Development of Empirical Model and Optimization of Electrode Rotation Electrical Discharge Machining for EN31

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Abstract

Electrical Discharge Machining (EDM) is most successful advanced machining process for recently developed high strength alloys, intricate geometrical shapes of hard to machine or difficult to cut materials, with dimensional accuracy. The experiments have been performed on EN31 Steel with electrolyte solid copper electrode. In this investigation the empirical models have been developed using regression analysis method by applying logarithmic data transformation of non-linear equation for forecasting the responses Three independent input variables of the model viz. peak current (P_c), pulse on time (T_{on}) and electrode rotation ($E_{rotation}$) speed are chosen as variables for evaluating the responses such as removal rate of material (RRM), wear rate of electrode (WRE) and surface roughness (R_a). Analysis of responses, by using full factorial design and ANOVA has been performed to identify the appreciable variables and their degree of contribution in process responses.

Analysed result represents the P_c and $E_{rotation}$ become the most significant and significant variable for R_a respectively. Experimental results further represents the electrode rotation methodology significantly improves the average RRM, and decreases the R_a and WRE.

Keywords: P_c, T_{on}, $E_{rotation,}$ RRM, Ra, WRE, EN31 steel, ANOVA.

1. Introduction

In EDM material removal takes place by melting and evaporation as a result of evolution of extremely high temperatures produced by the high intensity discharge energy [1]. The effect of input variables of the EDM process such as electrode material, polarity, current and pulse on and off time [2,3]. The performance of machining takes place when tool electrode and workpiece electrode are treated as cathode and anode and the best electrode for machining is copper [4]. Researcher concluded that as the amount of electrical discharge energy increases, material removal, surface roughness and percentage of surface cracks significantly increases. From the literature studies, limited research was found on using electrode rotation EDM with electrolyte copper electrode. Traditional electric discharge machining process lacks axial rotation in machining [5]. However, the advanced fabrication system has compensated for the limitation of EDM, the revised facility of EDM imparts a rotation to the electrode in its vertical axis.

EN31 Steel has widespread applications in manufacturing industries like Ball and Roller Bearings, spinning tools, Punches and Dies. EN31 steel has high resisting nature against wear and can be used for components which are subjected to severe abrasion, wear or high surface loading. The Electrical Discharge Machining of EN31 steel was done by using electrolyte solid copper electrode and the effects of peak current, pulse on time and electrode rotation on removal rate of material (RRM), Surface Roughness (R_a) and Wear Rate of Electrode (WRE) were studied.

2. Experimental Details

2.1. Machining Variables

Three machining variables, viz., P_c, T_{on} and electrode rotation were identified and there levels were fixed. The RRM, R_a & WRE responses were investigated.

2.2 Response variable evaluation

Removal rate of material (RRM) is calculated as the ratio of difference of weight of the work piece before and after machining to machined time:

$$RRM = (W_{w\,b} - W_{w\,a}) / T_m \quad \text{(gm/min.)} \tag{1}$$

Where $W_{w\,b}$ = Workpiece weight before machining in grams
$W_{w\,a}$ = Workpiece weight after machining in grams
T_m = Machining time in minutes.

Surface Roughness (R_a) is average value of high and low on the machined surface texture. It is expressed in µm. If R_a value is higher means the surface is rough and if lower then surface is smooth.

Wear rate of Electrode (WRE) is calculated as the ratio of the difference of weight of the electrode before and after machining to machined time:

$$WRE = (W_{e\,b} - W_{e\,a}) / T_m \quad \text{(gm/min.)} \tag{2}$$

Where $W_{e\,b}$ = Electrode weight before machining in grams
We_a = Electrode weight after machining in grams
Tm = Machining time in minutes.

2.3 Design of Experiments

The experimentation and analysis has been done with three factors and three levels using Response surface methodology (RSM) study with central composite design (CCD). The Process variables and their levels taken in experimentation as shown in table 1.

Table 1 Process variables and their levels

Process Variables	Notation	Levels		
		Low (-1)	Medium (0)	High (1)
Peak Current (amp.)	P_c	8	12	16
Pulse on Time (µsec)	T_{on}	50	200	600
Electrode Rotation (RPM)	$E_{rotation}$	200	400	600

3. Mathematical modelling

The Mathematical modelling representing the response variables and process variables was developed to simplify the optimization of electrode rotation EDM of EN 31 Steel. The mathematical modelling used is expressed by

$$Y = Ø\,(P_c,\ T_{on},\ E_{rotation}) \tag{3}$$

Where Y is the response, Ø is the response function; P_c (Peak current), T_{on} (Pulse on time), $E_{rotation}$ (Electrode rotation) are process variables.

$$\textbf{RRM} = 0.0001099 * P_c^{\,1.775} * T_{on}^{\,1.961} * E_{rotation}^{\,-01991} \tag{4}$$

Table 2 Analysis of Variance (ANOVA) for removal rate of material (RRM in gm/min.)

Source	**Sum of Squares**	**df**	**Mean Square**	**F-value**	**p-value**	
Model	0.1224	9	0.0136	29.7	< 0.0001	significant
P_c	0.0532	1	0.0532	116.14	< 0.0001	
T_{on}	0.0396	1	0.0396	86.42	< 0.0001	
$E_{rotation}$	0.0157	1	0.0157	34.26	0.0002	
$P_c * T_{on}$	0.0072	1	0.0072	15.64	0.0027	
$P_c * E_{rotation}$	0.0006	1	0.0006	1.21	0.2979	
$T_{on} * E_{rotation}$	0.0002	1	0.0002	0.3729	0.5551	
P_c^2	0.0003	1	0.0003	0.7573	0.4046	
T_{on}^2	0.0064	1	0.0064	13.95	0.0039	
$E_{rotation}^2$	0.006	1	0.006	13.05	0.0048	
Residual	0.0046	10	0.0005			
Lack of Fit	0.0046	5	0.0009			
Pure Error	0	5	0			
Cor Total	0.1269	19				

Std. Dev. : 0.0214 R^2 : 0.9639
Adjusted R^2 : 0.9315 Predicted R^2 : 0.9077

$$\textbf{WRE} = 0.0009908 * P_c^{\,2.579} * T_{on}^{\,-2.367} * E_{rotation}^{\,0.0082} \quad (5)$$

Table 3 Analysis of Variance (ANOVA) for Wear rate of electrode (WRE in gm/min.)

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	1085.19	9	120.58	41.36	< 0.0001	significant
P_c	457.57	1	457.57	156.94	< 0.0001	
T_{on}	345.19	1	345.19	118.4	< 0.0001	
$E_{rotation}$	4.68	1	4.68	1.6	0.2339	
$P_c * T_{on}$	103.08	1	103.08	35.36	0.0001	
$P_c * E_{rotation}$	0.0926	1	0.0926	0.0318	0.8621	
$T_{on} * E_{rotation}$	3.93	1	3.93	1.35	0.2726	
P_c^2	12.8	1	12.8	4.39	0.0626	
T_{on}^2	5.66	1	5.66	1.94	0.1938	
$E_{rotation}^2$	3.19	1	3.19	1.09	0.3203	
Residual	29.15	10	2.92			
Lack of Fit	29.15	5	5.83			
Pure Error	0	5	0			
Cor Total	1114.35	19				
Std. Dev. : 1.71				R^2 : 0.9738		
Adjusted R^2 : 0.9503				Predicted R^2 : 0.9387		

$$\mathbf{R_a} = 1.531 * P_c^{\,0.063} * T_{on}^{\,0.787} * E_{rotation}^{\,-0.0087} \tag{6}$$

Table 4 Analysis of Variance (ANOVA) for Surface Roughness (R_a in µm)

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	68.36	9	7.6	170.78	< 0.0001	significant
P_c	0.3214	1	0.3214	7.23	0.0228	
T_{on}	28.9	1	28.9	649.83	< 0.0001	
$E_{rotation}$	0.0272	1	0.0272	0.6109	0.4526	
$P_c * T_{on}$	0.3968	1	0.3968	8.92	0.0136	
$P_c * E_{rotation}$	18	1	18	404.74	< 0.0001	
$T_{on} * E_{rotation}$	2.29	1	2.29	51.4	< 0.0001	
P_c^2	12.02	1	12.02	270.34	< 0.0001	
T_{on}^2	12.39	1	12.39	278.53	< 0.0001	
$E_{rotation}^2$	0.9602	1	0.9602	21.59	0.0009	
Residual	0.4447	10	0.0445			
Lack of Fit	0.4447	5	0.0889			
Pure Error	0	5	0			
Cor Total	68.8	19				

Std. Dev. : 0.2109 — R^2 : 0.9935
Adjusted R^2 : 0.9877 — Predicted R^2 : 0.9520

4. Result and Discussion

The electrode rotation EDM methodology with reverse polarity were studied and the results are as follows.

4.1. Removal rate of material (RRM)

The ANOVA result of RRM is shown in table 2, which indicates predictability of RRM is at 99% confidence level, because the p is 0.0001. The coefficient of determination (R^2) value of 0.9639 shows that equation (4) is highly reliable. The p-value < 0.01 indicating that model is statistically significant [6].

As observed form the Residual Plots for RRM (gm/min.) Fig. 1, the normality of data was done by normal probability distribution plot. The normal probability distribution reveals that the residuals are lying on the straight line. This means the errors are normally distributed. The RRM has significant effect of current followed by pulse on time. The RRM is found to increase non-linearly with increase in current with slightly increase in pulse on time.

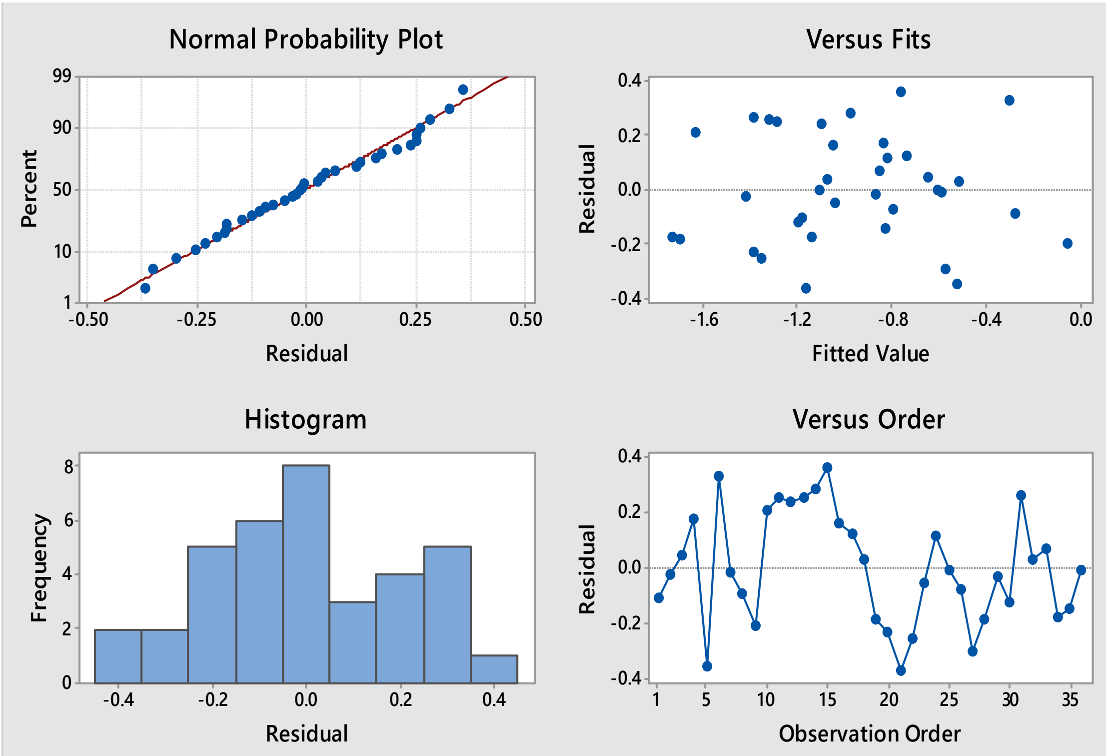

Fig. 1 Residual Plots for RRM (gm/min.)

4.2. Electrode Wear Rate (WRE)

Electrode wear rate observed form the Residual Plots for WRE (gm/min.) Fig. 2, the normality of data was observed by normal probability distribution plot. The normal probability distribution reveals that the residuals are falling on the straight line. This means the errors are normally distributed. The WRE slightly increases with increase in current as high current results in high discharge of energy on both the electrodes (tool and workpiece), but this effect is lower due to electrode rotation, it facilitates uniform distribution of discharge energy [7].

The ANOVA in table 3, shows the result of WRE, which indicates the predictability of model for WRE is at 99% confidence level, because the p is 0.0001 and significant. The coefficient of determination (R^2) value of 0.9738 shows that equation (5) is highly reliable. The p-value < 0.01 indicating that the model is statistically significant [6].

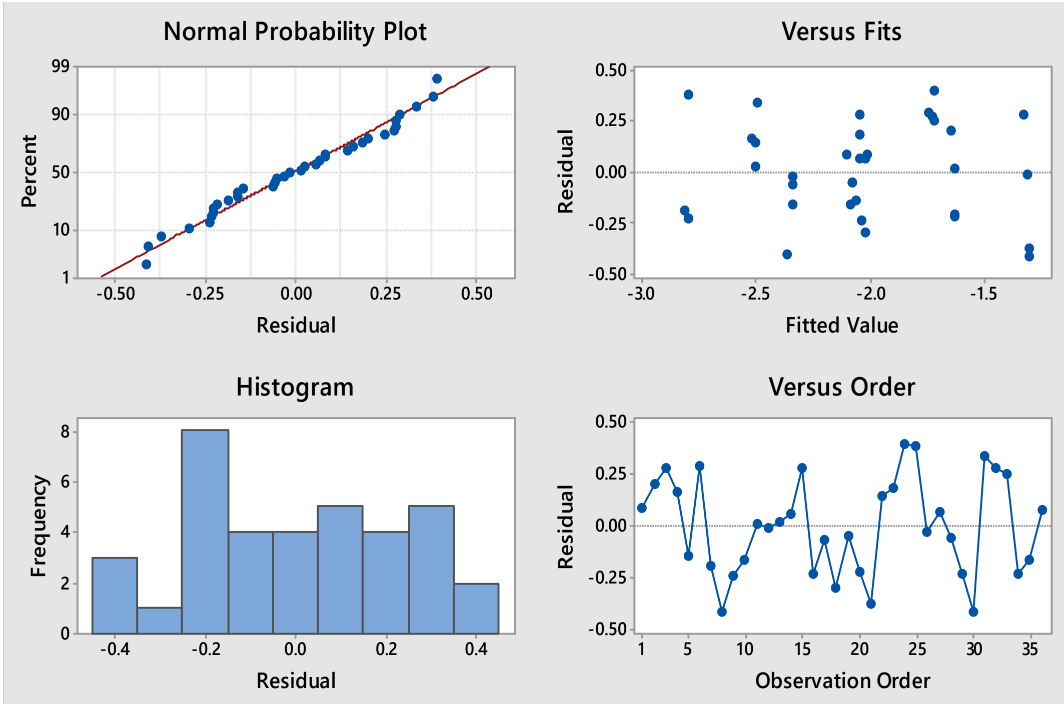

Fig. 2 Residual Plots for WRE (gm/min.)

4.3. Surface Roughness (µm)

Residual plot for surface roughness (R_a) reveals the data is distributed normally along the straight line. The surface roughness increases with increase in current and pulse on time due to pitting. The electrode rotation EDM methodology help to improve the quality of R_a i.e. the quality of surface finish increases. The pitting on the machined surface decreases by providing electrode rotation results in uniform distribution of thermal energy.

The ANOVA table 4 represents R_a, having p-value < 0.05 indicating that the model is statistically significant [6] because the p is 0.0001. The coefficient of determination (R^2) value of 0.9935 shows that equation (6) is highly reliable.

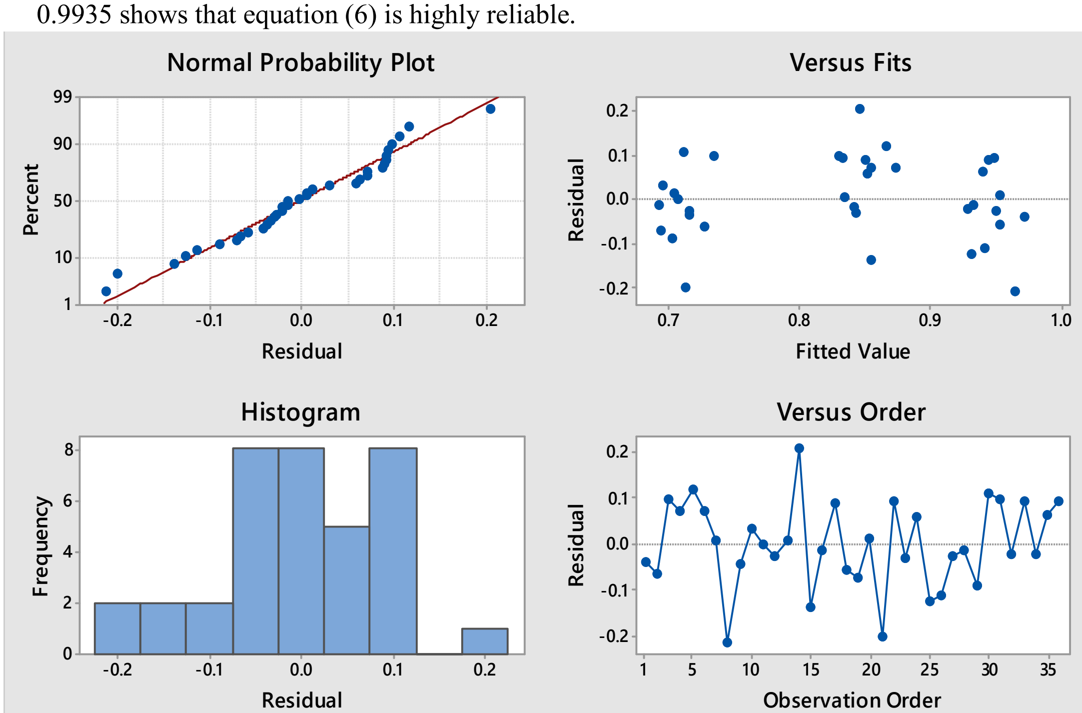

Fig. 3 Residual Plots for R_a

4.4. Interaction Effect

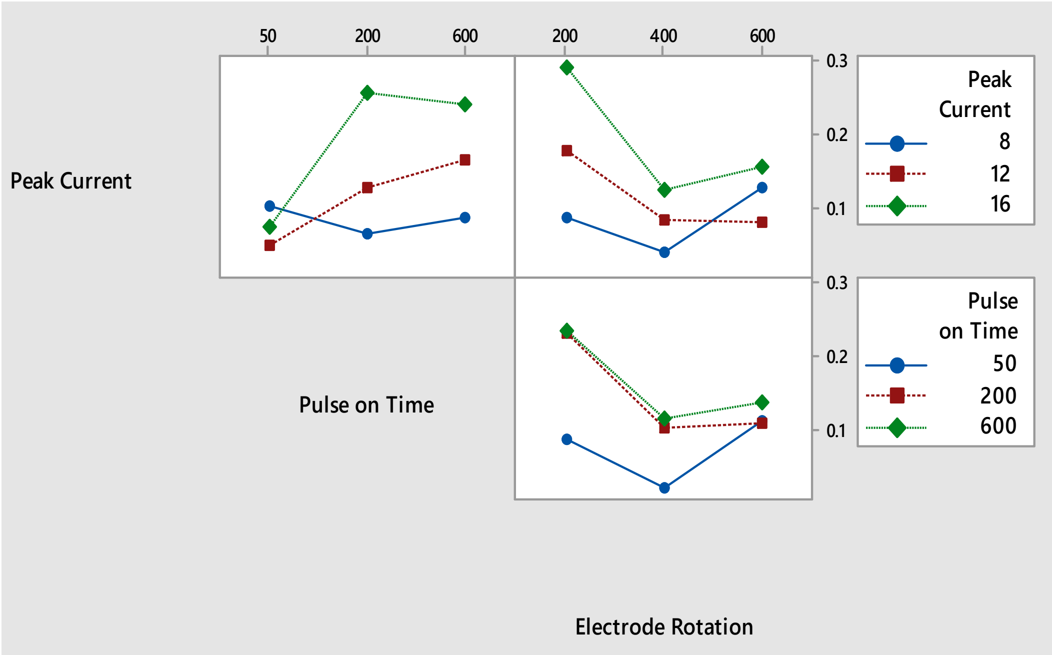

Fig. 4 Interaction Plot for RRM (gm/min.)

Fig. 4 represents the interaction plot for removal rate of material, interaction plot reveals the impact of peak current, pulse on time and electrode rotation on removal rate of material (RRM); Increase in peak current and pulse on time results, increase in RRM. Fig. 4 also represents the Pulse on time and electrode rotation have impact on RRM due to concentric discharge of thermal energy that reveals the RRM in the form of debris.

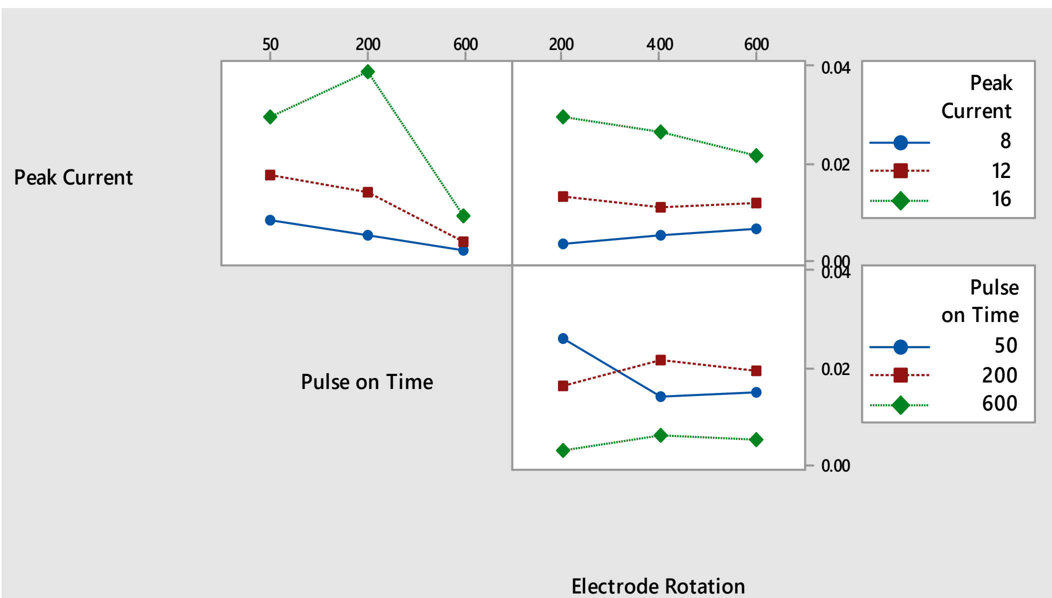

Fig. 5 Interaction plot for wear rate of electrode (gm/min.)

Fig. 5 represents the interaction plot for wear rate of electrode, interaction plot reveals the impact of peak current, pulse on time and electrode rotation on wear rate of electrode (WRE); Increase in peak current and pulse on time results in significant decrease in WRE. Fig. 5 also represents the Pulse on time and electrode rotation have impact on WRE i.e. lower WRE due to effective flushing by rotation of electrode.

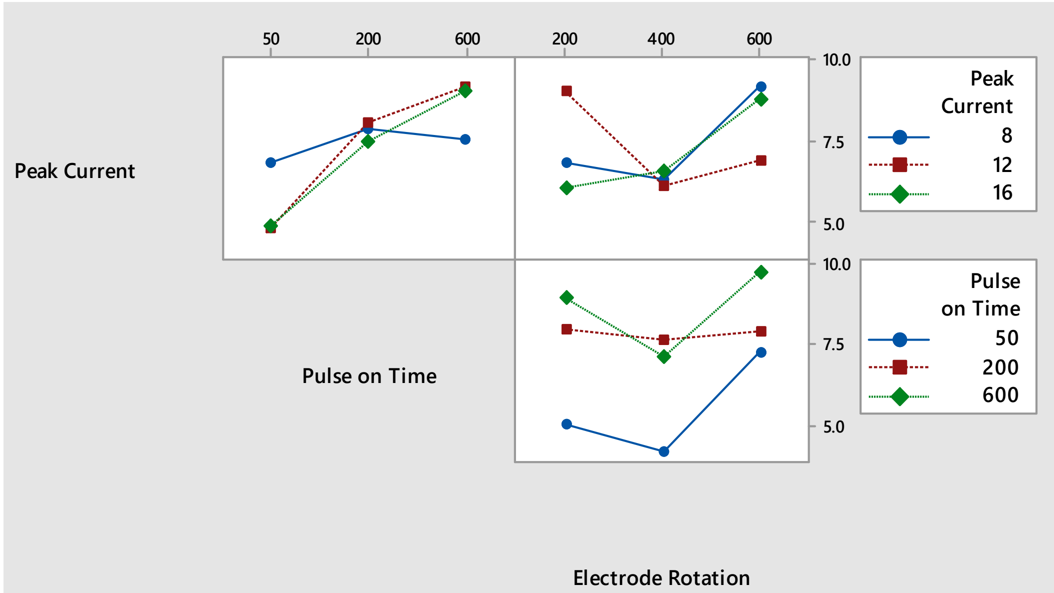

Fig. 6 Interaction Plot for R_a (µm)

Fig. 6 represents the interaction plot for surface roughness, interaction plot represents the effect of peak current, pulse on time and electrode rotation on surface roughness (R_a, µm); Increase in peak current and pulse on time results in significant increase in R_a due to concentric energy distribution.

4.5. Response optimizer

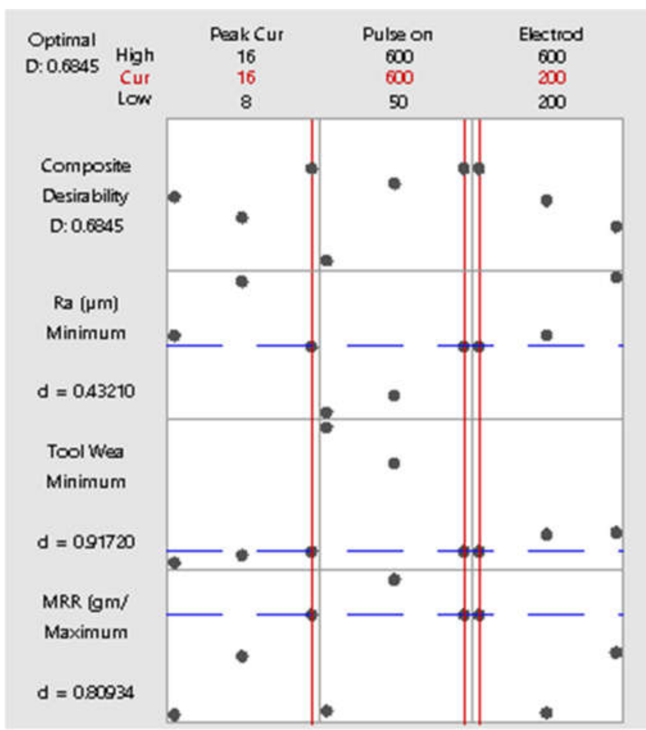

Fig. 7 Optimal Plot

The optimal plot is a Minitab Response Optimizer which represents the different experimental settings impact on responses. Fig. 7 shows the vertical red lines represents the current factor level and blue horizontal lines represents the response for current factor level. The optimal plot values for peak current, pulse on time and electrode rotation are 16, 600 and 200 respectively, predicts the maximum values of RRM and Minimum values of WRE and R_a at 95% Confidence Interval

& Prediction Interval.

5. Conclusion

In this paper the consequences of rotational electrode with various intensities of input variables on RRM, WRE and Surface Roughness are studied. Main conclusions are summarized as follows:

1. The average improvement in RRM by using rotary electrode, it applies a whirling force which helps in removing debris from machined surface, results high RRM.
2. The re-solidification of debris was reduced as rotation of electrode due to better cleaning from inter electrode gap.
3. The centrifugal force removes the melted material from the machined surface and improves the surface finish.
4. Uniform spark discharge energy distribution takes place by electrode rotation EDM.
5. Electrode wear rate significantly decreased by electrode rotation due to energy discharge transformation.
6. The main significant factors for surface roughness are peak current, electrode rotation and pulse on time, respectively.

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