EFFECT OF PARAMETERS ON ELECTRICAL DISCHARGE MACHINING OF EN-19 ALLOY STEEL THROUGH RESPONSE SURFACE METHODOLOGY APPROACH

Sachin C. Kulkarni[1], Maharudra S. Patil[2], Anand V.Kulkarni[3]

[1, 2, 3] Department of Mechanical Engineering, K.L.S Gogte Institute of Technology, Belgaum, (India)

ABSTRACT

In this study, an attempt has been made to investigate the effect of process parameters in electrical discharge machining of EN-19 alloy steel through response surface methodology approach. The controllable parameters used are discharge current, spark on time and spark off time and the resulting responses are work piece erosion rate and tool erosion rate. The experiments were conducted using copper and brass as tool electrodes. The design matrix has been obtained through Box Behnken design and is used to develop the mathematical models of the above responses. The lack of fitness and competency of the developed models has been verified by analysis of variance (ANOVA). Confirmative tests have been performed to authenticate the outcome and they are found to be in 95% confidence level.

Keywords: Analysis Of Variance (ANOVA), Box Behnken Design (BBD), Electrical Discharge Machining (EDM), Response Surface Methodology (RSM), Tool Erosion Rate (TER). Work Piece Erosion Rate (WER).

I. INTRODUCTION

The use of a thermoelectric source of energy in developing the non-conventional techniques has greatly helped in achieving an economical machining of extremely hard with low machinability and difficult machine materials. EDM is now unquestionably recognized as an important precision machining process for producing intricate shapes which are difficult to produce using traditional machining process. The process of material removal in this technique is by melting and evaporation. In EDM, the process of machining is by removing the material through a series of rapidly generated electrical sparks between the tool electrode and workpiece. [1]. With this manufacturing process it is possible to produce simple as well as intricate, profiles and geometries of exceptionally hard material which are difficult to machine using traditional methods. In this process hundreds of thousands of sparks are produced every second. Each spark attains a temperature ranges between 8,000°C - 12,000°C [2] or the elevated temperature measured is 20,000°C [3] and therefore melts and evaporates a tiny volume of the work piece. Thus a tiny depression is produced at the location of the spark. Each spark occurs at different locations depending on the minimum gap between work piece and the tool. Eventually the gap between workpiece and tool is uniform and therefore work piece surface attains the shape of the tool [4]. The plasma channel is the site where the vaporization of the electrode is confined [5]. Various parameters like discharge current, spark on time and spark off time, tool electrode and work material, dielectric flushing conditions affect the responses. The physical properties like high electrical and thermal conductivity, high melting point are the pre-requisites of an EDM tool. Materials with good electrical conductivity qualify as work material irrespective of their hardness. The alloy steel with composition, as stated in Table 2, is widely used in industrial components like axle shafts, crankshafts, connecting rods, gears, high tensile bolts and studs, propeller shaft joints, rifle barrels and breech mechanisms for small arms parts, hardened track pins etc. The spectrum of application of EDM is ever growing as a non-traditional technique. Hence, using controllable parameters like discharge current, spark on time and spark off time the performance measures like WER and TER were studied with different tool electrodes.

Mohammadreza Shabgard et al. [6] studied the effect of input parameters on the characteristics of the EDM process. The experiments were conducted using full factorial Design; pulse on-time and pulse current were chosen as parameters for the study. Y. H. Guu and H. Hocheng [7] have used electrical discharge machining to study the machinability of a rotating workpiece. Dilshad Ahmad Khan and Mohammad Hameedullah have studied the effect of tool polarity on the responses of silver steel using EDM. [8]. They have used 32 factorial design for planning of experimental conditions and silver steel of grade 28 as the work material, copper is used as tool electrode. At different current and pulse intervals the responses like MRR and TWR were measured with positive and negative polarity settings. Dhananjay Pradhan and Dr. S. C. Jayswal [9] have investigated the behavior of copper and aluminium electrodes on the EDM of EN-8 alloy steel. To examine this behavior copper and aluminium were used as electrode materials with Kerosene oil as the dielectric medium. Keeping all other machining parameters same, the hardened work material (EN-8) was machined with the two electrodes at predetermined values of peak current, Spark on time & duty factor according to the 23 full factorial design. It has been found that copper shows better results than aluminium in same dielectric media. Therefore, copper is recommended as a good electrode material. They observed the formation of a black layer [10] on the surface of the tool electrode and machined surface when machining is carried out. The relationship and parametric interaction between three controllable variables on MRR have been examined using an RSM approach by MohanKumar Pradhan & Chandan Kumar Biswas [11]. ANOVA at the 95 % confidence level was performed and they observed results were satisfactory. H.K. Kansal, Sehijpal Singh and P. Kumar [12] carried out the experiments on EN- 31 work piece material using copper tool electrode using die-sink ED machine. Optimization of process parameters of powder mixed electrical discharge machining (PMEDM) is the main objective of this study. A new experimental set-up was developed in the laboratory to perform the experiments. The results obtained give an insight of important parameters and aid in maximizing the MRR. The confirmatory tests were performed to verify the recommended optimal process conditions. An error of -7.85% was observed between experimental and predicted values of MRR. A.K.M. Asif Iqbal and Ahsan Ali Khan [13] have studied the influence of process parameters in electrical discharge machining of stainless steel AISI 304. They have used copper tool electrode in EDM, milling operation. In their research, experiments were designed by using response surface methodology (RSM).

II. EQUIPMENT USED AND EN19 ALLOY STEEL EDMED

In the present investigation, the experiments were performed using ELECTRONICA make “ELECTRA PRIDE-Z” die-sink type EDM machine. The work piece material used in the study is EN-19 alloy steel having the Ø60 mm x 8 mm thickness and the tool electrodes of being copper and brass with Ø 20mm x 100mm long.

The chemical composition of work material is indicated in Table 1 and the key properties of the work piece and electrode materials are shown in Table 2 and Table 3 respectively. Kerosene is used as a dielectric medium/fluid to carry away the debris and carbon formed during machining throughout the experiments.

Fig. 1, Fig. 2 and Fig.3 shows the photograph of the tools and work pieces used for the experiments. Oil quenching method was used to obtain the desired properties like hardness of 47 HRc and a density of 7.77 gm/cm^3. A surface grinding machine is used to grind the top and bottom faces of the work piece before experimentation. The polishing machine is used to remove the carbon deposition on the bottom surface of the tool electrode. The initial weights of the work piece and the tool electrodes were taken by using the digital electronic balance of accuracy 0.005g. The work piece was properly clamped on the fixture and was connected to positive (+) polarity and the tool electrode was connected to the negative (-) polarity of the power supply. The machining time was set to 20 minutes for every experiment. At the end of each experiment the work piece and the tool electrode were unclamped, washed, dried and weighed again on the electronic balance to observe the difference between the weights and hence the WER and TER were obtained. The procedure was repeated for each experiment and required data was collected.

Table 1 Chemical Composition of En-19 Alloy Steel

Work material	Elements					
	Carbon, C	Silicon, Si	Manganese, Mn	Chromium, Cr	Molybdenum, Mo	Iron , Fe
EN-19 alloy steel	0.35 - 0.45 %	0.1 - 0.35 %	0.50 - 0.80 %	0.90 - 1.50 %	0. 20 -0.40 %	Balance

Table 2 Key Properties of Work Piece Material

Work material	Properties							
	Thermal conductivity (W/m-°K)	Melting point (°C)	Electrical resistivity (10^{-9}W-m)	Specific heat capacity (J/kg-K)	Hardness (HRc)	Tensile strength (MPa)	Yield strength (MPa)	Percentage elongation at break (%)
EN-19 alloy steel	42.7	1415	222	473	43-47	655	417.1	25.7

Table 3 Key Properties of Electrode Material

Electrode materials	Thermal conductivity (W/m-°K)	Melting point (°C)	Electrical resistivity (ohm-cm)	Specific capacity (J/g-°C)
Copper	391	1,083	1.69	0.385
Brass	159	990	4.7	0.38

Figure 1 EDM Machine Used To Carry Out The Experiments

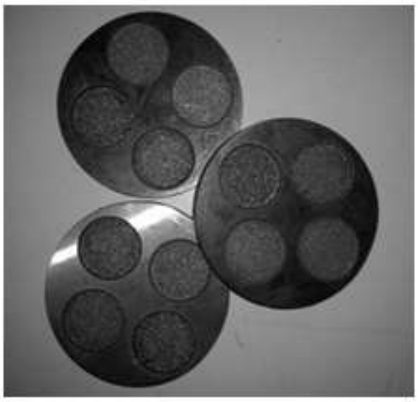

Figure 2 Work Pieces Used To Carry Out The Experiments.

Figure 3 Tool Electrodes Used To Carry Out The Experiments.

III. DESIGN OF EXPERIMENTS

In this section, we will have a macroscopic view of the methodology, design matrix, design factors and also the response variables that have been chosen for this study, these have been described in section 3.1.

3.1 Design factors selected

Discharge current (I), spark on time (T_i) and spark off time (T_o) be identified as controllable factors that affect the response variables. Preliminary experiments were conducted extensively to select various levels of the process parameters. These are summarized in Table 4.

Table 4 Experimental Parameters and Their Levels

	Machining parameters	Uncoded values	Coded values	Levels			Ranges
				Low (-1)	Mid (0)	High (+1)	
1.	Discharge current	I	X_1	8	14	20	1 to 20A
2.	Spark on time	T_i	X_2	60	74	98	0 to 99μs
3.	Spark off time	T_o	X_3	5	7	9	0 to 9μs

3.2 Response variables selected

The response variables chosen for the present study are work piece erosion rate (WER) and tool erosion rate (TER). These response variables are defined in Eqs. (1) and (2), respectively;

WER (gm/min) = Work piece removal weight / Time (1)

TER (gm/min) = Tool wear weight / Time (2)

3.3 Design of Experiments

The design of experiments (DOE) technique is an assortment of statistical techniques which can be applied to construct the model and analyze the influence of input parameters on the responses. [14–16]. Box Behnken design (BBD) was used to plan the experimentation. BBD considers one point at the center of each edge of the cube and takes three center points by default. The BBD is found to be a highly effective technique to obtain information on the effects of parameters and overall experimental error because it requires a minimum number of required runs [14, 17]. In this study the design matrix is based on the coded and the un-coded values which are obtained in 2 sets of 15 experiments. This matrix is shown in the Table 5 and 6 for copper and brass tool electrodes respectively.

The selected parameters at intermediate (0) level composes the middle positions and the combinations of each one of the process parameters at either it's minimum (-1) or maximum (+1) with the other selected parameters of the intermediary levels make up star points. The run number shows the succession of trials that are considered as in Table 5 and 6. X1, X2 and X3 correspond to the information used for the controllable parameters in Table 4. The intermediary levels of coded values were obtained from the subsequent relationship;

$$X_i = \frac{2X - (X_{\max} + X_{\min})}{X_{\max} - X_{\min}} \quad \textbf{(3)}$$

Where,

X_i: Essential value of parameter X in coded form

X: Some value of the parameter from $X_{max}$to X_{min}

$X_{max}$and X_{min}: High and low levels of X.

The coefficients of regression equation are determined by

$$b = (X^T X)^{-1} X^T Y \quad \textbf{(4)}$$

Where,

b, X, Y and X^T are matrices of parameter estimation , calculation matrix, response and transpose of X.

Mathematical correlation between the response (Y_n) and the various machining parameters is established using RSM [17- 20]. The influence of various parameters on the response criteria is best described by the general second degree polynomial response surface model. The model is described by equation

$$Y_n = b_0 + \sum_{i=1}^{3} b_i X_i + \sum_{i=1}^{3} b_{ii} X_i^2 + \sum_{i=1}^{2} \sum_{j=i+1}^{3} b_{ij} X_i X_j \quad \textbf{(5)}$$

Where,

Y_n: Response variable under consideration, i.e., WER and TER

X_i: Coded values for i = Discharge current (I), Spark on time (T_i), and Spark off time (T_o)

b_o, b_i, b_{ii}, b_{ij}: Second degree regression coefficients

The linear effect is given by the second term of this equation, the higher-degree effect is given by the third term, and the effect of the interactions is given by the fourth term.

The plots, response surfaces and the tabulations that are presented in the following sections are obtained using MINITAB V16 software.

Table 5 Design matrix for the second-order models of WER and TER using Copper tool electrode

Run Order	Uncoded variables			Coded variables			Y1=WER in gm/min	Y2=TER in gm/min
	Discharge current (I) in A	Spark on time (T_i) in µs	Spark off time (T_o) in µs	X_1	X_2	X_3		
1	14	79	7	0	0	0	0.295	0.0040
2	14	98	5	0	+1	-1	0.265	0.0023
3	20	60	7	+1	-1	0	0.375	0.0050
4	20	79	5	+1	0	-1	0.420	0.0039
5	8	98	7	-1	+1	0	0.130	0.0010
6	14	60	9	0	-1	+1	0.266	0.0060
7	20	79	9	+1	0	+1	0.449	0.0058
8	8	79	9	-1	0	+1	0.156	0.0025
9	14	98	9	0	+1	+1	0.273	0.0028
10	8	60	7	-1	-1	0	0.156	0.0023
11	8	79	5	-1	0	-1	0.138	0.0025
12	14	79	7	0	0	0	0.294	0.0035
13	20	98	7	+1	+1	0	0.365	0.0030
14	14	60	5	0	-1	-1	0.255	0.0039
15	14	79	7	0	0	0	0.298	0.0034

Table 6 Design matrix for the second-order models of WER and TER using Brass tool electrode

Run Order	Uncoded variables			Coded variables			Y3=WER in gm/min	Y4=TER in gm/min
	Discharge current (I) in A	Spark on time (T_i) in µs	Spark off time (T_o) in µs	X_1	X_2	X_3		
1	14	79	7	0	0	0	0.2340	0.0398
2	14	98	5	0	+1	-1	0.2210	0.0285
3	20	60	7	+1	-1	0	0.3375	0.0670
4	20	79	5	+1	0	-1	0.3385	0.0490
5	8	98	7	-1	+1	0	0.1223	0.0170
6	14	60	9	0	-1	+1	0.2438	0.0453

7	20	79	9	+1	0	+1	0.3485	0.0570
8	8	79	9	-1	0	+1	0.1277	0.0240
9	14	98	9	0	+1	+1	0.2475	0.0270
10	8	60	7	-1	-1	0	0.1175	0.0288
11	8	79	5	-1	0	-1	0.1152	0.0212
12	14	79	7	0	0	0	0.2320	0.0375
13	20	98	7	+1	+1	0	0.3228	0.0475
14	14	60	5	0	-1	-1	0.2190	0.0410
15	14	79	7	0	0	0	0.2323	0.0365

Table 7 Estimated Regression Coefficients For Y1=WER And Y2=TER Using Copper Tool Electrode

Terms		For Y1=WER model		For Y2=TER model	
		Coefficients	P-value	Coefficients	P-value
Constant	----	0.295583	0.000 *	0.003633	0.000 *
Discharge current	X_1	0.128594	0.000 *	0.001169	0.000 *
Spark on time	X_2	-0.002469	0.757	-0.001019	0.000 *
Spark off time	X_3	0.008375	0.319	0.000562	0.006 *
Discharge current × Discharge current	$X_1 \times X_1$	-0.006510	0.584	-0.000442	0.056
Spark on time× Spark on time	$X_2 \times X_2$	-0.032510	0.033 *	-0.000367	0.095
Spark off time × Spark off time	$X_3 \times X_3$	0.001677	0.886	0.000471	0.046 *
Discharge current × Spark on time	$X_1 \times X_2$	0.004062	0.720	-0.000175	0.354
Discharge current × Spark off time	$X_1 \times X_3$	0.002625	0.816	0.000463	0.043 *
Spark on time× Spark off time	$X_2 \times X_3$	-0.000750	0.947	-0.000388	0.073

* Indicates the significant terms

Table 8 Estimated Regression Coefficients for Y3=WER and Y4=TER using Brass tool electrode

Terms		For Y3=WER model		For Y4=TER model	
		Coefficients	P-value	Coefficients	P-value
Constant	----	0.232750	0.000 *	0.037917	0.000 *
Discharge current	X_1	0.108063	0.000 *	0.016188	0.000 *
Spark on time	X_2	-0.000531	0.824	-0.007750	0.000 *
Spark off time	X_3	0.009219	0.010 *	0.001688	0.070

Discharge current × Discharge current	$X_1 \times X_1$	-0.004031	0.281	0.002260	0.091
Spark on time× Spark on time	$X_2 \times X_2$	-0.003719	0.316	-0.000115	0.920
Spark off time × Spark off time					
Discharge current × Spark on time	$X_3 \times X_3$	0.003781	0.309	-0.002365	0.080
Discharge current × Spark off time	$X_1 \times X_2$	-0.004875	0.189	-0.001937	0.121
Spark on time× Spark off time	$X_1 \times X_3$	-0.000625	0.853	0.001313	0.262
	$X_2 \times X_3$	0.000437	0.897	-0.001438	0.225

* Indicates the significant terms

The significant terms are decided from the P-value. The definition of the P-value is the least significance level, which leads to not accepting of the null hypothesis. This P-value is almost nearby to or lower than 0.05 for 95% confidence level. With these important terms, the subsequent coefficients that are collected and the needed mathematical models for WER and TER are developed for both copper and brass tool electrodes.

Mathematical models for WER (Y1) and TER (Y2) when Copper tool electrode is used are given below;

$$\mathbf{Y1=0.295583+0.128594X_1-0.032510X_2^2} \qquad \mathbf{(6)}$$

$$\mathbf{Y2=0.003633+0.001169X_1-0.001019X_2+0.000562X_3+0.000471X_3^2+0.000463X_1X_3} \qquad \mathbf{(7)}$$

Similarly, the mathematical models for WER (Y3) and TER (Y4) when the Brass tool electrode is used are as follows:

$$\mathbf{Y3=0.232750+0.108063X_1+0.009219X_3} \qquad \mathbf{(8)}$$

$$\mathbf{Y4=0.037917+0.016188X_1-0.007750X_2} \qquad \mathbf{(9)}$$

To verify the lack of fit and satisfactoriness of the proposed mathematical models at the desired level of significance, ANOVA and F-test were carried out. The important terms of ANOVA table include degrees of freedom (DF), mean square (MS) and sum of squares (SS). The linear, quadratic, interaction terms, residual error and lack of fit contribute in calculating the sum of squares. The aberration of the response from the fitted surface is lack of fit; whereas the replication of the points at the centre yields residual errors. Mean sum of squares is defined as the ratio of SS to DF. The level of significance is determined by the p-value. The formula of the F ratio is $F = MS_A / MS_{S/A}$. The F ratio is approximately 1.0 when the null hypothesis is true and is greater than 1.0 when the null hypothesis is false. It is observed that the obtained values are within the assumed significance level.

Table 9 Analysis of variance table for the second-order model of Y1=WER with Copper tool electrode

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	0.137033	0.137033	0.015226	33.23	0.001
Linear	3	0.132901	0.132901	0.044300	96.70	0.000
DISCHARGE CURRENT	1	0.132291	0.132291	0.132291	288.76	0.000
SPARK ON TIME	1	0.000049	0.000049	0.000049	0.11	0.757
SPARK OFF TIME	1	0.000561	0.000561	0.000561	1.22	0.319
Square	3	0.004037	0.004037	0.001346	2.94	0.138

DISCHARGE CURRENT* DISCHARGE CURRENT	1	0.000069	0.000157	0.000157	0.34	0.584
SPARK ON TIME * SPARK ON TIME	1	0.003957	0.003903	0.003903	8.52	0.033
SPARK OFF TIME* SPARK OFF TIME	1	0.000010	0.000010	0.000010	0.02	0.886
Interaction	3	0.000096	0.000096	0.000032	0.07	0.974
DISCHARGE CURRENT* SPARK ON TIME	1	0.000066	0.000066	0.000066	0.14	0.720
DISCHARGE CURRENT* SPARK OFF TIME	1	0.000028	0.000028	0.000028	0.06	0.816
SPARK ON TIME* SPARK OFF TIME	1	0.000002	0.000002	0.000002	0.00	0.947
Residual Error	5	0.002291	0.002291	0.000458		
Lack-of-Fit	3	0.002284	0.002284	0.000761	212.42	0.005
Pure Error	2	0.000007	0.000007	0.000004		
Total	14	0.139324				

R-Sq = 98.36% R-Sq(pred) = 73.76% R-Sq(adj) = 95.40%

Table 10 Analysis of variance table for the second-order model of Y2=TER with Copper tool electrode

Analysis of Variance for Y2=TER (gm/min)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	0.000026	0.000026	0.000003	24.14	0.001
Linear	3	0.000022	0.000022	0.000007	61.76	0.000
DISCHARGE CURRENT	1	0.000011	0.000011	0.000011	93.04	0.000
SPARK ON TIME	1	0.000008	0.000008	0.000008	70.69	0.000
SPARK OFF TIME	1	0.000003	0.000003	0.000003	21.55	0.006
Square	3	0.000002	0.000002	0.000001	6.17	0.039
DISCHARGE CURRENT X DISCHARGE CURRENT	1	0.000001	0.000001	0.000001	6.13	0.056
SPARK ON TIME X SPARK ON TIME	1	0.000001	0.000000	0.000000	4.23	0.095
SPARK OFF TIME X SPARK OFF TIME	1	0.000001	0.000001	0.000001	6.97	0.046
Interaction	3	0.000002	0.000002	0.000001	4.48	0.070
DISCHARGE CURRENT X SPARK ON TIME	1	0.000000	0.000000	0.000000	1.04	0.354
DISCHARGE CURRENT X SPARK OFF TIME	1	0.000001	0.000001	0.000001	7.28	0.043
SPARK ON TIME X	1	0.000001	0.000001	0.000001	5.11	0.073

SPARK OFF TIME						
Residual Error	5	0.000001	0.000001	0.000000		
Lack-of-Fit	3	0.000000	0.000000	0.000000	1.23	0.478
Pure Error	2	0.000000	0.000000	0.000000		
Total	14	0.000026				

R-Sq = 97.75% R-Sq(pred) = 74.89% R-Sq(adj) = 93.70%

Table 11 Analysis of variance table for the second-order model of Y3= WER with Brass tool electrode

Analysis of Variance for Y3=WER (gm/min)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	0.094373	0.094373	0.010486	254.84	0.000
Linear	3	0.094102	0.094102	0.031367	762.33	0.000
DISCHARGE CURRENT	1	0.093420	0.093420	0.093420	2270.40	0.000
SPARK ON TIME	1	0.000002	0.000002	0.000002	0.05	0.824
SPARK OFF TIME	1	0.000680	0.000680	0.000680	16.52	0.010
Square	3	0.000173	0.000173	0.000058	1.40	0.345
DISCHARGE CURRENT X DISCHARGE CURRENT	1	0.000061	0.000060	0.000060	1.46	0.281
SPARK ON TIME X SPARK ON TIME	1	0.000060	0.000051	0.000051	1.24	0.316
SPARK OFF TIME X SPARK OFF TIME	1	0.000053	0.000053	0.000053	1.28	0.309
Interaction	3	0.000097	0.000097	0.000032	0.79	0.550
DISCHARGE CURRENT X SPARK ON TIME	1	0.000095	0.000095	0.000095	2.31	0.189
DISCHARGE CURRENT X SPARK OFF TIME	1	0.000002	0.000002	0.000002	0.04	0.85
SPARK ON TIME X SPARK OFF TIME	1	0.000001	0.000001	0.000001	0.02	0.897
Residual Error	5	0.000206	0.000206	0.000041		
Lack-of-Fit	3	0.000203	0.000203	0.000068	57.08	0.017
Pure Error	2	0.000002	0.000002	0.000001		
Total	14	0.094579				

R-Sq = 99.78% R-Sq(pred) = 96.55% R-Sq(adj) = 99.39%

Table 12 Analysis of variance table for the second-order model of Y4=TER with Brass tool electrode.

Analysis of Variance for Y4=TER (gm/min)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	0.002673	0.002673	0.000297	68.83	0.000
Linear	3	0.002600	0.002600	0.000867	200.84	0.000
DISCHARGE CURRENT	1	0.002096	0.002096	0.002096	485.86	0.000
SPARK ON TIME	1	0.000481	0.000481	0.000481	111.37	0.000
SPARK OFF TIME	1	0.000023	0.000023	0.000023	5.28	0.070
Square	3	0.000043	0.000043	0.000014	3.31	0.115
DISCHARGE CURRENT X DISCHARGE CURRENT	1	0.000022	0.000019	0.000019	4.37	0.091
SPARK ON TIME X SPARK ON TIME	1	0.000000	0.000000	0.000000	0.01	0.920
SPARK OFF TIME X SPARK OFF TIME	1	0.000021	0.000021	0.000021	4.78	0.080
Interaction	3	0.000030	0.000030	0.000010	2.33	0.191
DISCHARGE CURRENT X SPARK ON TIME	1	0.000015	0.000015	0.000015	3.48	0.121
DISCHARGE CURRENT X SPARK OFF TIME	1	0.000007	0.000007	0.000007	1.60	0.262
SPARK ON TIME X SPARK OFF TIME	1	0.000008	0.000008	0.000008	1.92	0.225
Residual Error	5	0.000022	0.000022	0.000004		
Lack-of-Fit	3	0.000016	0.000016	0.000005	1.93	0.359
Pure Error	2	0.000006	0.000006	0.000003		
Total	14	0.002694				

R-Sq = 99.20% R-Sq(pred) = 90.02% R-Sq(adj) = 97.76%

To determine the accuracy of the proposed response model certain conformity readings were taken using different input setting parameters within the selected range. The obtained intermediary values are allotted to process parameters except those used in the design matrix and confirmative test runs were conducted. The obtained response values were measured and compared aligned with predicted values of WER and TER shown in Table 13, 14, 15 and 16 respectively.

The obtained results of the model are found to be accurate as the percentage error is very small. The experimental and future predicted values of work piece erosion rate and Tool erosion rate for validation data set are illustrated in Figs 13, 14 and 15, 16 respectively. The obtained outcome of the conformity tests are as shown in the Table 13, 14, 15 & 16.

Table 13 Confirmative tests for WER with Copper tool electrode

Run Order	Uncoded variables			Coded variables			WER in gm/min		
	I (A)	T_i (μs)	T_o (μs)	X_1	X_2	X_3	Predicted	Experimental	% Error
1	10	65	7	-2/3	-14/19	0	0.1954	0.2018	-3.27
2	12	75	9	-1/3	-4/19	+1	0.2491	0.2522	-1.24
3	16	85	6	1/3	6/19	-1/2	0.3348	0.3195	4.57
4	18	95	8	2/3	16/19	1/2	0.3668	0.3843	-4.77

Table 14 Confirmative tests for TER with Copper tool electrode

Run Order	Uncoded variables			Coded variables			TER in gm/min		
	I (A)	T_i (μs)	T_o (μs)	X_1	X_2	X_3	Predicted	Experimental	% Error
1	10	65	7	-2/3	-14/19	0	0.0036	0.0035	2.77
2	12	75	9	-1/3	-4/19	+1	0.0043	0.0042	2.32
3	16	85	6	1/3	6/19	-1/2	0.0034	0.0035	-2.94
4	18	95	8	2/3	16/19	1/2	0.0041	0.0040	2.44

Table 15 Confirmative tests for WER with Brass tool electrode

Run Order	Uncoded variables			Coded variables			WER in gm/min		
	I (A)	T_i (μs)	T_o (μs)	X_1	X_2	X_3	Predicted	Experimental	% Error
1	10	65	7	-2/3	-14/19	0	0.1607	0.1525	5.10
2	12	75	9	-1/3	-4/19	+1	0.2059	0.2052	0.34
3	16	85	6	1/3	6/19	-1/2	0.2641	0.2608	1.25
4	18	95	8	2/3	16/19	1/2	0.3094	0.3060	1.10

Table 16 Confirmative tests for TER with Brass tool electrode

Run Order	Uncoded variables			Coded variables			TER in gm/min		
	I (A)	T_i (μs)	T_o (μs)	X_1	X_2	X_3	Predicted	Experimental	% Error
1	10	65	7	-2/3	-14/19	0	0.0328	0.0323	1.52
2	12	75	9	-1/3	-4/19	+1	0.0342	0.0355	-3.80
3	16	85	6	1/3	6/19	-1/2	0.0408	0.0390	4.41
4	18	95	8	2/3	16/19	1/2	0.0422	0.0418	0.95

IV. RESULTS AND DISCUSSION

For the response variable WER, a first order model was proposed and this was rejected because of the values obtained for the curvature test that can be seen in Table 9, 10, 11 and 12. As in the case of P having a value of lower than 0.05 it is found that there are no pure quadratic effects and hence the model is rejected and thus second order model is selected. Table 9, 10, 11 and 12 represent the ANOVA and the total numbers of degrees of freedom are equal to 14. With an observation in this table, the factors having a value of P lower than 0.05 are considered to be significant for confidence level of 95 %. The main effects of discharge current, Spark on time and spark off time that are arranged in the order of importance and lastly the interaction between them. The model R^2 values are as shown in Table No 17.

Table 17 R^2 values of the responses

Responses	Parameter	R^2 statistic	R^2 adjusted
Y1	WER with copper tool	98.36	95.40
Y2	TER with copper tool	97.75	93.70
Y3	WER with brass tool	99.78	99.39
Y4	TER with brass tool	99.20	97.76

4.1. Direct Effects of Process Parameters on WER and TER Using Copper Tool Electrode

4.1.1. Effect of Discharge Current on WER and TER

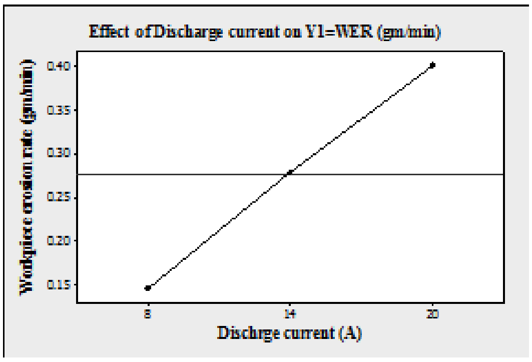

Figure 3 Effect of discharge current on WER (For Copper tool electrode)

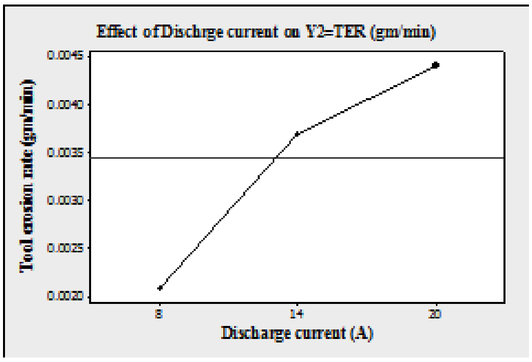

Figure 4 Effect of discharge current on TER (For Copper tool electrode)

The WER and TER are affected by the discharge current when copper tool electrode is used as shown in Fig. 3 and Fig. 4 respectively. The values of workpiece erosion rate and tool erosion rate increases in a nonlinear fashion with the discharge current. This happens due to the cause that the spark discharge energy is increased to facilitate the process of melting and vaporization [21]. The, work material, tool material and dielectric flushing also affect the workpiece erosion rate. As per the earlier analysis the tool erosion rate increases with the discharge current [22, 23].

4.1.2. Effect of spark on time, on WER and TER

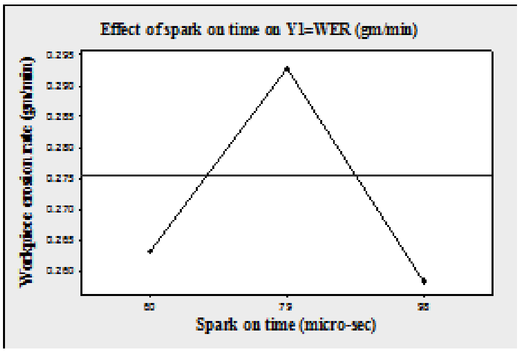

Figure 5 Effect of Spark on time, on WER (For Copper tool electrode)

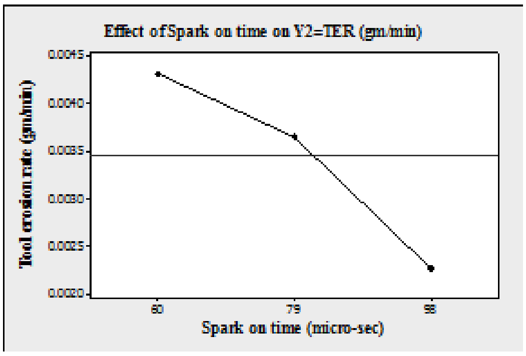

Figure 6 Effect of Spark on time, on TER (For Copper tool electrode)

Effect of spark on time using copper tool electrode is stated in Fig. 5.It has been viewed that there is a nonlinear response between the WER and Spark on time. With the increase in Spark on time the WER also increases till a value of 79 µs and further decreases thereafter. During EDM process, the work material melts and evaporates. The evaporated metal is in the form of micron size conductive particles, expanding away from the melting zone. This can be compared to a moving cloud from each of the melt spots one on work piece and one on tool. Thus at one point these cloud meet in between leading to short circuit of spark. During this period there is no spark taking place hence no melting and evaporation. It means that lesser amount of vaporization is due to tiny spark on time. On the other hand the expansion of the plasma channel is due to the longer spark on time thus with lesser amount of energy density that is inadequate to melt and vaporize the work material [24].

The significant main effect of spark on time, on TER is shown in Fig. 6. As the spark on time increases, the effective spark existing times reduces due to short circuit or quenching as a result of conductive debris or cloud and also wear resistance of the tool due to carbon attached to the tool surface [27, 28, 29] .Hence the tool erosion rate decreases.

4.1.3. Effect of spark off time on TER

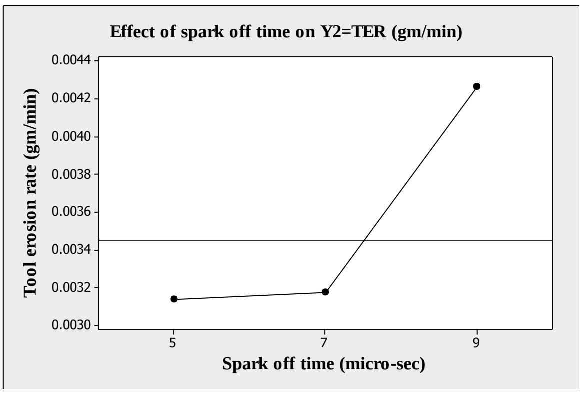

Figure 7 Effect of Spark off time on TER (For Copper tool electrode)

From Fig. 7 it is clear that the tool erosion rate nearly constant from 5 µs till the value of 7 µs in the beginning but then rapidly increases linearly for further increase in the value of spark off time i.e., from 7 to 9 µs.

4.2 Direct effects of the process parameters on WER and TER using brass as tool electrode

4.2.1. Effect of discharge current on WER and TER.

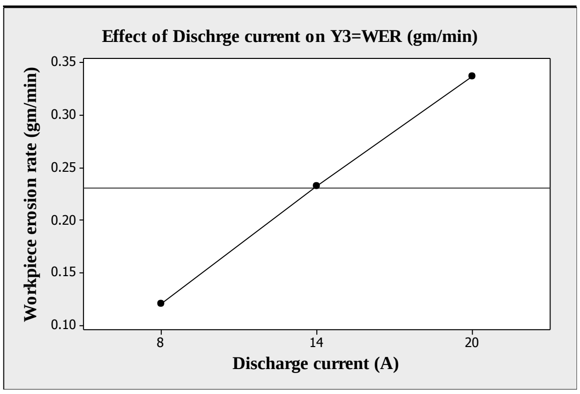

Figure 8 Effect of discharge current on WER (For Brass tool electrode)

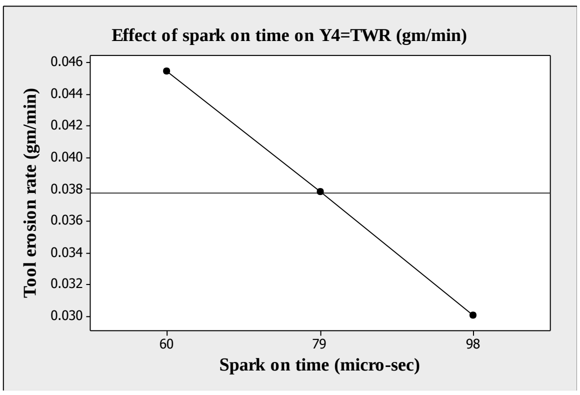

Figure 9 Effect of discharge current on TER (For Brass tool electrode)

Fig.8 and Fig.9 show how WER and TER is affected by discharge current when brass tool electrode is used. We can observe there is a linear response of WER with discharge current. The increase in discharge current may increase the spark discharge energy which facilitates the action of melting and vaporization.

4.2.2. Effect of Spark on Time on TER

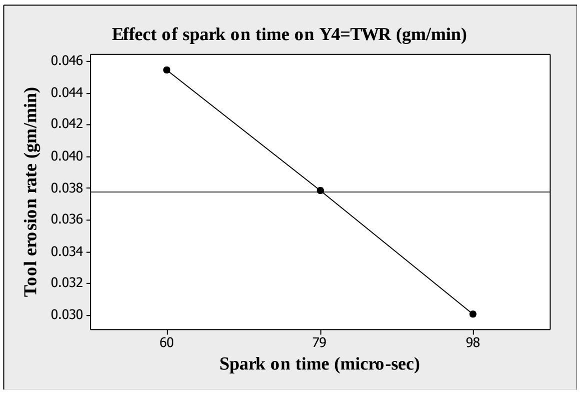

Figure 10 Effect of Spark on time on TER (For Brass tool electrode)

From Fig.10 it is observed that the TER there is an inverse relation between TER and Spark on time. It can happen due to more chopping on between electrode and work material. The TER increases when Spark on time increase

4.2.3. Effect of Spark off Time on WER

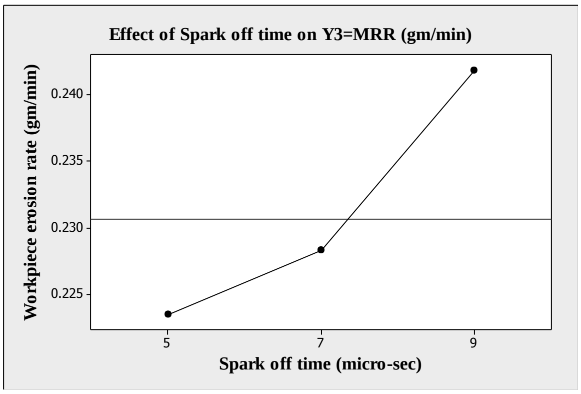

Figure 11 Effect of Spark off time on WER (For Brass tool electrode)

The effect of spark off time on WER is shown in the Fig.11. It is observed that work piece erosion rate increases when the Spark off time is increased. The main reason for the increase in WER is due to the removal of debris formed during erosion in the predetermined gap. These debris are carried away by proper flushing condition and spark off time.

4.3. Interaction effects of process parameters on WER and TER using copper tool electrode

Fig.12 shows this effect and it is clear that for the low value of a discharge current (8A) the TER decreases from the lower value of Spark off time till the middle value of Spark off time and after that it increases from the middle value to till higher value of Spark off time. For the middle value of discharge current, i.e. 14A, it is viewed that the TER linearly increases from lower value till the Spark off time reaches a higher value. For a high value of discharge current (20A) the TER slowly increases from lower value (5 µs) to the middle value (7 µs) of the Spark off time and further increases rapidly for the more increase in the value (9 µs) of Spark off time.

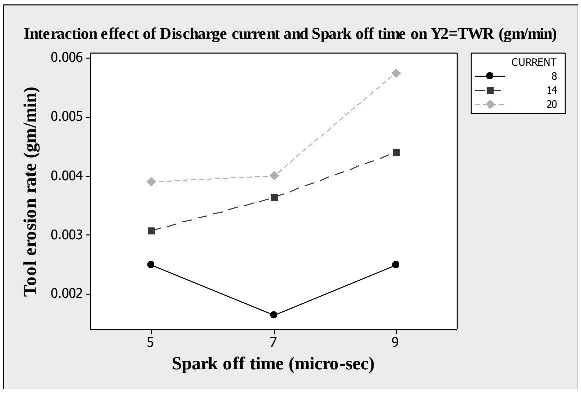

Figure 12 **Interaction effect of Discharge current & Spark off time on TER (For Copper tool electrode)**

4.4 Comparative Study of the Theoretical and Experimental Values of WER and TER for Copper Tool Electrode

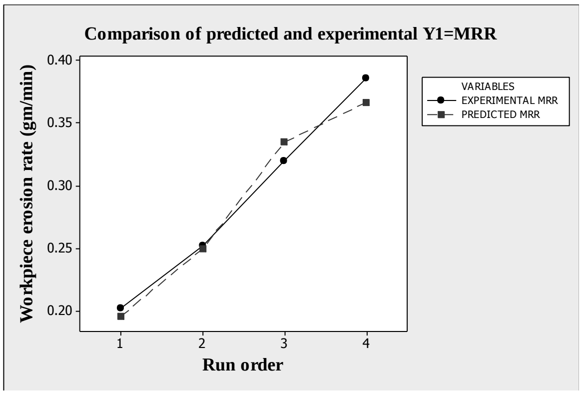

Figure 13 Comparison of predicted and experimental WER

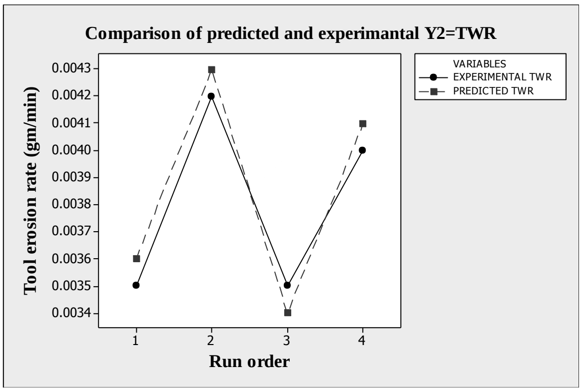

Figure 14 Comparison of predicted and experimental TER

Fig. 13 showcases the comparison between the above theoretical and experimental values of WER. The error between the both is in the range of -4.77% to 4.57%.

Fig. 14 shows the compared value of theoretical and experimental values of TER and the error observed between these two values in the range -2.94% to 2.77%.

4.5. Comparison of Theoretical and Experimental Values of WER and TER for Brass Tool Electrode

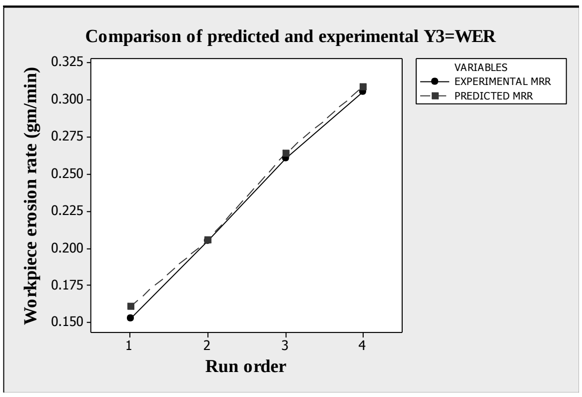

Figure 15 Comparison of predicted and experimental WER

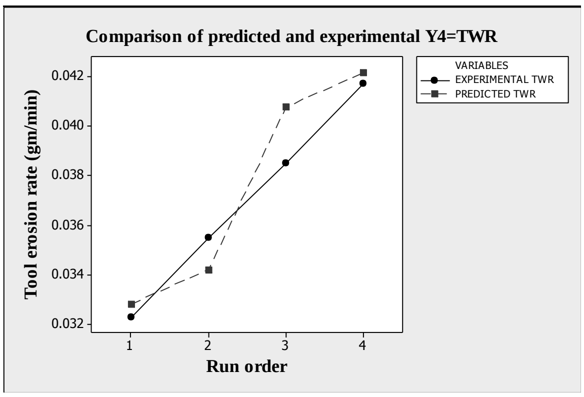

Figure 16 Comparison of predicted and experimental TER

Fig.15 and Fig. 16 show the compared values of experimental and theoretical results of WER and TER respectively. The difference between the both is well within the range i.e. 0.34% to 5.10% for WER and -3.80% to 4.41 for TER respectively.

4.6 Comparison of Responses When Copper and Brass Tool Electrodes Are Used

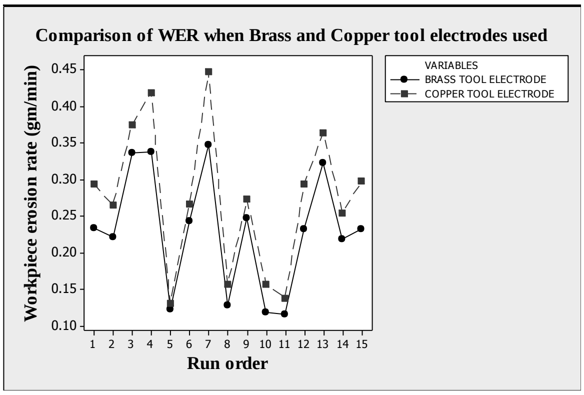

Figure 17 Comparison of WER when brass and copper tool electrodes used

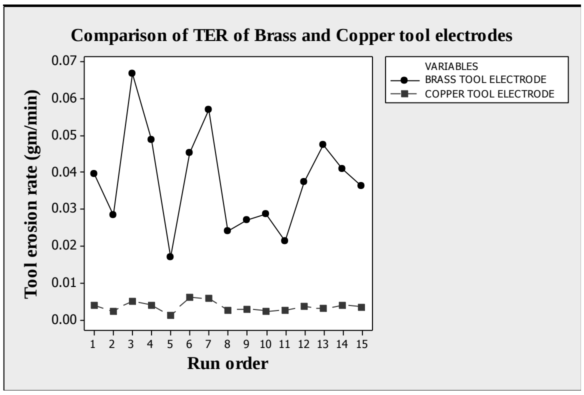

Figure 18 Comparison of TER of brass and copper tool electrodes

Fig.17 and Fig.18 depicts the comparison between WER and TER. From the figures it is observed that, when copper tool is used, the WER is higher and the TER is lower. Whereas, when brass tool is used, the WER is lower and TER is higher. Thus for efficient material removal (higher WER and lower TER) in EDM, copper is preferred tool material.

V. CONCLUSIONS

In this work the most important controllable EDM parameters were selected to determine the responses such as WER and TER using RSM approach. The flushing pressure is kept constant all till the completion of the experiment. For the prediction of responses during EDM of EN-19 alloy steel mathematical models are developed. Thus successful application of these models is done to estimate the values of WER with different machining conditions. The following conclusions were obtained by investigating the EN-19 alloy steel using electric discharge machining and are summarized as below: Discharge current being the most important and significant parameter which affects the WER and TER. The other statistically significant factors which affect the WER and TER are spark on time and spark off time. With these individual parameters the effect of interaction effect of the discharge current and Spark off time on TER of copper electrode is observed. An increase in the value of discharge current always increases the WER and TER. The developed mathematical models can be used to evaluate the WER and TER with low % error. Higher WER can be achieved using copper tool electrode instead of a brass tool electrode. In case of copper tool electrode the TER is very low compared with a TER of brass tool electrode. EDM process can be optimized by maximizing the WER while by minimizing Tool erosion rate.

REFERENCES

[1] A.Ghosh and A.Mallik, Manufacturing Science (New Delhi, Affiliated East- West press Pvt. Ltd, 2006).

[2] W. Konig, D. F. Dauw, G. Levy, and U. Panten., EDM-future steps towards the machining of ceramics, Annl CIRP, 37(2), 1988, 623–631.

[3] G. Boothroyd, A. K. Winston, Non-conventional machining processes. Fundamentals of machining and machine tools (New York, Marcel Dekker,).

[4] S. Kalpajian, S.R. Schmid, Material removal processes: abrasive, chemical, electrical and high-energy beam (New Jersey, Manufacturing processes for engineering materials, Prentice Hall, 2003).

[5] J. A. McGeough, Electro-discharge machining. Advanced methods of machining (London, Chapman and Hall, 1988).

[6] M.Shabgard, M. Seyedzavvar and S.N. Bavil Oliaei, Influence of input parameters on the characteristics of the EDM processes, Journal of Mechanical Engineering, 57, 2011, 689-696.

[7] Y.H. Guu and H. Hocheng, Effects of work piece rotation on machinability during electrical discharge machining, Journal of materials and manufacturing processes, 16, 2001, 91-101.

[8] D. A.Khan, and M. Hameedullah, Effect of tool polarity on the machining characteristics in electric discharge machining of silver steel and statistical modeling of the process, International Journal of Engineering Science and Technology, 3, 2011,5001-5010.

[9] D. Pradhan and S. C. Jayswal, Behaviour of Copper and Aluminium electrodes on EDM of EN-8 Alloy Steel, International Journal of Engineering Science and Technology (IJEST), 3, 2011, 5492-5499.

[10] J. Marafona, Black layer characterization and electrode wear ratio in electrical discharge machining (EDM), Journal of Materials Processing Technology, 184, 2007, 27–31.

[11] M. Pradhan, and C. Biswas, Modelling of Machining Parameters For WER in EDM using Response Surface Methodology, Proceedings of National Conference on Mechanism Science and Technology: From Theory to Application, 2008,535-542.

[12] H.K. Kansal, S. Singh, and P. Kumar, Parametric optimization of powder mixed electrical discharge machining by response surface methodology, Journal of Materials Processing Technology, 169, 2005,427–436.

[13] A.K.M. Asif Iqbal and A.A. Khan, Influence of process parameters on electrical discharge machined job surface integrity, American Journal of Engineering and Applied Sciences, 3, 2010, 396-402.

[14] D.C. Montgomery, Design and Analysis of Experiments (New York, 5th ed., Wiley, 2001).

[15] C. J. Luis Perez, Surface roughness modeling considering uncertainty measurements, International Journal of Production Research, 40(10),2002, 2245–2268.

[16] C. J. Luis Perez, Analysis of the surface roughness and dimensional accuracy capability of fused deposition modelling processes, International Journal of Production Research, 40(12), 2001, 2865–2881.

[17] W.G Cochran, and G.M. Cox, Experimental designs. (New York. 2nd ed., Wiley, 1992)

[18] G.E.P Box, and D.W. Behnken, Some New Three Level Designs for the Study of Quantitative Variables, Technometrics 2(4), 1960,455–475.

[19] G.E.P. Box, and N.R. Draper, Empirical Model-Building and Response Surfaces (John Wiley & Sons.1987).

[20] A.I. Khuri,. and J.A. Cornell, Response Surfaces: Design and Analyses (New York. Marcel Dekker Inc.,1987)

[21] M.M. Rahman, M.A.R. Khan, K. Kadirgama, M.M. Noor and R.A. Bakar, Experimental Investigation into Electrical Discharge Machining of Stainless Steel 304, Journal of Applied Sciences,11, 2011, 549-554.

[22] M.S. Hewidy, T.A. El–Taweel and M.F. El-Safty, Modeling the machining parameters of wire electrical discharge machining of Inconel 601 using RSM'. Journal of Material Processing Technology,169 (2)2005, 328–336.

[23] J. H, Zhang, T. C. Lee, and W. S. Lau, Study on the electro-discharge machining of a hot pressed aluminum oxide based ceramic', Journal of Material Processing Technology, 63(1-3), 1997, 908–912.

[24] C.C. Wang and B.H. Yan, Blind hole drilling of Al_2O_3/6061Al composite using rotary EDM, Journal of Material Processing Technology, 102(1-3), 2000, 90– 102.

[25] C.A. Cogun, and S. kaslan, The effect of machining parameter on tool electrode wear and machining performance in electric discharge machining, KSME International Journal, 16 (1), 2002, 46-59.

[26] S.H. Lee, and X.P. Li, Study of the effect of machining parameters on the machining characteristics in electrical discharge machining of tungsten carbide, Journal of Material Processing Technology, 115(3), 2001, 344-358.

[27] N. Mohri, M. Suzuki, M. Furuya and N. Saito, Electrode wear process in electrical discharge machining, Annl CIRP, 44(1), 1995 ,165–168.

[28] Y. Chen, and S. M. Mahdavian, Parametric study into erosion wear in a computer numerical controlled electro-discharge machining process, Wear , 236, 1999, 350–354.

[29] S. L. Chen, B. H. Yan and F.Y. Huang, Influence of kerosene and distilled water as dielectrics on the electric discharge machining characteristics of Ti-6Al-4 V, Journal of Material Processing Technology,87(1-3), 1999,107–111.