# ELECTRICAL DISCHARGE MACHINING OF S G IRON: EFFECT OF PROCESS VARIABLES ON MATERIAL REMOVAL RATE AND OVERCUT WITH MULTI-OPTIMISATION

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***ABSTRACT***

*Electrical discharge machining (EDM) process can be used effectively to machine S G Iron if mathematical models correlating the input process parameters and the major outputs are developed. The primary objective of this work is to develop mathematical models based on the design of experiments to correlate the controllable process parameters of EDM with major outputs like material removal rate (MRR) and overcut. The functional requirement such as high MRR together with low overcut depends on a number of process variables. Hence, the next objective is to use multi-criteria optimisation based on desirability function to find out the value of operating parameters that will ensure a high rate of material removal along with low overcut. Central composite design is practised here to develop the mathematical models. The variation in outputs along with process parameters are explained with the help of developed models. The values of operating parameters for high MRR with low overcut conditions are also found. The work material is S G Iron of grade 450/12.*

***KEYWORDS:*** *EDM, S G Iron, Multi- optimisation, Central composite design, desirability function, Material removal rate, Overcut.*

## I. INTRODUCTION

The EDM process is generally used to machine very hard, high strength electrically conductive materials. Since no cutting force is generated hence very intricate shapes can be machined economically with high accuracy. However, there are many operating parameters that dictate the machinability such as open circuit voltage, discharge voltage, discharge current, current pulse profile, pulse on-time, pulse off time, a gap between the work piece and the tool (spark gap), electrode rotation, dielectric medium, polarity of tool and work piece. Material removal rate (MRR) is considered as one of the most important responses for any type of machining. Most of the referred articles are highlighting that MRR mainly depends on process variables like discharge current[1-8], current pulse profile[9-10], pulse-on time[2,3,8], inter-electrode gap and relative motion between electrode and work-piece[6,11], etc. MRR increases with increase in current [1-8]. However, the effect of pulse on time on MRR is nonlinear. MRR increases initially with an increase in pulse on time up to a limit, beyond that increase in Pulse on time leads to a decrease in MRR [2, 3, 8]. Beyond a certain level of pulse current high energy input becomes inefficient leading to a decrease in MRR. An additional factor cited is that the surface temperature increases as the pulse on time is increased resulting in larger and thicker melted zone. This prevents flushing out of all the molten material thereby, resulting in low MRR [8]. The other reason forwarded [7] is that as pulse duration increases beyond a limit, the discharge column expands leading to lower electrical energy density resulting in lower MRR. Electrode rotation improves flushing thereby improving the stability of machining. The quality of the hole produced is also superior to that produced using a relative motion between electrode and work-piece [6]. Diametric overcut is a measure of machining accuracy. Diametric overcut depends on initiating voltage and an increase in spark frequency

[5], discharge energy [11], flushing and electrode material [1].With an increase in the frequency of sparking, the overcut reduces. Electrode rotation has a nonlinear effect on overcut. As discharge energy increases, overcut increases. It is reported that up to certain limit overcut increases as rotation speed is increased. Beyond that, there is little influence of rotational speed on overcut. The trend is explained on the basis that as rotational speed increases the centrifugal force increases leading to more debris being removed from the work piece. The removed debris is located between the tool and work piece leading to more side sparks and hence more overcut [11]. Some of the recent developments in EDM are; the use of different dielectric fluids and powders in fluids for improving the tool properties, and also, the use of different tool materials. It's also realised that the use of cryogenically treated electrodes with powder mixed dielectric will reduce the tool wear rate (TWR), [15]. A Recent review on EDM [16] finds that most numbers of research works have been carried out to optimise the electrical process parameters in EDM process. The major four important responses so far evaluated are material removal rate (MRR), tool wear rate, surface roughness (Ra) and circularity. The study of surface integrity and dimensional accuracy in EDM is also another interesting topic of nowadays research. The dimensional accuracy is characterised by the over cut (OC). Most of the findings reported in literature correlating process parameters to material removal rate (MRR) , tool wear ratio, overcut and surface finish of the machined surface are based on specific ranges of process parameters and particular work piece – tool combination. So for any new work piece – tool combination or different process parameter ranges, new models need to be developed for predicting the MRR and Overcut of the machined surface. Statistical design of experiments is an effective tool for studying the complex effects of a number of independent process variables on response factor. Central Composite Design [12] is an effective tool to model the effects of EDM process parameters on MRR and overcut. From the productivity point of view maximum MRR and from the accuracy point of view minimum overcut are desirable. Hence, use of multi-objective optimisation methods is necessary to achieve the goal of maximum MRR along with minimum overcut. Desirability function [13] is one such method that can be used effectively for selecting the process parameters that will maximise MRR and minimise overcut in the design space.

S G Iron is also called as nodular iron, ductile iron, and so on. This metal is being utilised largely in many industrial applications such as in heavy engineering and automotive sectors. Compares to Cast Iron, the improved mechanical properties such as high strength and ductility with wear resistance and good fatigue properties of this material rank this above carbon and low alloy steels [17].

The remainder of the paper is organised as follows. Section II describes the objectives of the work and Section III describes the proposed methodology. Section IV presents and discusses the results obtained using the proposed method. Section V explains the multi-optimisation using the desirability function and finally, the conclusions and future scopes are presented in Section VI.

## II. OBJECTIVES

The primary objective is to develop a second order regression equation for material removal rate (MRR) and Overcut for predicting and explaining their nature with respect to different process parameter combinations. The secondary objective is to utilise these mathematical models for finding the optimum combination of process variables for high MRR along with lower overcut.

## III. METHODOLOGY

### 3.1 Determining the useful limits of the variables:

Four controllable EDM parameters are selected. They are Current, Pulse on time (Ton), Inter electrode gap and Electrode rotation. The useful limits of Current, Pulse on time, Inter electrode gap and Electrode rotation are chosen based on preliminary trial experiments conducted and information available in the literature.

### 3.2 Selecting the Design Matrix:

Central composite design is selected for developing the mathematical models. The design matrix used for experimentation is a thirty point central composite design. The matrix contains four process variables (Current, Pulse on time ($T_{on}$), Inter electrode gap and Electrode rotation) at five levels. For simplifying the recording of the conditions of the experiments and processing of the experimental data, the variables are coded as +2, +1, 0, -1 & -2 by using the following relationship:

$$X_c = \frac{4X - 2(X_{max} + X_{min})}{(X_{max} - X_{min})}$$

The actual and coded values of the four process variables are given in Table 1. The design matrix is shown in Table 2.

## 3.3 Experimentation:

For carrying out the experiments, EDM Machine Agietron 250 C is used along with a round shaped tool made of copper. The dielectric fluid which is used for machining is Castrol SE 180 EDM Fluid. The specification of work piece SG Iron 450/12 grade received courtesy M/s. Hindustan Malleable & Forging Ltd., Dhanbad, India is given in Table 3.

**Table 1.** The Actual and Coded Values of Different Variables

| Variables | Symbol | Levels | | | | | Unit |
|---|---|---|---|---|---|---|---|
| | | **-2** | **-1** | **0** | **1** | **2** | |
| Current | A | 24 | 32 | 40 | 48 | 56 | Amp |
| $T_{on}$ | B | 8 | 28 | 48 | 68 | 88 | µs |
| Gap | C | 0.01 | 0.25 | 0.50 | 0.75 | 1 | mm |
| Rotation | D | 0 | 10 | 20 | 30 | 40 | rpm |

**Table 2.** The Design Matrix

| Run | Current | T on | Gap | Rotation |
|---|---|---|---|---|
| 1 | -1 | -1 | -1 | -1 |
| 2 | 1 | -1 | -1 | -1 |
| 3 | -1 | 1 | -1 | -1 |
| 4 | 1 | 1 | -1 | -1 |
| 5 | -1 | -1 | 1 | -1 |
| 6 | 1 | -1 | 1 | -1 |
| 7 | -1 | 1 | 1 | -1 |
| 8 | 1 | 1 | 1 | -1 |
| 9 | -1 | -1 | -1 | 1 |
| 10 | 1 | -1 | -1 | 1 |
| 11 | -1 | 1 | -1 | 1 |
| 12 | 1 | 1 | -1 | 1 |
| 13 | -1 | -1 | 1 | 1 |
| 14 | 1 | -1 | 1 | 1 |
| 15 | -1 | 1 | 1 | 1 |
| 16 | 1 | 1 | 1 | 1 |
| 17 | -2 | 0 | 0 | 0 |
| 18 | 2 | 0 | 0 | 0 |
| 19 | 0 | -2 | 0 | 0 |
| 20 | 0 | 2 | 0 | 0 |
| 21 | 0 | 0 | -2 | 0 |
| 22 | 0 | 0 | 2 | 0 |
| 23 | 0 | 0 | 0 | -2 |
| 24 | 0 | 0 | 0 | 2 |

| | | | | |
|---|---|---|---|---|
| 25 | 0 | 0 | 0 | 0 |
| 26 | 0 | 0 | 0 | 0 |
| 27 | 0 | 0 | 0 | 0 |
| 28 | 0 | 0 | 0 | 0 |
| 29 | 0 | 0 | 0 | 0 |
| 30 | 0 | 0 | 0 | 0 |

**Table 3.** Work piece Chemical compositions

| **% C** | **% Si** | **% Mn** | **% Mg** | **% S** | **% P** | **% Fe** | **% Others** |
|---|---|---|---|---|---|---|---|
| **3.36** | **2.39** | **0.238** | **0.085** | **< 0.15** | **0.07** | **90.75** | **2.947** |

The microstructure captured by using JEOL 5600 Scanning Electron Microscope (SEM) at 500x magnification, is shown in Figure 1. The material has a pearlitic matrix. It can also observe that the graphites in the pearlitic matrix are in nodular forms.

All the experiments were conducted at IDTR-Jamshedpur, India. The experiments are conducted according to the design matrix, but in random order to avoid any systematic error creeping into the results.

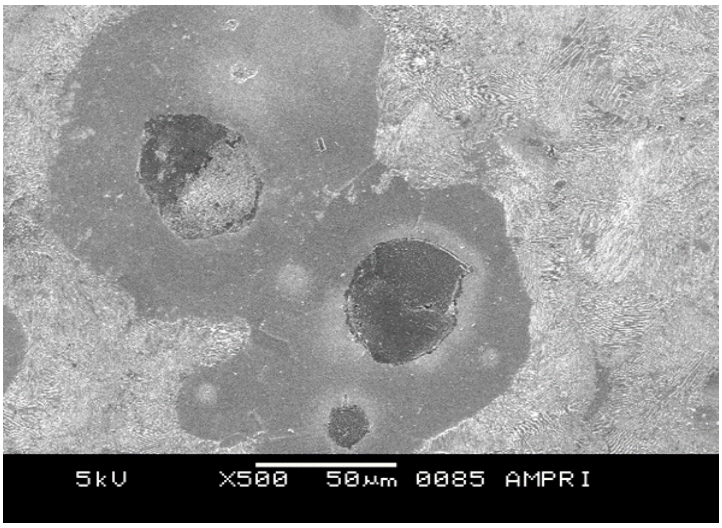


**Figure 1.** Microstructure of work piece material

MRR is calculated as: **MRR = $(W_i - W_f) / \rho T$**; and Overcut (OC) is calculated as: **OC= $(D_c - D_t) / 2$.**
Where, $W_i$ (Initial Weight of the work piece, gm), $W_f$ (Final Weight of the work piece, gm), T(Machining Time, min), ρ (Density of the Work piece, gm /cm³), $D_c$ (Diameter of the machined cavity, mm), $D_t$ (Diameter of the tool, mm) and MRR (Material Removal rate, $cm^3$/min).

The initial and final weight of the specimen is calculated from Mettler PM 1200 weighing machine.

### 3.4 Developing the Mathematical Model:

To correlate the effects of the variables, i.e. Current, Pulse on time ($T_{on}$), Inter electrode gap, Electrode rotation and the response factor, i.e. material Removal Rate (MRR) and Overcut, the following second order polynomial is selected.

$$Y= \beta_0 + \beta_1 A + \beta_2 B + \beta_3 C + \beta_4 D + \beta_{11} A^2 + \beta_{22} B^2 + \beta_{33} C^2 + \beta_{44} D^2 + \beta_{12} AB + \beta_{13} AC + \beta_{14} AD + \beta_{23} BC + \beta_{24} BD + \beta_{34} CD,$$

Where **β**’s are regression coefficients, **Y** is the response parameter (MRR, Overcut) and **A, B, C** and **D** are the EDM process parameters which already mentioned in Table 1.

### 3.5 Checking the Adequacy of the Models:

The analysis of variance (ANOVA) technique [12] is used to check the adequacy of the developed models. F-ratios of the models developed are calculated and are compared with the corresponding

tabulated values for 95% level of confidence. If the calculated value of F-ratio did not exceed the corresponding tabulated value, then the model is considered adequate. The mean sum of square of experimental error (**σ**) is also finds out. The goodness of fit of the models is tested by calculating the $R^2$, $R^2_{(adjusted)}$ & $R^2_{(predicted)}$. This analysis has been done using Design-Expert V9® software. The coefficients of the models developed and the model statistics for MRR are given in Table 4, and for Overcut it is mentioned in Table 5. All the models are statistically adequate.
To validate the models, further experiments were carried out at levels different than those of design matrix. The conditions and results are given in Table 6.

**Table 4.** The Coefficients of the Models Developed and the Statistical Model Parameters for MRR

| | MRR* | |
|---|---|---|
| | | |
| | $B_0$ | 0.011443 |
| | $B_1$ | 0.031733 |
| | $B_2$ | 0.024474 |
| | $B_3$ | 0.00312643 |
| | $B_4$ | 0.00363598 |
| | $B_{11}$ | -0.00478842 |
| | $B_{22}$ | -0.012287 |
| | $B_{33}$ | -0.00331805 |
| | $B_{44}$ | -0.00459076 |
| | $B_{12}$ | 0.015463 |
| | $B_{13}$ | -0.00343442 |
| | $B_{14}$ | -0.00585278 |
| | $B_{23}$ | 0.00632863 |
| | $B_{24}$ | 0.000879314 |
| | $B_{34}$ | -0.00545521 |
| | $F_{Ratio}$ | 2.80 |
| | $\sigma^2_{(mean\ sq.)}$ | 9.285E-05 |
| | **$R^2$** | **0.9416** |
| | **$R^2_{(adj)}$** | **0.8871** |
| | **$R^2_{(pred)}$** | **0.7017** |

***(MRR)** 0.5 Transformation formula used.***

The confidence interval is calculated based on the procedure given in reference [14]. The calculated confidence intervals with predicted response are given in Table 6. The EDM parameter values are depicted in codes. All the experimental values are within the confidence intervals. The predictions based on fitted equations are adequate only in the immediate neighbour-hood of the design [12].

### 3.6 Calculation of Desirability Function:

The Design-Expert V9® software is used for finding the optimum values of process variables for material removal rate and overcut based on desirability function. Each response parameter is transformed into a desirability function using criteria larger– the -better, Smaller – the- better or target –the- best [13]. The overall desirability considering two or more response parameters is found by calculating the geometric mean of the individual desirability functions. The geometric mean is then maximised over the region of interest. Normally the value of the desirability function varies between 0 and 1.

### 3.7 Analysis of the results:

From the developed models, contour graphs are plotted for both material removal rate and overcut. The ANOVA analysis shows that Current and Pulse on time are the most significant parameters influencing the responses. Hence, the contour graphs are plotted with Current in X-axis and Pulse on time on the Y axis. The remaining factors Inter electrode gap and electrode rotation are kept at various levels.

**Table 5.** The Coefficients of the Models Developed and the Statistical Model Parameters for Overcut

| | Overcut | |
|---|---|---|
| | | |
| | $B_0$ | 0.14711 |
| | $B_1$ | -0.01301 |
| | $B_2$ | -0.02131 |
| | $B_3$ | 0.00470875 |
| | $B_4$ | -0.00346042 |
| | $B_{11}$ | 0.012621 |
| | $B_{22}$ | 0.0040459 |
| | $B_{33}$ | -0.010545 |
| | $B_{44}$ | -0.028117 |
| | $B_{12}$ | 0.00565938 |
| | $B_{13}$ | -0.00589062 |
| | $B_{14}$ | -0.010141 |
| | $B_{23}$ | 0.00208438 |
| | $B_{24}$ | -0.013528 |
| | $B_{34}$ | 0.00424688 |
| | $F_{Ratio}$ | 2.60 |
| | $\sigma^2$ (mean sq.) | 1.620E-04 |
| | **$R^2$** | **0.9160** |
| | **$R^2$ (adj)** | **0.8375** |
| | **$R^2$(pred)** | **0.5745** |

**Table 6.** Validation Runs and their results within 95% Confidence interval for the developed Models.

| | **Validation Run No.** | **1** | | **Confidence Interval (±)** | **2** | | **Confidence Interval (±)** |
|---|---|---|---|---|---|---|---|
| **EDM Parameters** | | | | | | | |
| | Current (Amp) | 1.5 | 52 | | 0.5 | 44 | |
| | Pulse On time (µs) | 1.6 | 80 | | 0.8 | 64 | |
| | Gap (mm) | -0.8 | 0.3 | | 1.4 | 0.85 | |
| | Rotation (rpm) | 0.8 | 28 | | 0.2 | 22 | |
| **From Experiments** | Material Removal Rate (cm³/min) | **0.0359** | | | **0.0184** | | |
| | Overcut (mm) | **0.1243** | | | **0.1542** | | |
| **From Model** | Material Removal Rate (cm³/min) | **0.0354** | | 0.0128 | **0.023** | | 0.0097 |
| | Overcut (mm) | **0.08675** | | 0.04423 | **0.112** | | 0.0419 |

## IV. Results and Discussion

Figures. 2-4 show how MRR varies with the operating variables. Origin Lab® software was used for plotting the graphs.
The overall trends observed are as follows:

- MRR increases with increase in current and pulse-on time for any setup levels of gap and rotation. This is due to the increase in discharge energy. The size of the crater formed by each pulse is related to discharge energy.
- As the gap increase, the effect of rotation on MRR reduces. When the gap is at the lowest level, MRR increases with increase in rotation. However, as gap increases, the rate of increase in MRR with an increase in rotation decreases. As the rotation of the tool, i.e. relative motion between work-piece and tool increases, along with the gap, the dielectric fluid circulation increases, leading to enhanced flushing of the debris from the spark gap.
- The dominant trend observed is that as the gap between tool and work piece increases MRR increases. Though the electrical resistance increases with the increase in the gap but, flushing improves as gap increases. At large gap between tool and work-piece, the effect of rotation is negligible and MRR decreases. Hence, it may be concluded that gap has more influence on MRR than electrode rotation.

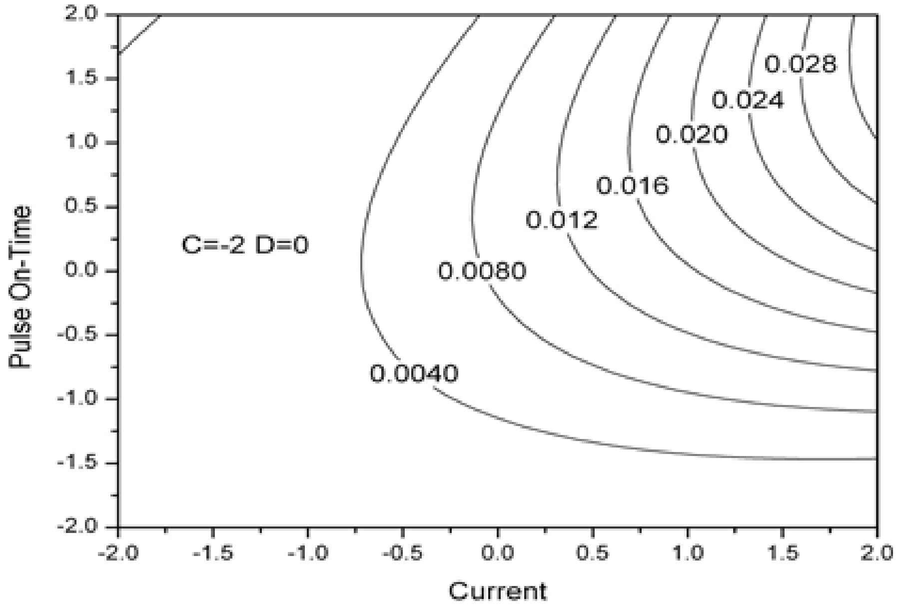


**Figure 2.** Variation of MRR at gap -2 level and electrode rotation at 0 level

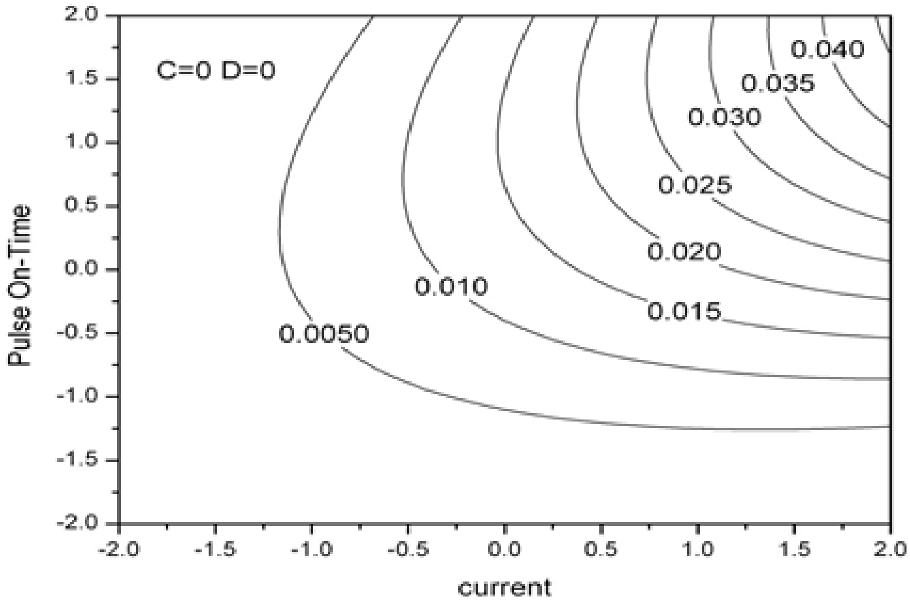


**Figure 3.** Variation of MRR at gap 0 level and electrode rotation at 0 level

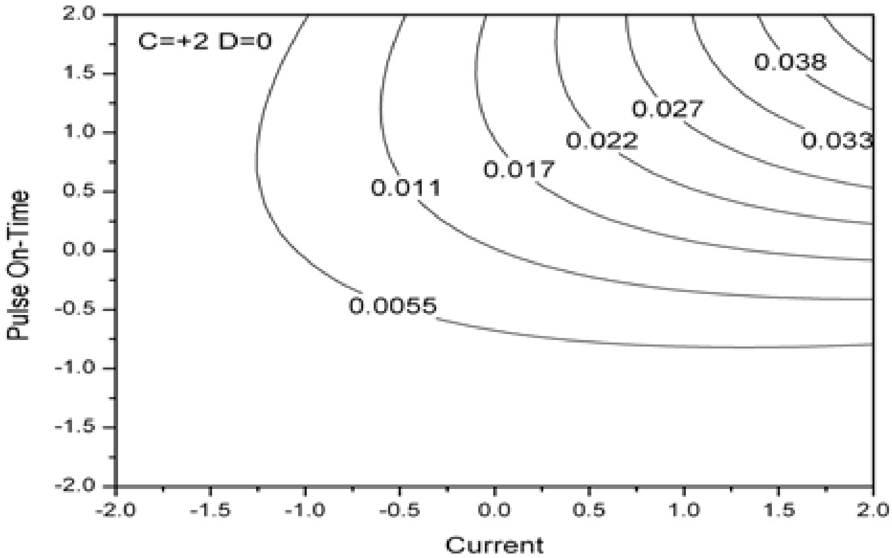


**Figure 4.** Variation of MRR at gap +2 level and electrode rotation at 0 level

Figures. 5-9 show how overcut varies with the operating variables. Origin Lab® software was used for plotting the graphs.
The overall trends observed are as follows:

- The Minimum value of overcut increases with increase in the gap up to zero level of the gap and then it decreases as the gap increases further (fig.5-7). A Similar trend has been observed in the case of rotation also (fig. 8, 6, 9). However, the effect of the gap is much smaller than the effect of rotation on overcut. The increase in overcut with the increase in rotation speed has been attributed to the location of removing debris between the tool and work piece leading to more side sparks and hence more overcut [11] .The other trend, i.e. the decrease in overcut with further increase in the rotation beyond 0 levels is due to better flushing.
- The minimum contour of overcut increases with increase in the rotation up to zero level and then it decreases as the rotation increases to +2 level.
- With the gap at any level, as rotation increases, the minimum contour of overcut shifts from lower to higher levels of current.
- The dominant trend observed is that the minimum value of overcut is observed close to the maximum value of pulse on time.

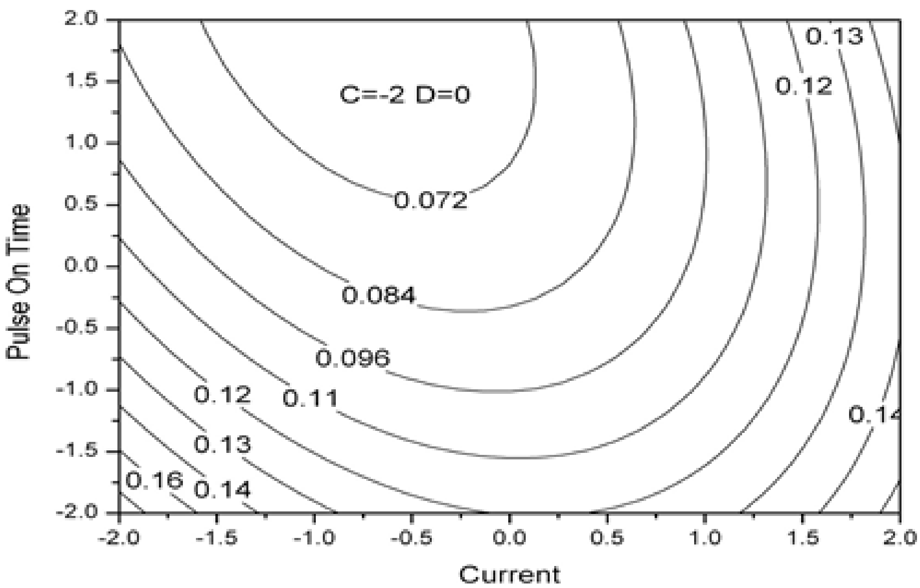


**Figure 5.** Variation of overcut at gap -2 level and electrode rotation at 0 level

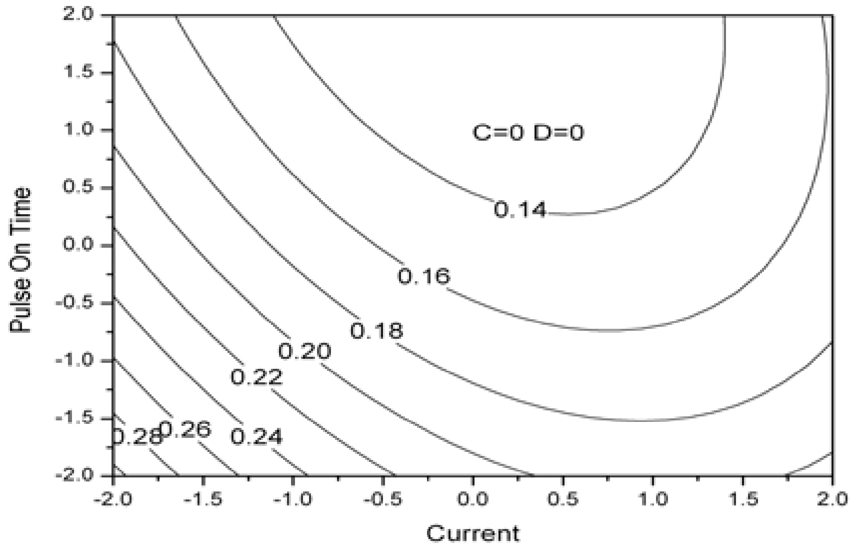


**Figure 6.** Variation of overcut at gap 0 level and electrode rotation at 0 level

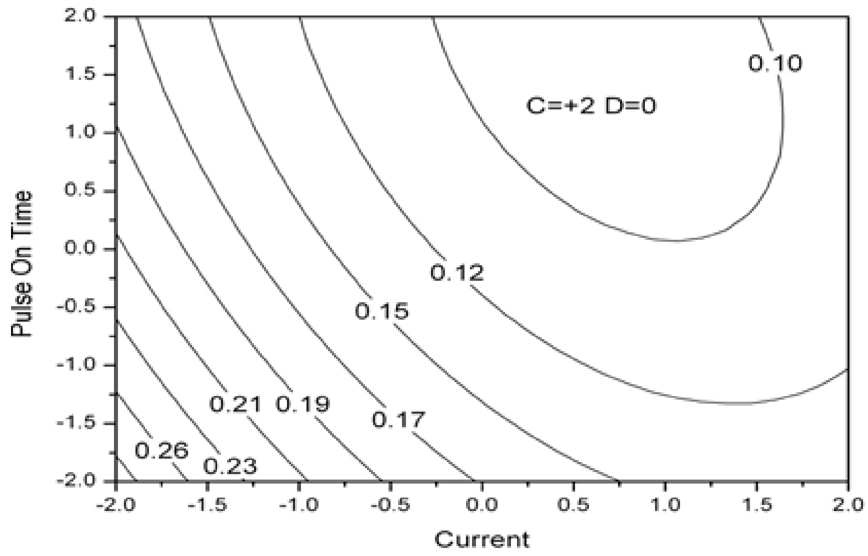


**Figure 7.** Variation of overcut at gap +2 level and electrode rotation at 0 level

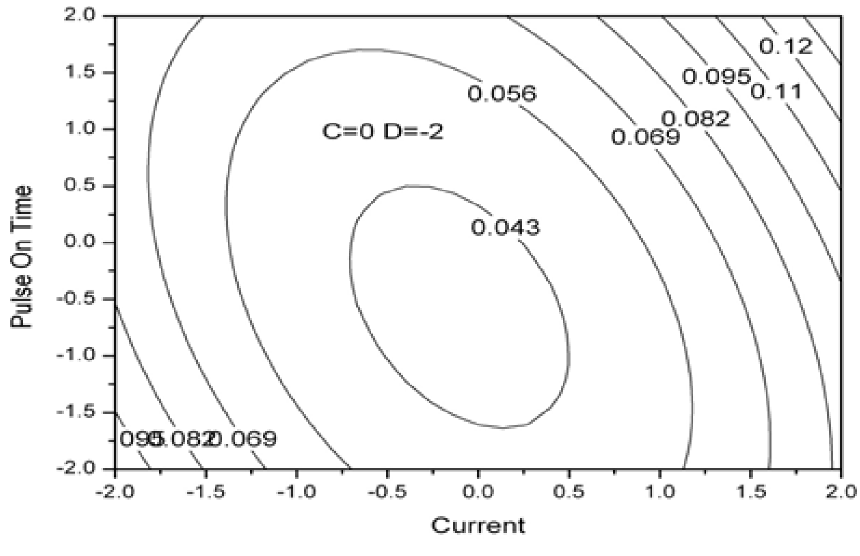


**Figure 8.** Variation of overcut at gap +0 level and electrode rotation at -2 level

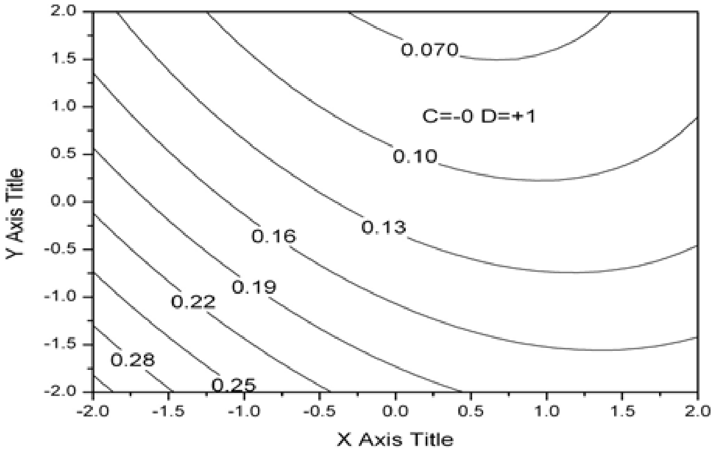


**Figure 9.** Variation of overcut at gap +0 level and electrode rotation at +1 level

## V. MULTI-OPTIMISATION USING THE DESIRABILITY FUNCTION

The conditions for multi-factor optimisation are given in table 7. The process variables are given in their coded values and the responses (surface texture parameters) are in their actual values. The desirability value obtained (1 set) for maximum MRR and Minimum Overcut is 0.969 corresponding to the coded process parameter values of current=2.000 , Pulse on time=1.148, electrode gap= -1.999 and rotation=1.64.The optimum values of the responses are MRR= 0.032 $cm^3$/min and Overcut =0.015 mm. The region for optimum desirability is shown in figure 10.

**Table 7.** The conditions for multi-optimisation

| Name | Goal | Lower Limit | Upper Limit | Lower Weight | Upper Weight | Importance |
|---|---|---|---|---|---|---|
| A:Current | is in range | -2 | 2 | 1 | 1 | 3 |
| B:Pulse on Time | is in range | -2 | 2 | 1 | 1 | 3 |
| C:Gap | is in range | -2 | 2 | 1 | 1 | 3 |
| D:Rotation | is in range | -2 | 2 | 1 | 1 | 3 |
| R1 (MRR) | maximize | 0.00041 | 0.03407 | 5 | 1 | 3 |
| R2 (Overcut) | minimize | 0.0154 | 0.2266 | 1 | 5 | 3 |

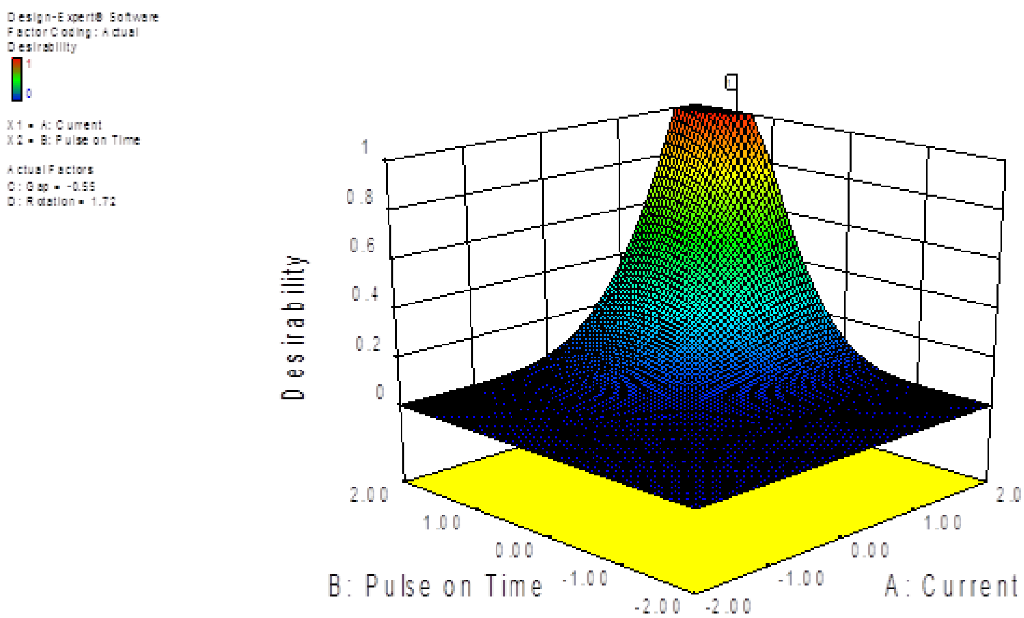


**Figure 10.** Graph showing the distribution of overall desirability function

As the results of validation runs are within the predicted range of 95% confidence level (Table 6), it can be assumed that the optimum values obtained using the desirability function should be within the predicted levels.

## VI. CONCLUSIONS AND FUTURE SCOPE

### 6.1 Conclusions:

- Mathematical models based on Central composite design have been developed to predict the effect of process variables on Material removal rate and Overcut.
- Current and Pulse On time are the major influencing factors for the responses. MRR increases with increase in current and pulse-on time for any fixed levels of gap and rotation. This is due to the increase in discharge energy.
- As the gap increase, the effect of rotation on MRR reduces. When the gap is at the lowest level, MRR increases with increase in rotation. However, as the gap increases, the rate of increase in MRR with an increase in rotation decreases. Gap has more influence on MRR than electrode rotation.
- The minimum value of overcut increases with increase in the gap up to zero level of the gap and then it decreases as the gap increases further. A Similar trend has been observed in the case of rotation also. However, the effect of the gap is much smaller than the effect of rotation on overcut.
- With the gap at any level, as rotation increases, the minimum contour of overcut shifts from lower to higher levels of current.
- The dominant trend observed is that the minimum value of overcut is observed close to the maximum value of pulse on time.
- The desirability value obtained (1 set) for maximum MRR and Minimum Overcut is 0.969 corresponding to the coded process parameter values of current=2.000 , Pulse on time=1.148, electrode gap= -1.999 and rotation=1.64.The optimum values of the responses are MRR= 0.032 $cm^3$/min and Overcut =0.015 mm.

### 6.2 Future Scope:

This work can be extended by using different material – metaheuristic optimisation combinations with different machining parameters and also with the same parameters for comparative studies.

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