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Mathematical modeling of electric discharge machining of cast Al–4Cu–6Si alloy–10 wt.% SiC_P composites

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Abstract

Aluminum matrix composites (AMC) are hard to machine due to the presence of hard and brittle ceramic reinforcements. Electrical discharge machining (EDM) is an important process for machining such materials. The present work evaluates the effect of current (c), pulse-on time (p) and air gap voltage (v) on metal removal rate (MRR), tool wear rate (TWR), radial over cut (ROC) on electric discharge machining of Al–4Cu–6Si alloy–10 wt.% SiC_P composites. The experiments were performed in a systematic manner with three successive trials using a PS LEADER ZNC EDM machine and a cylindrical brass electrode of 30 mm diameter. Three factor, three level full factorial design was adopted for analyzing the results. A second order, non-linear mathematical model has been developed for establishing the relationship among machining parameters. Analysis of variance (ANOVA) has been performed to verify the fit and adequacy of the developed mathematical models.

Keywords: Aluminum matrix composites; Electric discharge machining; Three level full factorial design; Mathematical modeling; ANOVA

1. Introduction

Metal matrix composites (MMCs) are well known for their superior mechanical properties over un-reinforced alloys. These composite materials are composed of a metallic base material called matrix, which is reinforced with ceramic fiber, whisker or particulates that impart a combination of properties not achievable in either of the constituents individually. A full-scale application of these advanced materials however has been hindered due to their high cost of machining. They can be machined with either electroplated diamond-grinding wheel or with carbide poly crystalline diamond cutting tools. In view of difficulties encountered—e.g. high tool wear and high tooling cost, during conventional machining, non-contact material removal processes such as the electric discharge machining (EDM) offer an effective alternative [1,3].

EDM is a complex phenomenon where several disciplines of science and engineering are included in the theory. It is a process of eroding electrically conductive materials with a series of succeeding electric sparks. EDM of LM 25 Al alloy–SiC composites using copper electrode was done by Karthikeyan et al. and the effects of volume percent of SiC_P, current and pulse duration on MRR, TWR and surface roughness were studied [2]. An experimental study on the effects of current, pulse on time and flushing pressure on responses like MRR, TWR, taper and surface roughness was done using 2.7 mm diameter electrode [3].

In the present work Al–4Cu–6Si alloy, which finds widespread applications in automotive components, was reinforced with 10 wt.% silicon carbide particulates. Al alloy–10 wt.% SiC composite plates were cast using stir die casting process and further machined to good finish on milling machine. The electric discharge machining of Al–4Cu–6Si alloy–10 wt.% SiC_P composites was done using 30 mm brass electrode and the effects of pulse current, gap voltage and pulse duration on the metal removal rate (MRR), tool wear rate (TWR) and radial over cut (ROC) were studied using design of experiment (DOE) technique. A mathematical model was also developed to predict the MRR, TWR and radial over cut within

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Table 1
Process parameters and their levels

Process parameters	Levels		
	Low (−1)	Medium (0)	High (1)
Gap voltage (V) ($X1$)	40	50	60
Pulse current (A) ($X2$)	20	30	40
Pulse duration (μs) ($X3$)	200	300	400

the operating region. The main and interactive effect plots were plotted between the input and output parameters.

2. Experimental procedure

2.1. Machining parameters and the response variables

Three machining parameters, viz., gap voltage, pulse current and pulse duration were identified and their levels were fixed as shown in Table 1. The responses studied were MRR, TWR, and ROC.

The variables were coded according to the equations: $X1=(V-50)/10$, $X2=(I-30)/10$, $X3=(T-300)/100$.

2.2. Response variables evaluation

Material removal rate (MRR) is expressed as the ratio of difference of weight of the work piece before and after machining to the machining time:

$$\mathrm{MRR}=\frac{(w_{\mathrm{jb}}-w_{\mathrm{ja}})}{t}, \quad (1)$$

where w_{jb} and w_{ja} are weights of the work piece before and after machining, and the machining time. Tool wear rate (TWR) is expressed as the ratio of the difference of weight of the tool before and after machining to the machining time:

$$\mathrm{TWR}=\frac{(w_{\mathrm{tb}}-w_{\mathrm{ta}})}{t}, \quad (2)$$

where w_{tb} and w_{ta} are weights of tool before and after the machining. Radial over cut (ROC) is expressed as half the difference of diameter of the hole produced to the tool diameter, that is

$$\mathrm{ROC}=\frac{(d_{\mathrm{jt}}-d_{\mathrm{t}})}{2}, \quad (3)$$

where d_{t} is the diameter of the tool and d_{jt} is the diameter of the hole drilled.

2.3. Design of experiments

The experimental program was planned using a complete 3^3 factorial design [4]. For a three factor, three level full factorial design set up the total number of experiments to be conducted is 27. The range of values was set at the three levels shown earlier: low (−1), medium (0) and high (1).

2.4. Conduct of experiments

Al alloy with 10 wt.% silicon carbide particulates was drilled using brass electrode of diameter 30 mm on a PS leader ZNC EDM machine. Positive polarity was maintained for the work piece and negative polarity for the tool. Commercial grade kerosene was used as the dielectric fluid and impulse jet flushing was used to flush away the eroded materials from the sparking zone. Table 2 shows the experimental layout and the machine setting. Tables 3 and 4 shows the composition of the matrix and tool materials respectively. Tables 5–7 show the experimental readings of the material removal rate (MRR), tool wear rate (TWR) and radial over cut (ROC) respectively at different levels of input parameters.

Table 2
Factorial design matrix (3^3 level) for experimentation

Experiment no.	Machine stetting		
	Gap voltage ($X1$)	Pulse current ($X2$)	Pulse duration ($X3$)
1	−1	−1	−1
2	0	−1	−1
3	−1	0	−1
4	0	0	−1
5	−1	−1	0
6	0	−1	0
7	−1	0	0
8	0	0	0
9	1	0	0
10	0	1	0
11	1	1	0
12	0	0	1
13	1	0	1
14	0	1	1
15	1	1	1
16	−1	1	1
17	1	−1	1
18	−1	−1	1
19	1	1	−1
20	−1	1	−1
21	1	−1	−1
22	1	−1	0
23	1	0	−1
24	0	1	−1
25	−1	0	1
26	−1	1	0
27	0	−1	1

Table 3
Composition of the matrix material

Constituents	Percentage (by weight)
Aluminum	89.7
Silicon	4
Magnesium	6
Manganese	0.3

3. Mathematical modeling

The purpose of developing the mathematical model relating the response variables and the process parameters was to facilitate the optimization of the electric discharge machining of aluminum matrix composites. The mathematical model commonly used is represented by

$$Y=\phi(V, I, T),$$

Table 4
Tool material specifications

Constituents	wt.%
Copper	62
Zinc	37
Impurities	1

Table 5
Experimental readings of material removal rate (MRR) in mm^3 per minute

Voltage gap (in V)	Pulse duration								
	−1			0			1		
	−1[a]	0[a]	1[a]	−1[a]	0[a]	1[a]	−1[a]	0[a]	1[a]
−1	347.25	829.50	1090.83	426.85	818.12	1090.83	545.42	892.50	1155.15
0	446.25	818.12	981.75	446.25	701.25	1090.83	490.87	818.12	1197.18
1	392.70	701.25	981.75	409.06	613.59	892.50	446.25	701.25	981.75

[a] Current.

Table 6
Experimental readings of tool wear rate (TWR) in mm^3 per minute

Voltage gap (in V)	Pulse duration (in μs)								
	−1			0			1		
	−1[a]	0[a]	1[a]	−1[a]	0[a]	1[a]	−1[a]	0[a]	1[a]
−1	9.73	20.89	25.13	15.53	24.80	34.21	14.55	21.65	28.40
0	12.99	20.80	22.62	14.07	23.16	30.42	13.10	22.82	32.74
1	11.43	20.41	25.00	14.38	23.60	33.55	14.61	20.01	28.57

[a] Current (in A).

Table 7
Experimental readings of the radial over cut (ROC) in millimeters

Voltage gap (in V)	Pulse duration								
	−1 (low)			0 (medium)			1 (high)		
	−1[a]	0[a]	1[a]	−1[a]	0[a]	1[a]	−1[a]	0[a]	1[a]
−1	0.20	0.30	0.40	0.40	0.52	0.54	0.50	0.60	0.74
0	0.40	0.50	0.60	0.48	0.56	0.80	0.72	0.76	0.78
1	0.34	0.40	0.60	0.64	0.64	0.74	0.76	0.78	0.74

[a] Current.

where Y is the response, ϕ the response function; V (gap voltage), I (pulse current) and T (pulse duration) are the process variables. In this study the model chosen was quadratic (second order) in nature involving linear and quadratic interactions of process variables. A program was written in MATLAB to obtain the desired model as reported in literature [4]. The second order model equations obtained are as follows:

$$\begin{aligned}\mathrm{MRR} = {} & 759.4985 - 59.7972 \times x_1 + 306.2039 \times x_2 \\ & + 35.5050 \times x_3 - 36.9272 \times x_1^2 - 20.7739 \times x_2^2 \\ & + 46.6294 \times x_3^2 - 34.1083 \times x_1 \times x_2 - 1.4 \times x_2 \times x_3 \\ & - 22.7 \times x_1 \times x_3.\end{aligned}$$

Table 8
Analysis of variance (ANOVA) for material removal rate (MRR in mm^3 per minute)

Source of variation	Sum of squares	Degrees of freedom	Mean square	T	P-value
$X1$ (V)	64,363	1	64,363	−5.38	0.000
$X2$ (A)	1,687,695	1	1,687,695	27.54	0.000
$X3$ (μs)	22,691	1	22,691	3.19	0.005
$X1 \times X1$	8,182	1	8,182	−1.92	0.072
$X2 \times X2$	2,589	1	2,589	−1.08	0.296
$X3 \times X3$	13,046	1	13,046	2.42	0.027
$X1 \times X2$	13,961	1	13,961	−2.50	0.023
$X2 \times X3$	23	1	23	−0.10	0.920
$X1 \times X3$	6,163	1	6,163	−1.66	0.114
Error	37,825	17	2,225		
Total	1,856,538	26			

$S = 47.17$; R-Sq = 98.0%. The multiple regression coefficient of the model R^2 indicates that the model can explain variation in MRR to the extent of 98% thus the model is adequate to represent the process.

Table 9
Analysis of variance (ANOVA) for tool wear rate (TWR in mm^3 per minute)

Source of variation	Sum of squares	Degrees of freedom	Mean square	T	P-value
$X1$ (V)	0.62	1	0.62	−0.41	0.689
$X2$ (A)	1092.78	1	1092.78	17.14	0.000
$X3$ (μs)	41.86	1	41.86	3.35	0.004
$X1 \times X1$	0.02	1	0.02	0.07	0.944
$X2 \times X2$	4.31	1	4.31	−1.08	0.297
$X3 \times X3$	71.16	1	71.16	−4.37	0.000
$X1 \times X2$	0.13	1	0.13	−0.18	0.856
$X2 \times X3$	6.53	1	6.53	1.32	0.203
$X1 \times X3$	0.52	1	0.52	−0.37	0.713
Error	63.26	17	3.72		
Total	1281.26	26			

$S = 1.929$; R-Sq = 95.1%. The multiple regression coefficient of the model R^2 indicates that the model can explain variation in TWR to the extent of 95.1%. Thus the model is adequate to represent the process.

$$\begin{aligned}\text{TWR} = {} & 24.2741 - 0.1850 \times x_1 + 7.7917 \times x_2 + 1.5250 \times x_3 \\ & + 0.0561 \times x_1^2 - 0.8472 \times x_2^2 - 3.4439 \times x_3^2 \\ & - 0.1025 \times x_1 \times x_2 + 0.7375 \times x_2 \times x_3 \\ & - 0.2083 \times x_1 \times x_3.\end{aligned}$$

$$\begin{aligned}\text{ROC} = {} & 0.6326 + 0.0800 \times x_1 + 0.0844 \times x_2 + 0.1478 \times x_3 \\ & - 0.0778 \times x_1^2 + 0.0156 \times x_2^2 - 0.0278 \times x_3^2 \\ & - 0.020 \times x_1 \times x_2 - 0.03 \times x_2 \times x_3.\end{aligned}$$

4. Results and discussion

From the data obtained by experiments, the parameters for mathematical model were determined as shown earlier. The significance of the models and parameters was analyzed using analysis of variance (ANOVA) method [4]. The results of the analysis of variance (ANOVA) for MRR, TWR and ROC are shown in Tables 8–10, respectively.

4.1. Material removal rate (MRR)

As observed from the main effects plot of MRR (Fig. 1) and ANOVA table, current has major effect on MRR followed

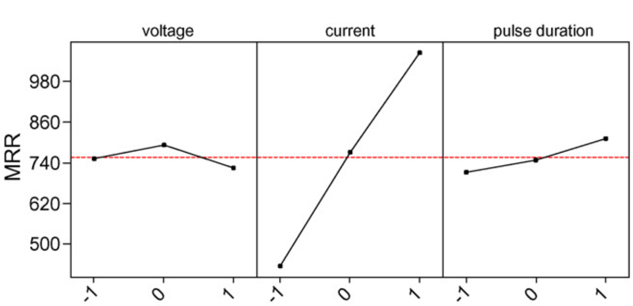

Fig. 1. Main effect plots for material removal rate (MRR in mm^3 per minute) with voltage, current and pulse duration.

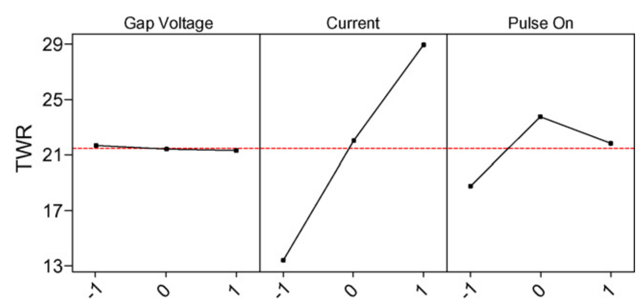

Fig. 2. Main effect plots for tool wear rate (TWR in mm^3 per minute) with voltage, current and pulse duration.

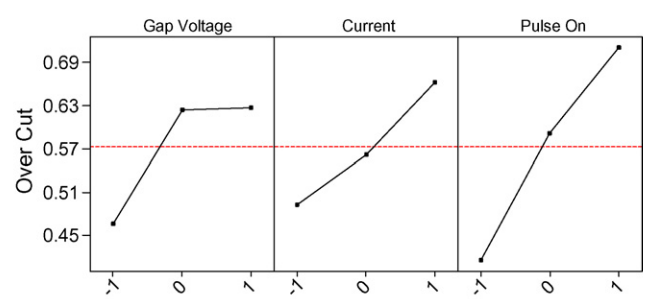

Fig. 3. Main effect plots for radial over cut (ROC in mm) with voltage, current and pulse duration.

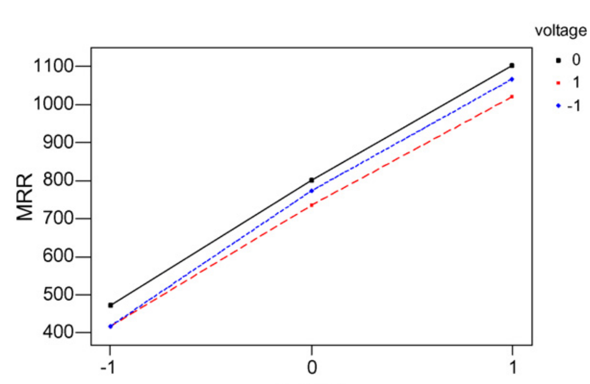

Fig. 4. Interactive effect of current and gap voltage on material removal rate (MRR in mm^3 per minute).

Table 10
Analysis of variance (ANOVA) for radial over cut (ROC in mm)

Source of variation	Sum of squares	Degrees of freedom	Mean square	*T*	*P*-value
*X*1 (V)	0.1152	1	0.1152	6.34	0.000
*X*2 (A)	0.128356	1	0.128356	6.69	0.000
*X*3 (μs)	0.393089	1	0.393089	11.71	0.000
*X*1 × *X*1	0.036296	1	0.036296	−3.56	0.002
*X*2 × *X*2	0.001452	1	0.001452	0.71	0.486
*X*3 × *X*3	0.004630	1	0.004630	−1.27	0.221
*X*1 × *X*2	0.004800	1	0.004800	−1.29	0.213
*X*2 × *X*3	0.010800	1	0.010800	−1.94	0.069
*X*1 × *X*3	0.000000	1	0.000000	0.00	1.000
Error	0.048696	17	0.002864		
Total	0.743319	26			

$S = 0.05352$; R-Sq = 93.4%. The multiple regression coefficient of the model R^2 indicates that the model can explain variation in ROC to the extent of 93.4%. Thus the model is adequate to represent the process.

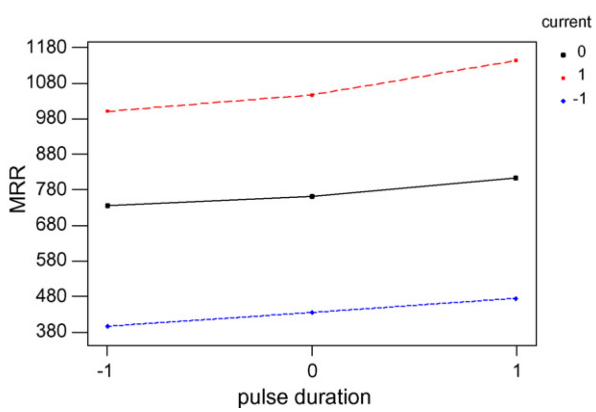

Fig. 5. Interactive effect of pulse duration and current on material removal rate (MRR in mm^3 per minute).

by pulse duration and voltage. The MRR is found to increase non-linearly with increase in current for constant gap voltage and pulse-on time. MRR is also found to increase slightly with increase in pulse duration as clearly shown in Fig. 1 and this in agreement with the results reported by Singh et al. [3].

4.2. Tool wear rate (TWR)

As observed from the main effects plot of TWR (Fig. 2) and also from ANOVA table it is found that TWR also increases with

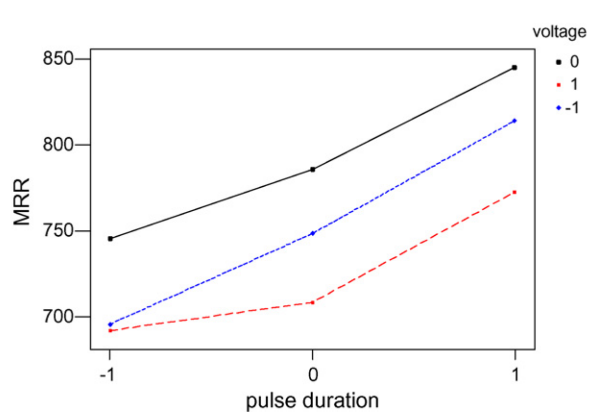

Fig. 6. Interactive effect of pulse duration and voltage on material removal rate (MRR in mm^3 per minute).

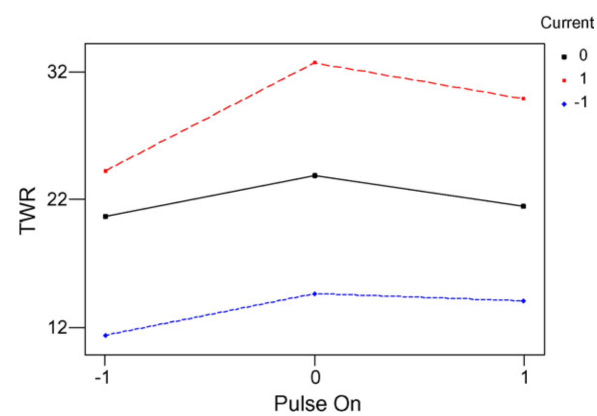

Fig. 7. Interactive effect of pulse duration and current on tool wear rate (TWR in mm^3 per minute).

increase in current as high current results in higher thermal loading on both electrodes (tool and work piece) leading to higher amount of material being removed from either electrodes. It is generally found to first increase and then decrease for increasing amounts of pulse duration within the scope of this experiment. The effect of gap voltage on TWR is negligible as compared to current.

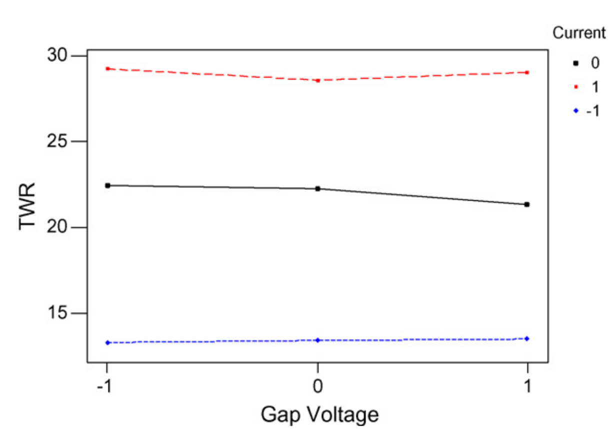

Fig. 8. Interactive effect of gap voltage and current on tool wear rate (TWR in mm^3 per minute).

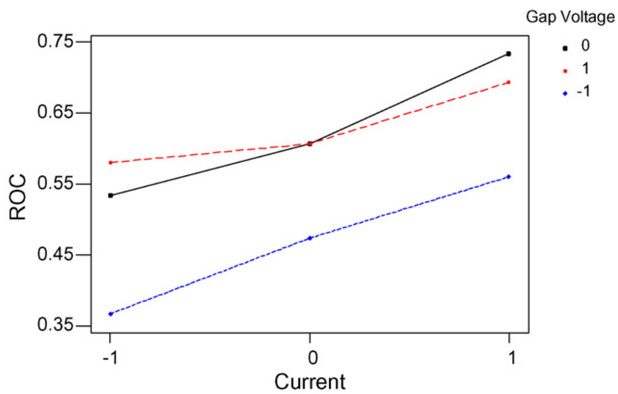

Fig. 9. Interactive effect of current and gap voltage on radial over cut (ROC in mm).

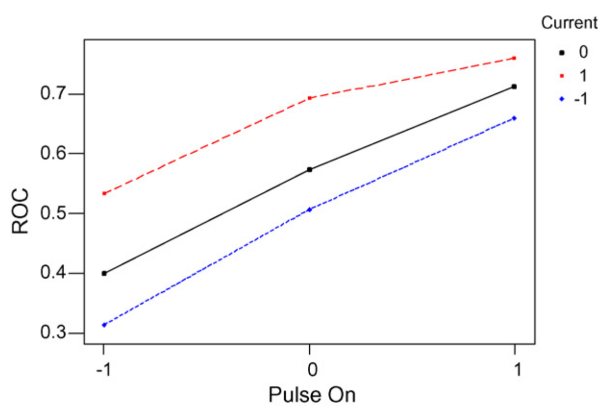

Fig. 10. Interactive effect of pulse duration and current on radial over cut (ROC in mm).

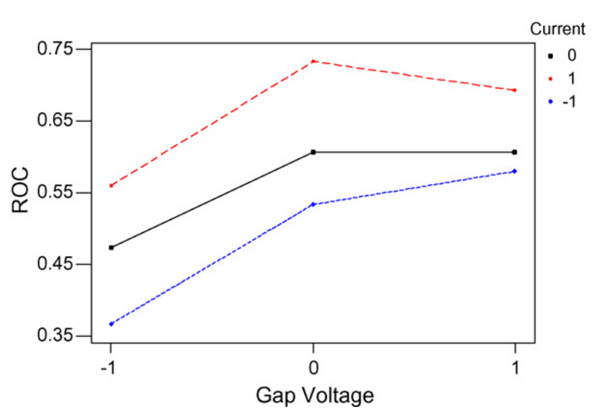

Fig. 11. Interactive effect of gap voltage and current on radial over cut (ROC in mm).

4.3. *Radial over cut (ROC)*

From Fig. 3, it is evident that an increase in current increases the radial over cut due to increase in MRR. An increase in pulse duration (keeping all other factors constant as in earlier cases) also increases the radial over cut due to the prolonged presence of sparks thus producing an increase in energy per spark. Figs. 4–11 show the interactive effects of different input parameters on the material removal rate (MRR), tool wear rate (TWR) and the radial over cut (ROC).

5. Conclusions

1. The present work evaluates the feasibility of electric discharge machining of Al alloy–10 wt.% SiC_P composite.
2. The mathematical model developed here can be used to predict the optimal conditions suitable for ED Machining of the given work material.
3. The optimum conditions for maximum MRR with reduced TWR and ROC can also be obtained using linear programming.
4. The MRR, TWR and ROC increase significantly in a non-linear fashion with increase in current.
5. The material removal rate and radial over cut increases with increase in pulse duration.
6. Gap voltage was found to have little, but some effect on the three responses. This was interpreted directly as a result of the formulation of mathematical models.

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