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MULTI-RESPONSE OPTIMIZATION OF EDM PERFORMANCE CHARACTERISTICS USING RESPONSE SURFACE METHODOLOGY AND DESIRABILITY FUNCTION

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ABSTRACT

In the present investigation, the experiments were conducted on a CNC Electrical discharge machine for machining of AISI D2 steel with cylindrical copper rods as electrodes to determine the effect of process parameters such as electrode rotation, voltage, current and spark gap on the responses material removal rate (MRR), surface roughness (Ra) and electrode wear rate (EWR) using response surface methodology (RSM).The second order polynomial model in terms of process parameters were developed for the responses on the basis of experimental results and has been validated with F-test. The adequacy of these models has been tested on the responses with analysis of variance (ANOVA). Finally, to overcome the problem of conflicting nature of responses with single response optimization, multi- response optimization has been carried out using response surface methodology with integration of desirability function. Confirmation experiments are further conducted to validate the results.

Keywords: EDM, surface roughness, MRR, EWR, RSM, optimization, desirability function.

1. INTRODUCTION

Electrical discharge machining (EDM) is a common non-conventional metal removal process and has been used extensively in the tool and dies industry. In EDM, the mechanism involved in material removal is primarily electro-thermal via a series of successive discrete discharge or sparks between the electrode and the work piece. The material is eroded predominantly by melting of two conductors at instantaneous and very high temperature of 8000-12000ºC generated due to high current discharges through the dielectric medium [1]. Therefore, it has the advantage of allowing the work-piece to be full hardness before machining of EDM and hence minimizes dimensional variability due to post treatment. It is also useful for machining brittle materials as there is virtually no contact between the tool and the work piece. Basically, EDM is a process for eroding and removing material by transient action of electric sparks on electrically conductive materials. This process is achieved by applying consecutive spark discharges between charged work piece and electrode immersed in a dielectric liquid and separated by a small gap [2]. The schematic diagram and principle of working of EDM is shown in Figure-1. Usually, localized breakdown of the dielectric liquid occurs where the local electrical field is highest. Each spark melts and even evaporates a small amount of material from both electrode and work piece. Part of this material is removed by the dielectric fluid and the remaining part re-solidifies rapidly on the surfaces of the electrodes. The net result is that each discharge leaves a small crater on both work piece and electrode. Application of consecutive pulses with high frequencies together with the forward movement of the electrode towards the work piece, results with a form of a complementary shape of the electrode on the work piece.

Material removal rates (MRR), electrode wear rate (EWR) and surface roughness (Ra) are the most important responses in EDM which decide the cutting performance. Several researchers carried-out various investigations for improving the process performance. Proper selection of machining parameters for the best process performance is still a challenging job. As EDM is very complex and stochastic process, it is very difficult to determine optimal parameters for best machinery performance i.e., productivity and accuracy. In the present study, MRR, EWR and Ra have been considered as responses which are conflict in nature. Higher the MRR is better whereas, lower the EWR and Ra is better. MRR reflects the productivity and EWR and Ra reflect the accuracy of the product.

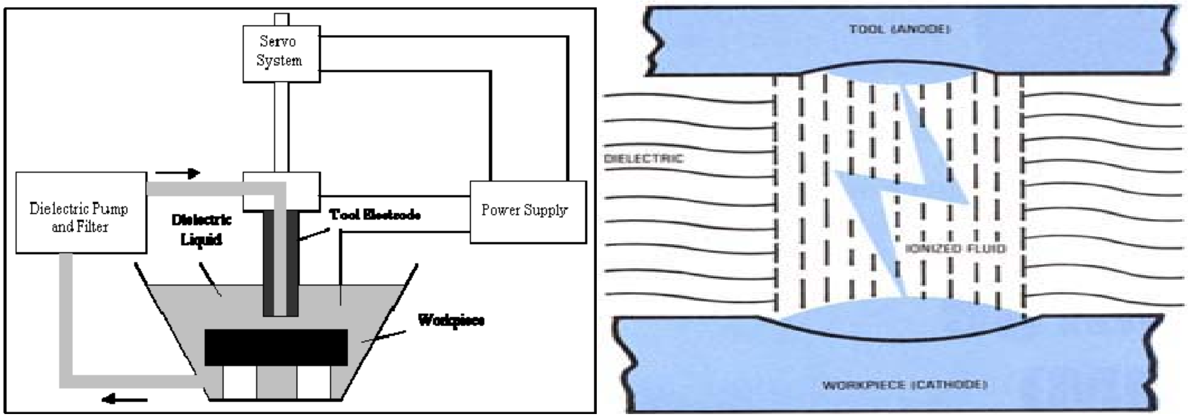

Figure-1. Principle of electrical discharge machining.

2. METHODOLOGY

2.1. Response surface methodology

Response Surface Methodology (RSM) is a combination of mathematical and statistical technique that is useful for the modeling and analysis of problem in which a response of interest is influenced by several variables and the objective is to optimize the response [3, 4]. In RSM, it is possible to represent independent process parameters in quantitative form as:

$$Y = f\,(X_1, X_2, X_3 \ldots X) \quad \pm e \qquad (1)$$

Where, Y is the response (yield), 'f' is the response function, 'e' is the experimental error, and X_1, X_2, X_3 . . . X are independent parameters. By plotting the expected response of Y, a surface, known as the response surface is obtained. The form of 'f' is unknown and maybe complicated. Thus, RSM aims at approximating 'f' by a suitable lower order polynomial in some region of the independent process variables. If the response can be well modeled by a linear function of the independent variables, the function (Equation (1)) can be written as:

$$Y = C_0+C_1X_1+C_2X_2+\ldots +CnXn \pm e \qquad (2)$$

However, if a curvature appears in the system, then a higher order polynomial such as the quadratic model (Equation (3)) may be used:

$$Y=C_0 + \sum_{i=1}^{n} C_iX_i + \sum_{i=1}^{n} C_{ii}X_i^{\,2} \pm e \qquad (3)$$

The objective of using RSM is not only to investigate the response over the entire factor space, but also to locate the region of interest where the response reaches its optimum or near optimal value. By studying carefully the response surface model, the combination of factors, which gives the best response, can then be established.

2.2. Desirability function

Derringer and Suich (1980) describe a multiple response method called desirability. It is an attractive method for industry for optimization of multiple quality characteristic problems. The method makes use of an objective function, D(X), called the desirability function and transforms an estimated response into a scale free value (d) called desirability [3, 4]. The desirable ranges are from zero to one (least to most desirable respectively). The factor settings with maximum total desirability are considered to be the optimal parameter conditions.

The simultaneous objective function is a geometric mean of all transformed responses:

$$D= (d_1Xd_2Xd_3X\ldots\ldots X\,d_n)^{1/n} = \left(\prod_{i=1}^{n} d_i\right)^{1/n}$$

Where, n is the number of responses in the measure. If any of the responses or factors falls outside the desirability range, the overall function becomes zero.
It can be extended to

$$D= (d_1^{\,w1}X\,d_2^{\,w2}X\,d_3^{\,w3}X\ldots\ldots X\,d_n^{\,wn})^{1/n}$$

to reflect the possible difference in the importance of different responses, where the weight *W satisfies* $0< wi <1$ *and* $w_1+w_2+w_3+\ldots\ldots +w_n=1$

Desirability is an objective function that ranges from zero outside of the limits to one at the goal. The numerical optimization finds a point that maximizes the desirability function. The characteristics of a goal may be altered by adjusting the weight or importance. For several responses and factors, all goals get combined into one desirability function.

For simultaneous optimization each response must have a low and high value assigned to each goal. The "Goal" field for responses must be one of five choices: "none"," maximum", minimum", "target", or "in range". Factors will always be included in the optimization, at their design range by default, or as a maximum, minimum of target goal. The meanings of the goal parameters are:
Maximum:

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$d_i = 0$ if response < low value,
$0 \leq d_i \leq 1$ as response from low to high
$d_i = 1$ if response > high value

Minimum:
$d_i = 1$ if response < low value
$1 \geq d_i \geq 0$ as response varies from low to high
$d_i = 0$ if response > high value
Target:
$d_i = 0$ if response < low value,
$0 \leq d_i \leq 1$ as response varies from low to target
$1 \geq d_i \geq 0$ as response varies from target to high
$d_i = 0$ if response > high value
Range:
$d_i = 0$ if response < low value
$d_i = 1$ as response varies from low to high
$d_i = 0$ if response > high value
The d_i for "in range" are included in the product of the desirability function "D", but are not counted in determining "n" where $D = (\prod d_i)^{1/n}$

If the goal is none, the response will not be used for the optimization. Desirability function has been used to determine the optimum parameters for EDM parts for optimization of responses in the present investigation. Second order polynomials have been used to find optimum combination of factors and levels in EDM machining. The multi response optimizations were achieved through desirability function.

3. EXPERIMENTAL DETAILS

The experiments were carried out on a standard EDM machine; model Sparkman (S-10) of sparkonix with straight polarity. AISI D2 steel (specimen of 80 mm x 25 mm x3mm, chemical composition of C-1.5%, Si-0.3%, Cr-12%, Mo-0.8%. V-0.9% and balance iron) hardened to 55-58 HRC was used as work piece material with SPARK2 oil (rust lick) as the dielectric fluid under Jet flushing. The dielectric fluid was circulated by jet flushing and cylindrical Cu electrodes (diameter of 8 mm) were used for experimentation. EDM involves several control variables such as electrode rotation, voltage, current intensity, electrode material, duty cycle, flushing pressure, dielectric flow rate and spark gap. However, based on the literature survey and trail experiments, the variables namely, Electrode rotation (RPM), voltage (volts), current intensity (amps) spark gap (mm) were considered as decision variables and MRR, EWR and Ra were considered as the output responses. The experimental process parameters and their levels selected for the study are listed in Table-1. MRR was calculated as the ratio of volume of material removed from work piece to the machining time and R_a was measured in perpendicular to the cutting direction using MITUTOYO surface roughness tester at a 0.8-mm cutoff value and measured at six different locations perpendicular to the direction of the machining on the surface of machined work piece and an average of these measurements is recorded as the response of Ra. EWR was calculated as the ratio of volume of material removed from electrode to the machining time. The experimental observations of the responses based on the L_{27} orthogonal array at different levels of control factors of input parameters are listed in Table-2.

Table-1. Levels of independent factors.

S. No.	Parameter	Symbol	Units	Levels		
				-1	0	1
1	Electrode rotation	x_1	RPM	250	500	750
2	Voltage	x_2	volts	80	120	160
3	Current	x_3	amps	4	8	12
4	Spark gap	x_4	mm	0.1	0.15	0.2

Table-2. Experimental observations of the responses.

S. No.	**Electrode rotation** (x_1)	**Voltage** (x_2)	**Current** (x_3)	**Spark Gap** (x_4)	**MRR** (mg/min)	**Ra** (µm)	**EWR** (mg/min)
1	250	80	4	0.1	22.67	0.89	8.580
2	250	120	4	0.15	31.83	1.12	13.09
3	250	160	4	0.2	33.96	1.22	17.14
4	250	120	8	0.1	43.17	1.85	23.44
5	250	160	8	0.15	51.45	1.91	24.44
6	250	80	8	0.2	40.03	1.43	16.75
7	250	160	12	0.1	122.9	2.81	67.10
8	250	80	12	0.15	64.94	2.32	27.65
9	250	120	12	0.2	109.9	2.63	54.72
10	500	120	4	0.1	33.72	1.20	15.67
11	500	160	4	0.15	41.07	1.69	16.60
12	500	80	4	0.2	23.27	0.98	14.95
13	500	160	8	0.1	59.48	2.18	32.44
14	500	80	8	0.15	40.26	1.61	14.81
15	500	120	8	0.2	53.55	1.96	23.16
16	500	80	12	0.1	91.89	2.58	50.36
17	500	120	12	0.15	126.9	2.89	68.11
18	500	160	12	0.2	180.7	3.41	87.64
19	750	160	4	0.1	42.61	1.72	18.50
20	750	80	4	0.15	36.70	1.38	15.58
21	750	120	4	0.2	34.20	1.23	19.76
22	750	80	8	0.1	55.99	2.02	22.03
23	750	120	8	0.15	66.90	2.33	29.28
24	750	160	8	0.2	81.54	2.40	38.00
25	750	120	12	0.1	173.1	3.21	98.79
26	750	160	12	0.15	251.3	3.63	110.3
27	750	80	12	0.2	128.9	2.97	53.42

4. DEVELOPMENT OF EMPIRICAL MODELS

In the present study, empirical relationships between the process variables and the responses were developed using the response surface methodology and these models are further used for the optimization [5-6, 17]. To determine the regression coefficients of the developed model, the Statistical analysis software, design expert 9 version was used. The second order models were developed for the responses due to lower predictability of the first order models to the present problem [8, 9]. The following equations were obtained in terms of actual factors

$$MRR = 155.2 - 0.139\, x_1 - 0.986\, x_2 - 45.30\, x_3 + 908\, x_4 + 0.00008\, x_1^2 + 0.0008\, x_2^{\,2} + 1.965\, x_3^2 - 2025\, x_4^2 + 0.00056\, x_1x_2 + 0.0193\, x_1x_3 - 0.574\, x_1x4 + 0.133\, x_2x_3 - 0.36\, x_2x_4 + 9.3\, x_3x_4 \quad (4)$$

$$Ra = 0.24 + 0.00075\, x_1 + 0.00055\, x_2 - 0.06\, x_3 + 3.93\, x_4 + 0.000011\, x_2^2 + 0.0086\, x_3^2 - 23.8\, x_4^2 + 0.000075\, x_1x_3 - 0.00164\, x_1x_4 + 0.00034\, x_2x_3 + 0.0086\, x_2x_4 + 0.342\, x_3x_4 \quad (5)$$

$$EWR = 48.1 - 0.0203\, x_1 + 0.075\, x_2 - 20.69\, x_3 + 149\, x_4 + 0.00001\, x_1^2 - 0.00194\, x_2^2 + 1.074\, x_3^2 + 505\, x_4^2 + 0.000244\, x_1x_2 + 0.0082\, x_1x_3 - 0.34\, x_1x_4 + 0.069\, x_2x_3 - 0.174\, x_2x_4 - 15.37\, x_3x_4 \quad (6)$$

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Analysis of variance (ANNOVA) was carried out to check the adequacy of the developed models. Table-3 shows the analysis of Variance (ANOVA) for MRR. The p value for the model is lower than 0.05 (i.e. at 95% confidence level) indicates that the developed model is statistically significant. The same and similar analysis was carried out for Ra and EWR and listed in Table-4 and Table-5 respectively. The multiple regression coefficients (R^2) for MRR, Ra and EWR were found 0.9770, 0.9902 and 0.9867 respectively. This shows that second order models can explain the variation in the MRR, Ra and EWR up to the extent of 97.7%, 99.02% and 98.67% respectively. The R^2 values are very high and close to the unity, it indicates that the second order models were adequate to represent the machining process. The "Predicted R-Squared" values are in reasonable agreement with the "Adjusted R-Squared" of the responses. Normal probability plots are used to assess whether data come from the normal distribution. The statistical procedure makes the assumption that an underlying distribution is normal. Thus normal probability plots can provide assurance that the assumption is justified, or else provide a warning of problems with the assumption. An analysis of normality typically combines normal probability plots with hypothesis tests for normality. In a normal probability plot, if all the data points fall near the line, an assumption of normality is reasonable. Otherwise, the points will curve away from the line, and an assumption of normality is not justified the normal probability plots of residuals for MRR, Ra and EWR are shown in the Figure-2, Figure-3 and Figure-4 respectively. From these plots, it can be conclude that the residuals lies on a straight line which implies that the errors are distributed normally and the developed regression models are well fitted with the observed valves. The plots of predicted versus actual responses were studied and revels that the models are adequate without any violation of independence or constant assumption.

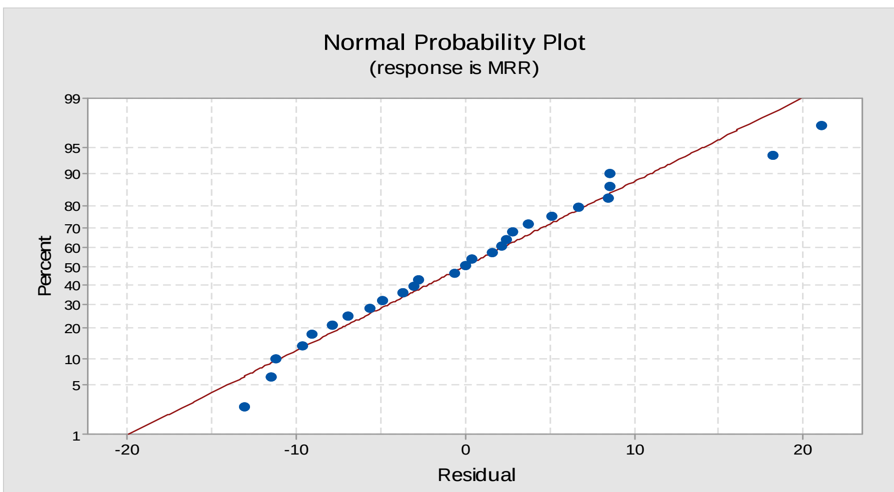

Figure-2. Normal probability plot of residuals for MRR.

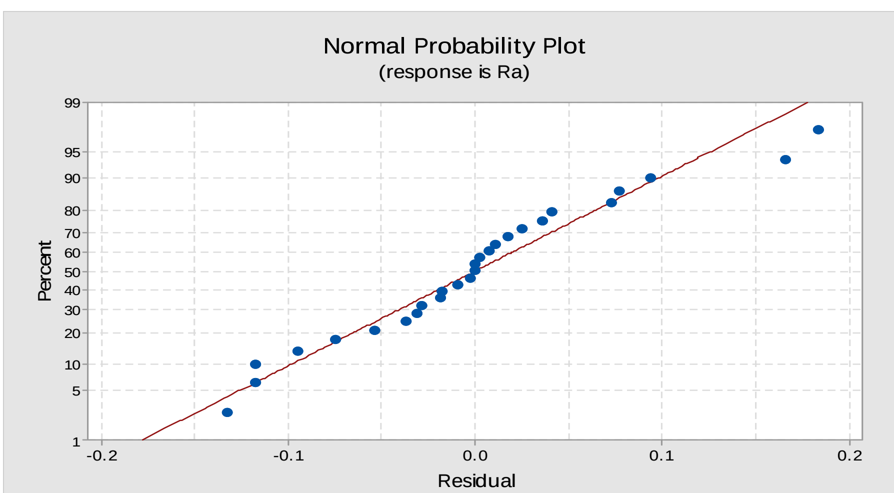

Figure-3. Normal probability plot of residuals for Ra.

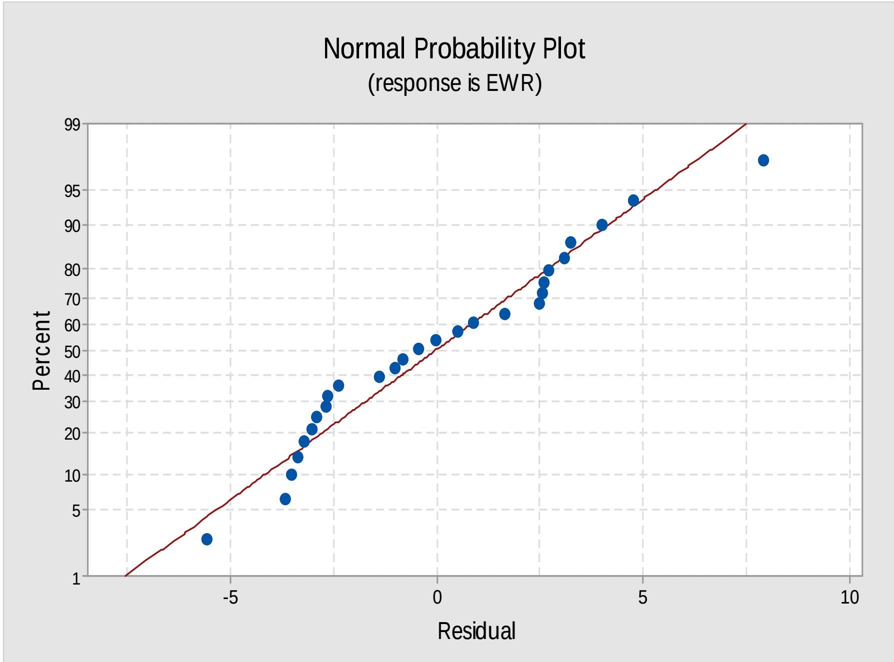

Figure-4. Normal probability plot of residuals for EWR.

Table-3. Analysis of Variance (ANOVA) for MRR.

Source	Sum of squares	df	Mean square	F Value	P-value Prob > F
Model	80629.93	14	5759.28	36.37	< 0.0001 significant
x_1	6820.73	1	6820.73	43.07	< 0.0001
x_2	7214.41	1	7214.41	45.56	< 0.0001
x_3	50191.68	1	50191.68	316.97	< 0.0001
x_4	91.22	1	91.22	0.58	0.4625
x_1x_2	357.24	1	357.24	2.26	0.1589
x_1x_3	4229.01	1	4229.01	26.71	0.0002
x_1x_4	579.64	1	579.64	3.66	0.0799
x_2x_3	5108.17	1	5108.17	32.26	0.0001
x_2x_4	5.79	1	5.79	0.037	0.8516
x_3x_4	38.76	1	38.76	0.24	0.6297
x_1^2	151.37	1	151.37	0.96	0.3475
x_2^2	9.90	1	9.90	0.063	0.8068
x_3^2	5928.75	1	5928.75	37.44	< 0.0001
x_4^2	153.76	1	153.76	0.97	0.3439
Residual	1900.20	12	158.35		
Total	82530.13	26			

Table-4. Analysis of variance (ANOVA) for Ra.

Source	Sum of squares	df	Mean square	F Value	p-value Prob > F
Model	15.35	14	1.10	86.59	< 0.0001 significant
x_1	1.23	1	1.23	97.34	< 0.0001
x_2	1.27	1	1.27	100.67	< 0.0001
x_3	12.53	1	12.53	989.88	< 0.0001
x_4	0.0029	1	0.0029	0.23	0.6386
x_1x_2	0.00122	1	0.00122	0.097	0.7609
x_1x_3	0.063	1	0.063	4.98	0.0454
x_1x_4	0.0047	1	0.0047	0.37	0.5536
x_2x_3	0.034	1	0.034	2.70	0.1264
x_2x_4	0.00329	1	0.0032	0.26	0.6193
x_3x_4	0.053	1	0.053	4.16	0.0640
x_1^2	0.00009	1	0.00009	0.007	0.9339
x_2^2	0.00178	1	0.00178	0.14	0.7143
x_3^2	0.12	1	0.12	9.14	0.0106
x_4^2	0.021	1	0.021	1.67	0.2200
Residual	0.15	12	0.013		
Total	15.50	26			

Table-5. Analysis of variance (ANOVA) for EWR.

Source	Sum of squares	Df	Mean square	F Value	p-value Prob > F
Model	20167.46	14	1440.53	63.68	< 0.0001 significant
x_1	1296.25	1	1296.25	57.31	< 0.0001
x_2	1964.18	1	1964.18	86.83	< 0.0001
x_3	12705.24	1	12705.24	561.68	< 0.0001
x_4	7.18	1	7.18	0.32	0.5835
x_1x_2	67.04	1	67.04	2.96	0.1108
x_1x_3	766.53	1	766.53	33.89	< 0.0001
x_1x_4	202.67	1	202.67	8.96	0.0112
x_2x_3	1386.39	1	1386.39	61.29	< 0.0001
x_2x4	1.36	1	1.36	0.060	0.8104
x_3x_4	106.34	1	106.34	4.70	0.0510
x_1^2	2.28	1	2.28	0.10	0.7565
x_2^2	57.56	1	57.56	2.54	0.1367
x_3^2	1771.14	1	1771.14	78.30	< 0.0001
x_4^2	9.57	1	9.57	0.42	0.5277
Residual	271.44	12	22.62		
Total	20438.90	26			

5. ANALYSIS OF THE RESPONSES

5.1. Analysis of material removal rate (MRR)

The ANOVA summary recommended that the quadric model is statistically significant for analysis of MRR and linear terms of electrode rotation, voltage and current, interaction terms of electrode rotation and current, voltage and current and square terms of current are significant model terms. Hence, analysis of MRR is extended for these terms only as their values of "Probability > F" less than 0.05.

The three dimensional surface plots for the MRR with respect to the significant process parameters are shown in Figures 5-6. In each of these graphs, two cutting parameters are varied while the other two parameters are held constant as its middle value. The interaction effect of electrode rotation and current on metal removal rate in the form of 3D surface graph at constant voltage of 120 volts and spark gap of 0.15 mm is represented in Figure-5 using design expert software and response surface methodology. From this Figure, it is observed that maximum metal removal rate (175 gm/min) was obtained at the highest current (12 amps) and highest electrode rotation (750 RPM) combination. The minimum metal removal rate (100 gm/min) was obtained at the lowest current (4 amps) and lowest electrode rotation (250 RPM) combination. It is seen from these graphs that there is significant amount of curvature indicating non -linearity in the variation. From this graph, it is observed that there is switching of the curvature effect. It indicates that the reversal in behavior depending on the combination of the machining parameters. It also points towards significant contribution from the interaction of the machining parameters. It is observed that material removal rate increases with increase in current and the electrode rotation. There is a significant increase in material removal rate with increase in electrode rotation however with increase in current there is slight increase in material removal rate.

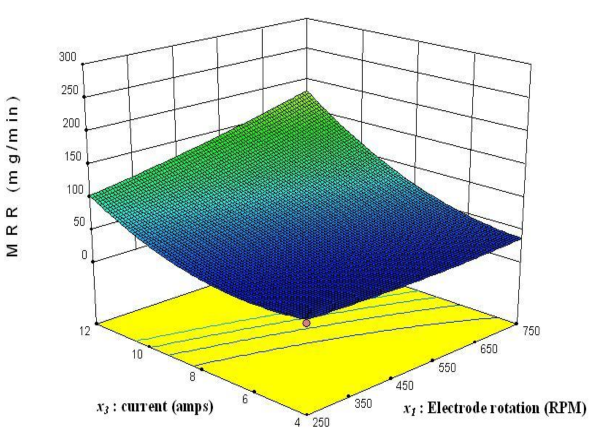

Figure-5. Interaction effect of current and electrode rotation on MRR.

The interaction effect of voltage and current on MRR in the form of 3D surface graph at constant electrode rotation of 500 RPM and spark gap of 0.15 mm is represented in Figure-6 using design expert software and response surface methodology. From this Figure, it is observed that maximum metal removal rate was obtained at the highest current (12 amps) and highest voltage (160 volts) combination. The minimum MRR was obtained at the lowest current (4 amps) and lowest voltage (80 volts) combination. It is observed that material removal rate increases with increase in current and the voltage. There is a significant increase in material removal rate with increase in voltage, however with increase in current there is a slight increase in material removal rate. As far as the current is concerned, more current leads to the more energy available per spark. This higher energy available per spark leads to the melting of more material per spark and hence more material is melted and removed per spark with the increase in current.

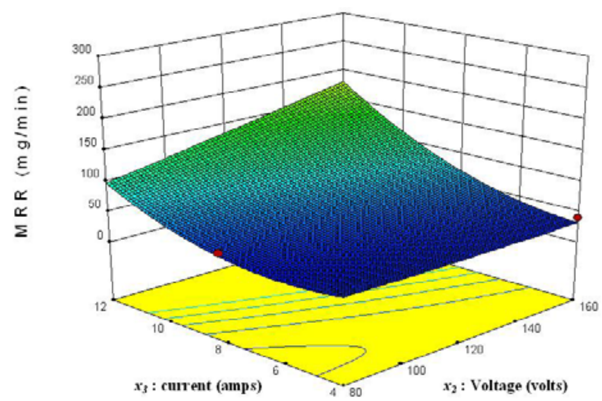

Figure-6. Interaction effect of current and voltage on MRR.

5.2. Analysis of surface roughness (Ra)

The Analysis of variance summary recommended that the quadric model is statistically significant for surface roughness and linear terms of electrode rotation, voltage and current, interaction terms of voltage and current and square terms of current are significant model terms. Hence, analysis of surface roughness is extended for these terms only. The three dimensional surface plots for the surface roughness with respect to the significant process parameters are shown in Figures 7-9. In each of these graphs, two machining parameters are varied while the other two parameters are held constant as its middle value.

The interaction effect of electrode rotation and current on surface roughness in the form of 3D surface graph at constant voltage of 120 volts and spark gap of 0.15 mm is represented in Figure-7 using design expert software and response surface methodology. From this Figure, it is observed that maximum surface roughness was obtained at the highest current (12 amps) and highest electrode rotation (750 RPM) combination. The minimum surface roughness was obtained at the lowest current (4 amps) and lowest electrode rotation (250RPM) combination. It is seen from these graphs that there is significant amount of curvature indicating non -linearity in the variation. It also points towards significant contribution from the interaction of the machining parameters. It is observed that surface roughness increases with increase in current and the electrode rotation. There is significant increase in surface roughness with increase in current, however with increase in electrode rotation there is slight increase in surface roughness. As for as the current is concerned, more current means more energy available per spark. This higher energy available per spark leads to melting of more material per spark and hence poor surface finish.

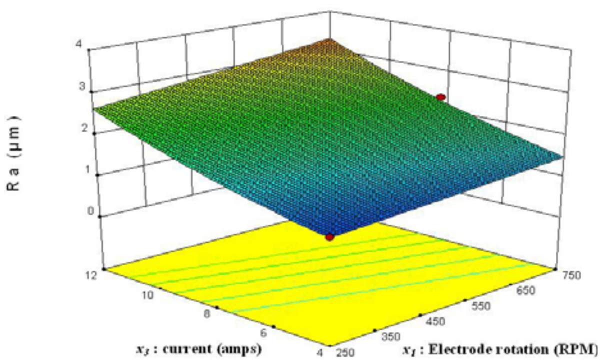

Figure-7. Interaction effect of current and electrode rotation on surface roughness.

The interaction effect of voltage and current on surface roughness in the form of 3D surface graph at constant electrode rotation of 500 RPM and spark gap of 0.15 mm is represented in Figure-8 using design expert software and response surface methodology. From this Figure, the minimum surface roughness was obtained at the lowest current (4 amps) and lowest voltage (80 volts) combination. It is observed that surface finish decreases with increase in current and the voltage and there is a significant decrease in surface finish with increase in current, however with increase in voltage there is slight decrease in surface finish.

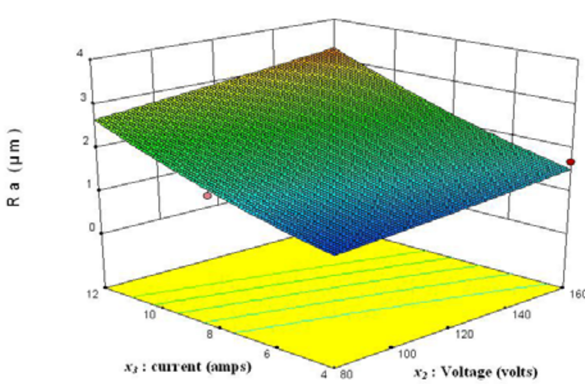

Figure-8. Interaction effect of current and voltage on surface roughness.

The interaction effect of current and spark gap on surface roughness in the form of 3D surface graph at constant voltage of 120 volts and electrode rotation of 500 RPM is represented in Figure-9 using design expert software and response surface methodology. From this Figure, it is observed that maximum surface roughness was obtained at the highest current (12 amps). The minimum surface roughness was obtained at the lowest current (4 amps) and lowest spark gap (0.1mm) combination. It also points towards significant contribution from the interaction of the machining parameters. It is observed that surface roughness increases with increase in current and the spark gap. There is a significant increase in surface roughness with increase in current, however with increase in spark gap there is no significant increase in surface roughness.

5.3. Analysis of electrode wear rate (EWR)

The three dimensional surface plots for the electrode wear rate with respect to the significant process parameters are shown in Figures 10-11. In each of these graphs, two cutting parameters are varied while the other two parameters are held constant as its middle value. The interaction effect of electrode rotation and current on electrode wear rate in the form of 3D surface graph at constant voltage of 120 volts and spark gap of 0.15 mm is represented in Figure-10 using design expert software and response surface methodology. From this Figure, it is observed that maximum electrode wear rate (82.5 gm/min) was obtained at the highest current (12 amps) and highest electrode rotation (750 RPM) combination. The minimum electrode wear rate (50 gm/min) was obtained at the lowest current (4 amps) and lowest electrode rotation (250 RPM) combination. It is observed that there is significant increase in electrode wear rate with increase in current and the electrode rotation.

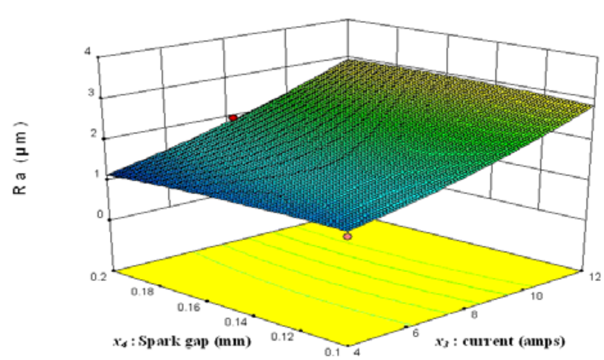

Figure-9. Interaction effect of current and spark gap on surface roughness.

The interaction effect of voltage and current on EWR in the form of 3D surface graph at constant electrode rotation of 500 RPM and spark gap of 0.15 mm is represented in Figure-11. From this Figure, it is observed that maximum electrode wear rate (85 gm/min) was obtained at the highest current (12 amps) and highest

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voltage (160 volts) combination. The minimum electrode wear rate (42gm/min) was obtained at the lowest current (4 amps) and lowest voltage (80 volts) combination. It is observed that there is significant increase in electrode wear rate with increase in current and voltage.

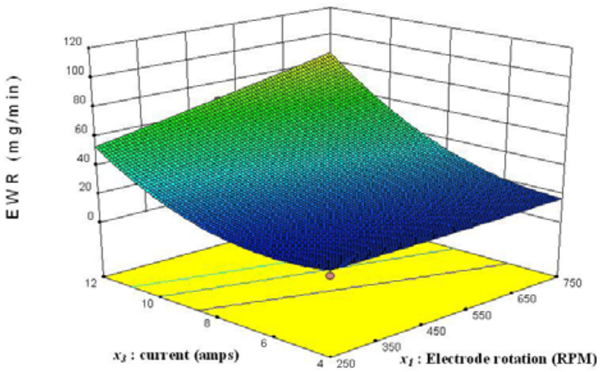

Figure-10. Interaction Effect of current and electrode rotation on EWR.

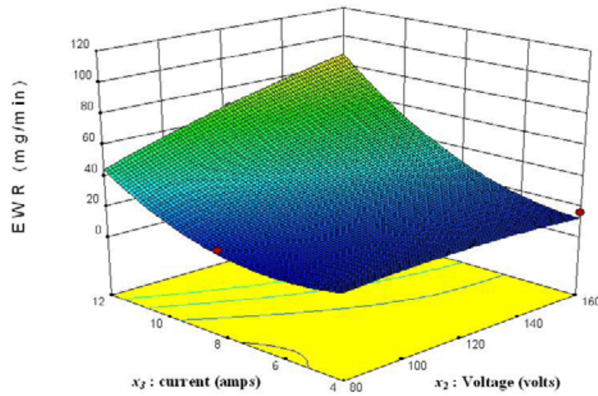

Figure-11. Interaction Effect of current and voltage rotation on EWR.

6. PROBLEM FORMULATION AND OPTIMIZATION

In the present work, the responses material removal rate, surface roughness and the electrode wear rate are conflict in nature [7, 8]. In the process of optimization, the objective is to minimize the surface roughness and electrode wear rate and maximize the metal removal rate. The optimization problem for MRR, Ra and EWR with feasible limits of control variables are represented in the following equations after eliminating the insignificant terms.

Maximize

$$MRR = 155.2 - 0.139\, x_1 - 0.986\, x_2 - 45.30\, x_3 + 908\, x_4 + 0.00008\, x_1^2 + 0.0008\, x_2^{\,2} + 1.965\, x_3^2 - 2025\, x_4^2 + 0.00056\, x_1x_2 + 0.0193\, x_1x_3 - 0.574\, x_1x4 + 0.133\, x_2x_3 - 0.36\, x_2x_4 + 9.3\, x_3x_4 \quad (7)$$

Minimize

$$Ra = 0.24 + 0.00075\, x_1 + 0.00055\, x_2 - 0.06\, x_3 + 3.93\, x_4 + 0.000011\, x_2^2 + 0.0086\, x_3^2 - 23.8\, x_4^2 + 0.000075\, x_1x_3 - 0.00164\, x_1x_4 + 0.00034\, x_2x_3 + 0.0086\, x_2x_4 + 0.342\, x_3x_4 \quad (8)$$

Minimize

$$EWR = 48.1 - 0.0203\, x_1 + 0.075\, x_2 - 20.69\, x_3 + 149\, x_4 + 0.00001\, x_1^2 - 0.00194\, x_2^2 + 1.074\, x_3^2 + 505\, x_4^2 + 0.000244\, x_1x_2 + 0.0082\, x_1x_3 - 0.34\, x_1x_4 + 0.069\, x_2x_3 - 0.174\, x_2x_4 - 15.37\, x_3x_4 \quad (9)$$

Subjected to

$250 \text{ RPM} \le x_1 \le 750 \text{ RPM}$
$80 \text{ volts} \le x_2 \le 160 \text{volts}$
$4 \text{ amps} \le x_3 \le 12 \text{ amps}$
$0.1 \text{ mm} \le x_4 \le 0.2 \text{ mm}$

Once the optimization problem is formulated, then it is solved using a Response surface optimization with desirability function. Multi- response optimization was carried out using desirability function with integration of response surface methodology to overcome the problem of conflicting responses of single response optimization [10, 11-12]. Various multi-characteristic models have been developed with their goals and limits for each response in order to determine their accurate impact on overall desirability. A maximum or minimum level is provided for all response characteristics which are to be optimized and weights are assigned to give added emphasis to upper or lower bounds or to emphasize a target value. The importance is assigned to each response relative to the other responses which varies from the least important (1) to the most important (5).

The ranges and goals of input parameters viz. electrode rotation, voltage, current and spark gap and the response characteristics viz. metal removal rate, surface roughness and electrode wear rate are given in Table-6. Metal removal rate has been assigned an importance of 5 relative to surface roughness, surface roughness and electrode wear rate each with an importance of 3.

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A set of optimal solutions is derived for the specified design space constraints (Table-7) for the output responses using Design expert statistical software. The set of conditions possessing highest desirability value is selected as optimum condition for the desired responses. Table-7 shows the optimal set of condition with higher desirability function required for obtaining desired response characteristics under specified constraints. The ramp view drawn using Design Expert software shows the desirability for the output responses (Figure-12). The dot on each ramp reflects the factor setting or response prediction for that response characteristic. The height of the dot shows how much desirable it is. A linear ramp function is created between the low value and the goal or the high value and the goal as the weight for each parameter was set equal to one. Bar graph (Figure-13) shows the overall desirability function of the responses. Desirability varies from 0 to 1 depending upon the closeness of the response towards target.

Desirability 3D-plots (Figures 14-17) were drawn keeping input parameters in range, metal removal rate at maximum, surface roughness and electrode wear rate at minimum at minimum. Table-8 shows point prediction at optimal setting of responses. The 95% CI (confidence interval) is the range in which one can expect the process average to fall into 95% of the time. The 95% PI (prediction interval) is the range in which one can expect any individual value to fall into 95% of the time. The prediction interval will be larger (a wider spread) than the confidence interval since one can expect more scatter in individual values than in averages. Confirmation experiments were conducted at optimum levels and the results were within 95% confidence interval.

Table-6. Range of input parameters and responses for desirability (MRR, Ra and EWR).

Parameter	Goal	Lower limit	Upper limit	Lower weight	Upper weight	Importance
x_1:Electrode rotation	is in range	250	750	1	1	3
x_2:Voltage	is in range	80	160	1	1	3
$x3$:current	is in range	4	12	1	1	3
x_4:Spark gap	is in range	0.1	0.2	1	1	3
MRR	maximize	22.67	251.3	1	1	5
Ra	minimize	0.89	3.63	1	1	3
EWR	minimize	8.58	110.3	1	1	3

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Table-7. A set of optimal solutions for desirability (MRR, Ra and EWR).

S. No.	Electrode rotation	Voltage	current	Spark gap	MRR	Ra	EWR	Desirability
1	749.997	160.000	8.400	0.150	114.928	2.627	49.359	0.438 Selected
2	749.993	160.000	8.409	0.151	115.077	2.629	49.386	0.438
3	749.999	159.572	8.422	0.150	115.246	2.630	49.633	0.437
4	749.995	159.995	8.456	0.159	115.171	2.638	49.086	0.437
5	748.534	160.000	8.404	0.146	115.257	2.627	49.822	0.437
6	749.996	159.994	8.640	0.141	121.861	2.687	53.467	0.436
7	749.996	154.210	8.564	0.156	113.968	2.624	49.581	0.436
8	750.000	159.999	8.658	0.181	116.279	2.666	49.582	0.435
9	715.412	159.999	8.495	0.156	111.627	2.612	48.159	0.434
11	704.183	159.999	8.686	0.147	115.640	2.649	50.897	0.433
12	744.454	159.999	8.655	0.115	121.767	2.659	56.873	0.432
13	683.023	159.996	8.635	0.164	109.651	2.609	47.577	0.432
14	749.992	159.999	8.277	0.104	112.702	2.557	54.012	0.431
15	750.000	158.185	8.089	0.100	106.602	2.494	51.876	0.429
16	749.990	128.983	9.370	0.167	112.181	2.638	50.501	0.428
17	750.000	133.679	9.314	0.188	110.521	2.629	49.633	0.427
18	657.960	160.000	9.099	0.194	112.952	2.665	50.312	0.427
19	618.838	160.000	9.210	0.184	113.161	2.671	50.508	0.426
20	704.925	159.998	8.481	0.100	109.476	2.544	54.143	0.425
21	749.999	124.806	9.338	0.131	110.937	2.604	52.826	0.425
22	611.287	159.999	9.414	0.200	114.462	2.691	52.144	0.423
23	585.720	159.989	9.483	0.200	113.337	2.683	51.972	0.422
24	578.860	160.000	9.536	0.200	113.973	2.690	52.363	0.422
25	749.998	89.196	10.651	0.165	108.760	2.700	46.170	0.421
26	637.964	159.505	8.718	0.200	99.299	2.528	44.743	0.421
27	464.314	160.000	9.765	0.179	109.551	2.655	50.408	0.421
28	250.003	160.000	10.661	0.197	110.283	2.644	52.174	0.420
29	319.850	159.998	10.339	0.189	108.614	2.642	50.930	0.419
30	250.006	152.808	10.627	0.200	104.080	2.567	50.342	0.418
31	250.010	149.332	10.995	0.200	110.253	2.634	53.835	0.418
32	749.988	80.003	10.898	0.138	107.758	2.707	46.732	0.417
33	250.162	140.875	11.193	0.200	108.365	2.612	53.644	0.417
34	250.002	134.651	11.345	0.200	106.992	2.598	53.296	0.416

Table-8. Point Prediction at optimal setting of responses (MRR, Ra and EWR).

Response	Predicted	95 % CI low	95% CI high	95 % PI low	95% PI high	Actual value
MRR	114.928	97.1119	132.745	82.23	147.63	112.26
Ra	2.62723	2.46791	2.78654	2.33	2.92	2.586
EWR	49.3592	42.6254	56.0929	37.00	61.72	48.64

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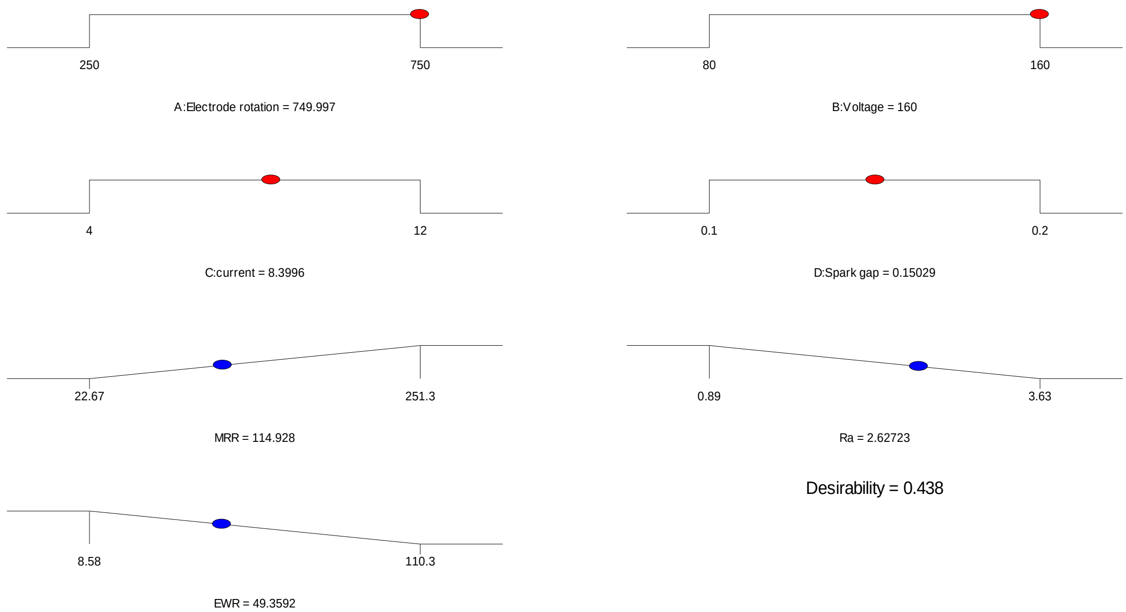

Figure-12. Ramp function graph of desirability for MRR, Ra and EWR.

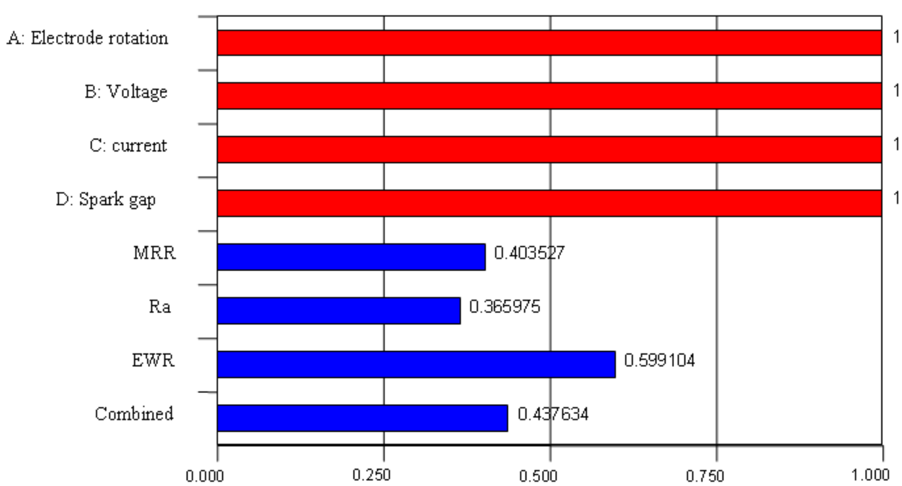

Figure-13. Bar graph of desirability for MRR, Ra and EWR.

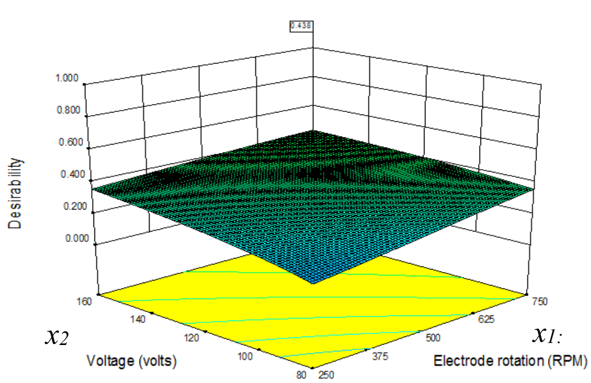

Figure-14. 3D Surface graph of desirability for MRR, Ra and EWR (x_1, x_2).

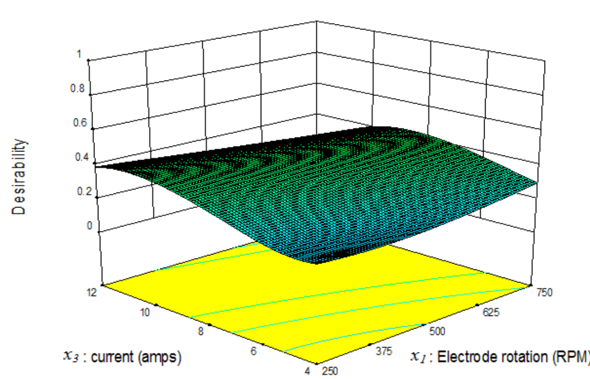

Figure-15. 3D surface graph of desirability for MRR, Ra and EWR (x_1, x_3).

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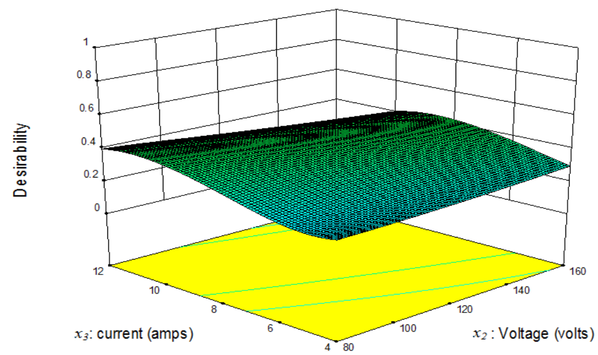

Figure-16. 3D Surface graph of desirability for MRR, Ra and EWR (x_2, x_3).

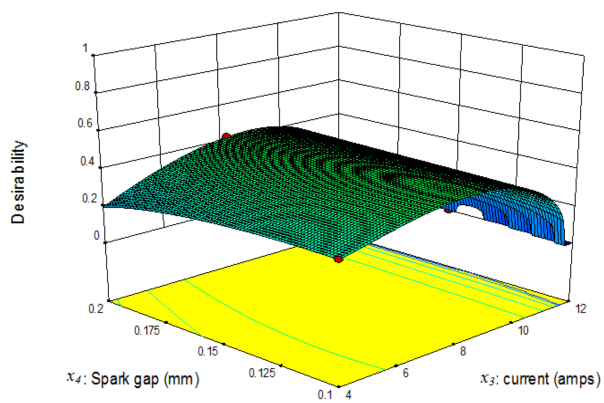

Figure-17. 3D Surface graph of desirability for MRR, Ra and EWR (x_3, x_4).

7. CONCLUSIONS

The experiments were conducted on a CNC electrical discharge machine for machining of AISI D2 steel. Response surface methodology was applied for developing the mathematical models in the form of multiple regression equations correlating the responses with the process parameters (electrode rotation, voltage, current and spark gap) and has been validated with F-test. The adequacy of these models has been tested on the responses with analysis of variance (ANOVA). The 3D response surfaces have been plotted to study the effects of the process parameters such as electrode rotation, voltage, current and spark gap on the responses MRR, Ra and EWR using RSM. Concept of desirability in integration with RSM has been used for simultaneous multi response optimization of responses of conflicting nature. The optimal values of process parameters were obtained and performed the confirmation experiments for validation of the results.

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