 + 0.0144t_i^2 - 0.0273t_o^2 \end{aligned} \tag{8}$$

The analysis of variance (ANOVA) and the *F*-ratio test have been performed to check the adequacy of the models as well as the significance of the individual parameters. The ANOVA table for R_a, R_q and R_{sm} are presented in Table (4-6). Table 4 presents the ANOVA table for the second order model proposed for R_a given in equation (6). It can be appreciated that the *P*-value is less than 0.05 which means that the model is significant at 95% confidence level. Also the calculated value of the *F*-ratio is more than the standard value of the *F*-ratio for R_a. It means the model is adequate at 95% confidence level to represent the relationship between the machining response and the machining parameters of the EDM process. Similarly, analysis of variance is carried out for all the response models. Calculated *F*-value of the lack-of-fit for R_a, R_q, and R_{sm} are 0.786, 0.819, and 0.541 respectively. These calculated F- values of the lack-of-fit for different surface parameters are very much lower than the tabulated value of the F-distribution found from the standard table at 95% confidence level. It implies that the lack-of-fit is not significant relative to pure error. Therefore, the developed second-order regression models for R_a, R_q and R_{sm} are adequate at 95% confidence level. The R^2 value is high, close to 1, which is desirable. Table 6 presents the summary of significant machining parameters for all the roughness parameters in EDM of tungsten carbide. Fig. 1-3 depicts the main effects plot for the roughness parameters and the design factors considered in the present study. From this figure also, the significant effects can be identified. The centre line average (*CLA*, R_a), root mean square roughness value R_q and mean line peak spacing R_{sm} decreases with increase in current and pulse -on-time where as the pulse -off-time having no significant effect. Figs. 4 show the estimated three-dimensional surface as well as contour plots for the roughness parameters as functions of the independent machining parameters. In all these figures, one of the three independent variables is held constant at central level. All these figures depict the variation of the roughness parameters with controlling variables within the experimental regime. Finally, since optimization of machining parameters increases the utility for machining economics as well as the product quality to a great extent, an effort has been made to estimate the optimum machining conditions to produce the best possible surface quality within the experimental constraints. In this context, a response surface optimization is attempted using Minitab software [21] for individual roughness parameters in EDM of tungsten carbide. The objective function for optimization is set as minimization of R_a, R_q and R_{sm}. Table 7 shows the RSM optimization results for the roughness parameters in EDM of tungsten carbide. It shows a very good agreement with predicted value.

Table 4: ANOVA for second order model for R_a in EDM

Source	*df*	*SS*	*MS*	*F*	*P*
Model	9	40.359	4.4843	4.77	0.011
Linear	3	32.096	10.698	11.39	0.001
Square	3	7.9877	2.6626	2.83	0.092
Interaction	3	0.2746	0.0915	0.1	0.96
Residual Error	10	9.3936	0.9394		
Lack-of-Fit	5	3.0096	0.6019	0.47	0.786
Pure Error	5	6.384	1.2768		
Total	19	49.752			

R-Sq = 81.1%   R-Sq(adj) = 64.1%

Table 5: ANOVA for second order model for R_q

Source	***df***	***SS***	***MS***	***F***	***P***
Model	9	56.7185	6.3021	5.68	0.006
Linear	3	47.2962	15.765	14.2	0.001
Square	3	9.006	3.002	2.71	0.102
Interaction	3	0.4163	0.1388	0.13	0.943
Residual Error	10	11.0926	1.1093		
Lack-of-Fit	5	3.2747	0.6549	0.42	0.819
Pure Error	5	7.818	1.5636		
Total	19	67.8112			

R-Sq = 83.6%   R-Sq(adj) = 68.9%

Table 6: ANOVA for second order model for R_{sm}

Source	***df***	***SS***	***MS***	***F***	***P***
Model	9	0.02055	0.00228	3.4	0.035
Linear	3	0.01589	0.00529	7.88	0.005
Square	3	0.00462	0.00154	2.29	0.14
Interaction	3	0.00004	0.00001	0.02	0.996
Residual Error	10	0.00671	0.00067		
Lack-of-Fit	5	0.00319	0.00063	0.91	0.541
Pure Error	5	0.00352	0.00070		
Total	19	0.02727			

R-Sq = 75.4%   R-Sq(adj) = 53.2%

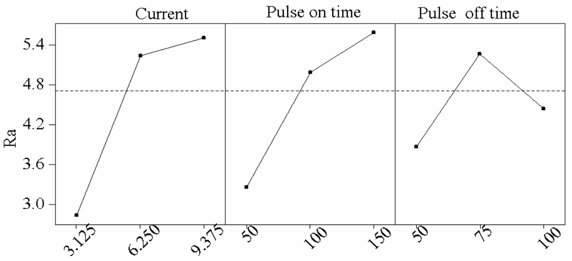


Fig 1: Main effect plot for R_a

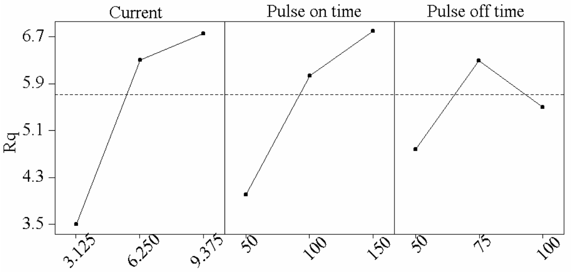


Fig 2: Main effect plot for R_q

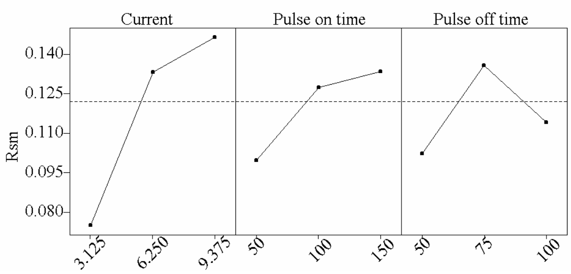
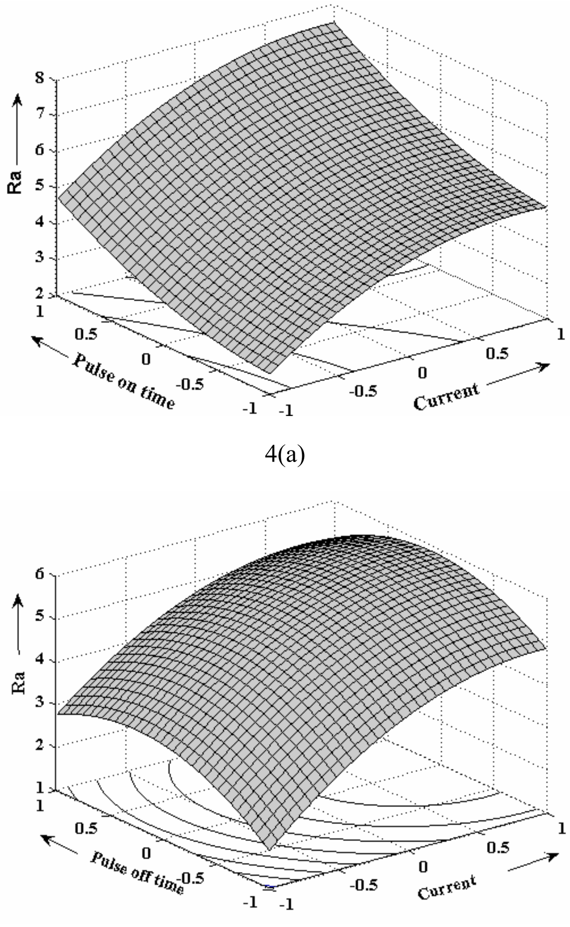


Fig 3: Main effect plot for R_{sm}



4(a)

4(b)

Fig 4: Surface and contour plots for R_a in EDM
(a) Current vs pulse on time (b) Current vs pulse -off time

Table 7: Summary of significant parameters on WC

Roughness Parameters	***Significant parameters***
R_a	Current(I), Pulse-on-time (t_i)
R_q	Current(I), Pulse-on-time (t_i)
R_{sm}	Current(I), Pulse-on-time (t_i)

Table 8: RSM optimization for roughness parameters

Param -eters	***Optimum combination***			***Predict value***	***Exp. value***	***% of error***
	I	t_i	t_0			
R_a	3.125	50	50	1.3021	1.3824	-6.1
R_q	3.125	50	50	1.7687	1.6423	7.12
R_{sm}	3.125	68	50	0.0448	0.0488	-8.9

5. CONCLUSIONS

The present study develops roughness models for three different roughness parameters using response surface method in case of EDM process. The second order response models have been validated with analysis of variance. The investigations indicate that among the different machining parameters, pulse current and pulse on time have the maximum influence on the roughness parameters while pulse of time has no significant effect on roughness parameters. Finally, an attempt has been made to estimate the optimum machining conditions to produce the best possible surface quality within the experimental constraints. Optimum EDM parameter combinations for different roughness parameters depend greatly on the workpiece material within the experimental domain. Thus it may be concluded that roughness modeling in EDM is specific to the roughness parameter of particular concern as well as to the workpiece-tool material combination employed in the process.

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7. NOMENCLATURE

Symbol	Meaning	Unit
I	Current	Amp
t_i	Pulse-on-time	(μ s)
t_o	Pulse-off-time	(μ s)
R_a	Centre Line Average(CLA)	(μ m)
R_q	Root mean Square	(μ m)
R_{sm}	Mean line peak spacing	mm