Optimization of Process Parameters during EDM of Stainless Steel 304 using Taguchi Method

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Abstract

The present work aims to investigate the influence of process parameters such as peak current (I), pulse on time (T_{on}) and pulse off time (T_{off}) on performance measures namely, material removal rate (MRR), tool wear rate (TWR) and surface roughness (SR) during electrical discharge machining (EDM) of stainless steel 304 .Taguchi methodology has been employed for planning experiments and to obtain optimal combination of parameters using signal to noise ratios (S/N ratio). The level of influence of process parameters on performance measures has been identified with the help of analysis of variance (ANOVA). Further empirical equations were developed using non-linear regression analysis to denote functional relationship between dependent performance measures with the process parameters. Experimental results reveal that peak current pulse on time and pulse off time are significant parameters affecting MRR, TWR and SR. While pulse off time has no significant affect on TWR.

Keywords: *Taguchi Method, Metal Removal Rate, Tool Wear Rate, Surface Roughness, ANOVA, Regression Analysis.*

1. INTRODUCTION

Electrical discharge machine (EDM) is an vital un conventional machining process, developed in the late 1940s and has recognized worldwide as a normal machining process for manufacture of forming tools to produce plastics moldings, die castings, forging dies and etc. Electrical discharge machine (EDM) technology is widely used in tool, die and mould making industries, for machining of heat treated tool steels, super alloys, ceramics, and metal matrix composites requiring high precision, complex shapes and high surface finish. In EDM material removal takes place due to the occurrence of series of discrete electrical discharges between two electrodes that are immersed in dielectric medium. The rotary motion of work piece improves the dielectric circulation through the discharge gap resulting in increase in material removal rate (MRR) [5]. Machining characteristics of EN8 steel with disc type rotating copper electrode during rotary EDM have been studied [3]. The effect of axial vibration of tool along with rotation on MRR and tool wear rate (TWR) during EDM was studied [4].The significant increase in the performance of PMEDM over conventional EDM was noticed with the addition of silicon powder into dielectric fluid [7]. The effects of Current intensity, pulse time and servo voltage on Electrode Wear and machining time have been investigated. It was observed that the best parameters for low electrode wear and low machining time are those that combine low intensity, high pulse time and low servo voltage [2]. Influence of Pulse on time, pulse off time and current on Electrode Wear and recast layer thickness have studied and noticed that pulse current is directly proportional with resolidified layer thickness and crack density [9]. The effects of parameters such as discharge current, pulse-on time, duty cycle and gap voltage on responses namely MRR, TWR and surface roughness. RSM (CCD) has been used to plan and analyze the experiments for optimization of MRR, TWR and SR has been studied [1]. Reference [12] have been used face centered central composite design matrix is to conduct the experiments on AISI D2 to explore the effect of discharge current, pulse duration, pulse off time and gap voltage on MRR. It was found that discharge current and pulse duration are significant factors for MRR. The effects of Pulse current, pulse on time and open circuit voltage on MRR and TWR have studied. It was observed that Increase of pulse energy by increasing pulse current or pulse on time leads to increase of average thickness and micro hardness of recast layer [6]. Reference [10] have studied the effect of Peak current, pulse-on time, and pulse-off time on MRR, EWR and surface roughness. Influence of discharge current, pulse on time, duty cycle, and gap voltage on MRR, EWR and surface roughness explored. It was noticed that EDMed material unevenness increases with discharge current and pulse-on time and the recast layer thickness increases with the pulse-on time [8]. From the literature, it has been observed that little work has been carried out so far EDM of stainless steel 304 using electrolyte copper as electrode. The present work aims to evaluate the effect of process parameters such as peak current, pulse on tome and pulse off time and their significance on machining characteristics namely material removal rate (MRR), tool wear rate (TWR), and surface roughness (SR). Then the machining conditions have been optimized for maximum MRR and minimum SR and TWR using Taguchi method.

2. DESIGN OF EXPERIMENTS, EXPERIMENTAL SETUP AND PROCEDURE

For conducting experiments, the work material stainless steel 304 with the dimensions of 100 × 20 × 8 mm^3 by means of wire-cut EDM has been used as work material for experimentation. The chemical composition and mechanical properties of stainless steel 304 are shown in Table 1 and Table 2 respectively. The electrolyte copper of diameter 14mm and length 70mm is selected as tool material to machine the stainless steel 304 and the physical properties of electrolyte copper are presented in the Table3.

TABLE1: CHEMICAL COMPOSITION OF STAINLESS STEEL 304

Element	Percentage (%)	Specifications(AISI304)
C	0.078	0.08Max
Mn	1.389	2.00Max
Si	0.328	1.00Max
P	0.033	0.045Max
S	0.008	0.030Max
Cr	18.072	18.00-20.00
Ni	8.163	8.00-10.50

TABLE2: MECHANICAL PROPERTIES OF STAINLESS STEEL 304

Density	7.8 (g/cm^3)
Specific capacity	400 (J/kg °k)
Thermal conductivity	18.4 (W/m °k)
Electrical resistivity	0.08×10^{-6} Ω m
Modulus of elasticity	196 G Pa

TABLE3: PHYSICAL PROPERTIES OF ELECTROLYTE COPPER

Density	8.95 (g/cm^3)
Specific capacity	383 (J/kg °C)
Thermal conductivity	394 (W/m °C)
Electrical resistivity	1.673×10^{-8} Ω m
Melting point	1083°C

All the experiments were conducted on EDM machine model MOLD MASTERS605. The dielectric fluid used to conduct all the experiments is commercial EDM oil grade SAE240, and for flushing purpose, side flushing has been used during all experimental runs. The experimental set up is shown in Figure1.

Figure 1: Experimental set up

Trial experiments were conducted to select the range of input factors. The working range of the selected process parameters and their levels are shown in Table 4. The design of experiment (DOE) chosen for this study was a Taguchi L9 Orthogonal array presented in Table 5, by conducting a total number of 9 experimental runs and each experimental run were repeated three times.

TABLE4: WORKING RANGE OF THE PROCESS PARAMETERS AND THEIR LEVELS

Parameter	Unit	Level1	Level2	Level3
Peak current, I	Amps	8	16	24
Pulse on time, T_{on}	µs	50	100	150
Pulse off time, T_{off}	µs	35	65	95

TABLE5: EXPERIMENTAL LAYOUT USING AN $L_9(3^4)$ OA

S.No	A	B	C
	Peak current	Pulse on time	Pulse off time
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

Machining time considered for conducting each experiment is 5 min. The work pieces and electrodes were cleaned and polished before machining. The work piece was firmly clamped in the vice and immersed in the dielectric. Apart from the parameters considered, there are other parameters that can have an effect on the performance measures. In order to minimize their effects, these parameters are held constant. These are given in Table6.

The Taguchi method uses signal to noise (S/N) ratio to measure the deviation of performance characteristics from the desired values. These are three categories of S/N ratios depending on the types of characteristics like higher-is-the-best (HB), lower-is-the-best (LB) and nominal is the best (NB).The characteristic that has higher value represents better machining performance as such for MRR "higher-the-better" is appropriate. The characteristic that should has lower values for better machining performance, such as TWR and SR, is called "lower-the-better". Therefore, "higher-the-better" for the MRR "lower-the-better" for TWR, and SR are selected for obtaining machining performance. MINITAB16 software was used to analyze the experimental data.

Material removal rate (MRR), tool wear rate (TWR), and surface roughness (SR) were chosen to evaluate machining performance. A digital weighing balance (citizen) having capacity up to 300 grams with a resolution of 0.1gms was used for weighing the work pieces and electrodes before machining and after machining. Then the material removal rate (MRR) and tool wear rate are calculated as follows.

$$MRR\left({mm^3}/_{min}\right) = \frac{\Delta W}{\rho_w \times t} \dots\dots (1)$$

$$TWR\left({mm^3}/_{min}\right) = \frac{\Delta T}{\rho_t \times t} \dots\dots\dots (2)$$

Where ΔW is the weight difference of work piece before and after machining (g), ρ_w is density of work material (g/mm³), ΔT is the weight difference of electrode before and after machining (g), ρ_t is density of electrode material (g/mm³) and t is machining time in minutes. The weight loss can be measured by using electronic balance. Surface roughness of the machined work pieces were measured using Talysurf surface roughness tester. Roughness measurements were carried out in the transverse direction on machined surface with sampling length of 0.8 mm and were repeated three times and average values are calculated.

3. RESULTS AND DISCUSSIONS

Statistical analysis of various parameters has been carried out using Minitab software. It can be used for Taguchi design as per the required levels and factor selections. Once results are stored in the worksheet then the analysis of Taguchi design can be performed. In this analysis means and signal to noise ratios are tabulated, factors are given rank based on delta values and main effects plots are extracted. The main effects plots for signal to noise ratios would be utilized for optimization purpose.

TABLE6: AVERAGE EXPERIMENTAL RESULTS AND S/N RATIOS OF MRR, TWR, AND SR

Ex. No.	Process parameters			MRR		TWR		SR	
	I (A)	T_{on} (μs)	T_{off} (μs)	Mean (mm³/min)	S/N Ratio	Mean (mm³/min)	S/N Ratio	Mean (μm)	S/N Ratio
1	8	50	35	1.26	2.007411	0.11	19.17215	4.653	-13.354
2	8	100	65	1.98	5.933304	0.22	13.15155	5.059	-14.081
3	8	150	95	2.13	6.567592	0.32	9.897	5.3025	-14.490
4	16	50	65	3.98	11.99766	0.44	7.130946	6.0595	-15.648
5	16	100	95	5.21	14.33675	0.52	5.679933	7.67725	-17.704
6	16	150	35	8.79	18.87978	0.59	4.58296	8.7555	-18.845
7	24	50	95	9.82	19.84223	0.67	3.478504	6.6195	-16.416
8	24	100	35	14.50	23.22736	0.78	2.158108	9.39075	-19.454
9	24	150	65	12.48	21.92429	0.76	2.383728	9.13275	-19.212

3.1. Effect of Process Parameters on MRR

The average values of MRR, TWR, and SR for each trial (run) and their respective S/N ratio values are presented in Table6. Figure 2 presents main effects plot for means of MRR. Figure 3 shows main effects plot for S/N ratios of MRR. A main effects plot is a plot of the means at each level of a factor. One can use these plots to compare the magnitudes of the various main effects and compare the relative strengths of the effects across factors. However it is important to proceed to evaluate significance by looking at the effects in the analysis of variance Table. From Figures2 and 3 it has been observed that MRR increases with increasing in peak current.

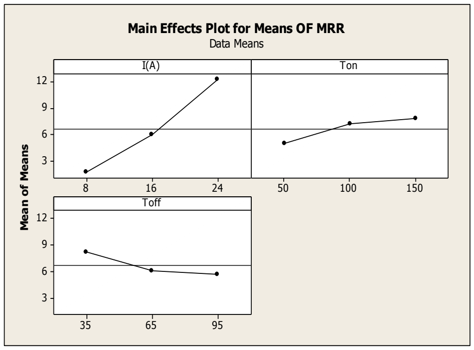

Figure 2: Effect of process parameters on mean data of MRR

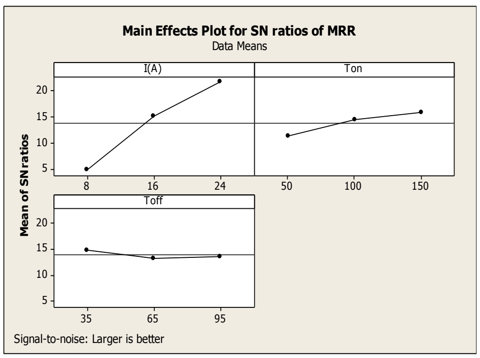

Figure 3: Effect of process parameters on S/N Ratios of MRR

The increase in peak current causes increase in spark energy resulting in higher current density. This rapidly over heats the work piece and increases MRR with peak current. Further as current increases, discharge strikes the surface of work piece intensively which creates an impact force on the molten material in the molten puddle and this results into ejection of more material out of the crater. Another observation from the present experiment is that the MRR increases with increase in pulse on time. The discharge energy in the plasma channel and the period of transferring this energy in to the electrodes increases with increase in pulse on time. This phenomenon leads to formation of bigger molten material crater on the work which results in increase in MRR [11]. However MRR decreases with increase in pulse off time. Since it is always desirable to maximize the MRR larger the better option is selected. Figure 3 suggested that when peak current is at 24A (level 3), pulse on time is at 150µs (level 3) and pulse off time is at 35µs (level 1), provide maximum MRR. Optimum value of MRR is calculated as 14.88(mm³/min) and corresponding S/N ratio is 24.4453 at the optimal parameter settings. Table7 shows response Table for means of MRR. Table8 presents response Table for S/N ratios for MRR.

TABLE 7: RESPONSE TABLE FOR MEANS OF MRR

Level	I(A)	T_{on}(µs)	T_{off}(µs)
1	1.790	5.020	8.183
2	5.993	7.230	6.147
3	12.267	7.800	5.720
Delta	10.477	2.780	2.463
Rank	1	2	3

TABLE8: RESPONSE TABLE FOR S/N RATIOS OF MRR

Level	I(A)	T_{on}(µs)	T_{off}(µs)
1	4.836	11.282	14.705
2	15.071	14.499	13.285
3	21.665	15.791	13.582
Delta	16.829	4.508	1.420
Rank	1	2	3

Larger the better

TABLE9: ANOVA FOR MRR (MM³/MIN), USING ADJUSTED SS FOR TESTS

Source	DF	Seq SS	Adj SS	Adj MS	F	P
I(A)	2	166.783	166.783	83.392	275.64	0.004
T_{on}(µs)	2	12.937	12.937	6.469	21.38	0.045
T_{off}(µs)	2	10.398	10.398	5.199	17.18	0.055
Error	2	0.605	0.605	0.303		
Total	8	190.724				

S = 0.550030 R-Sq = 99.68% R-Sq (adj) = 98.73%

The rank represents directly the level of effect of input based on the values of delta. Here according to ranks, the effects of various machining parameters on MRR in sequence are peak current, pulse on time and pulse off time. Table9 presents the ANOVA for MRR at 95% confidence level. The data presented in the ANOVA reveals the significance of input parameters on MRR which is as follows. The peak current, pulse on time and pulse off time are significant factors affecting the MRR since respective F values are higher than the F_{cr} .

Empirical expressions have been developed to evaluate the relationship between input and output parameters. The experimental values of MRR have been used to construct the empirical expressions. Hence regression analysis was done to find out the empirical model to represent functional relationship between dependent output parameter with the input parameters. Further mathematical model has been developed using non-linear regression analysis to predict the MRR values. Table 10 shows the regression coefficients of the model. The regression equation is

$$\begin{aligned} \mathrm{MRR} = 0.054306 + 0.137292\mathrm{I} + 0.093400\mathrm{T_{on}} \\ - 0.157333\mathrm{T_{off}} + 0.016172\mathrm{I}^2 \\ - 0.000328\mathrm{T_{on}^2} \\ + 0.000894\mathrm{T_{off}^2} \dots\dots\dots\dots\dots\dots (3) \end{aligned}$$

The predicted values of MRR using regression Equation (3), and corresponding residuals and % error are presented in the Table 11.

TABLE 10: ESTIMATED REGRESSION COEFFICIENTS FOR MRR

Term	Coef	SE Coef	T	P
Constant	0.054306	2.54739	0.021	0.985
I(A)	0.137292	0.19648	0.699	0.557
Ton(μs)	0.093400	0.03144	2.971	0.097
Toff(μs)	-0.157333	0.05668	-2.776	0.109
I(A)*I(A)	0.016172	0.00608	2.661	0.117
Ton(μs)*Ton(μs)	-0.000328	0.00016	-2.108	0.170
Toff(μs)*Toff(μs)	0.000894	0.00043	2.070	0.174

S = 0.550030 PRESS = 12.2526 R-Sq = 99.68% R-Sq(pred) = 93.58% R-Sq(adj) = 98.73%

TABLE 11: EXPERIMENTAL RESULTS AND PREDICTED VALUES USING REGRESSION MODEL OF MRR

Exp.No	I (A)	T_{on} (μs)	T_{off} (μs)	Experimental MRR (mm³/min)	Predicted MRR (mm³/min)	residual
1	8	50	35	1.26	1.6267	-0.366667
2	8	100	65	1.98	1.8000	0.180000
3	8	150	95	2.13	1.9433	0.186667
4	16	50	65	3.98	3.7933	0.186667
5	16	100	95	5.21	5.5767	-0.366667
6	16	150	35	8.79	8.6100	0.180000
7	24	50	95	9.82	9.6400	0.180000
8	24	100	35	14.50	14.3133	0.186667
9	24	150	65	12.48	12.8467	-0.366667

The values of R^2(99.68%) and R_{adj}^2(98.73%) of the model are in the acceptable range of variability in predicting MRR values. Further, percentage errors in predicting MRR values were calculated and are in acceptable range. Hence the model is adequate in predicting the MRR values.

3.2. Effect of Process Parameters on TWR

The average values of TWR for each trial and their respective S/N ratio values are presented in Table 6. Figure 4 presents main effects plot for means of TWR. Figure 5 shows main effects plot for S/N ratios of TWR. It is observed from Figure4 and 5 that the increase in tool wear rate with increase in peak current as well as pulse on time. This can be explained as increase in peak current causes increase in spark energy resulting in increase in TWR. Further spark energy and the period to transfer this energy in to the electrodes increases with increase in pulse on time which results in increase in TWR. However slight increase in TWR is noticed with increase in pulse off time due to overshoot effect for some time.

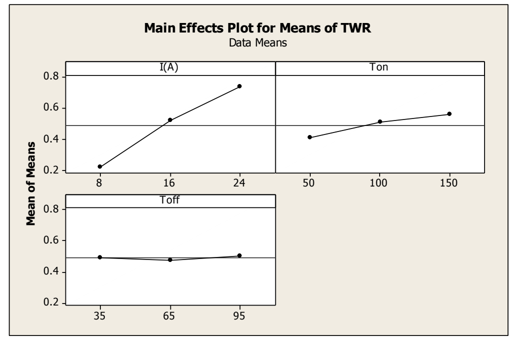

Figure 4: Effect of process parameters on mean data of TWR

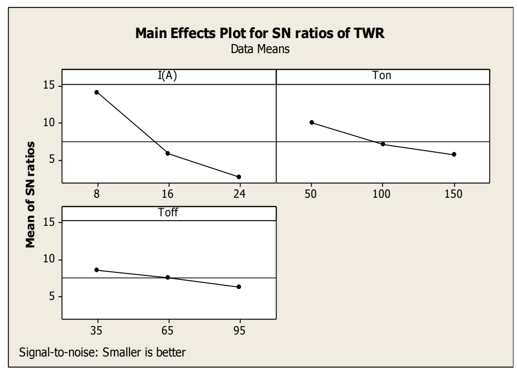

Figure 5: Effect of process parameters on S/N ratio data of TWR

Since it is always desirable to minimize the TWR smaller the better option is selected. From the Figure5 it is observed that minimum TWR value was achieved when peak current was at 8A (level 1), pulse on time at 50μs (level 1) and pulse of time at 35μs (Level1). Further optimum TWR value was calculated as 0..136mm³/min and corresponding S/N ratio is 17.608. Table 12 shows response Table for means of TWR. Table 13 presents response Table for S/N ratios for TWR.

TABLE 12: RESPONSE TABLE FOR MEANS OF TWR

Level	I(A)	T_{on}(μs)	T_{off}(μs)
1	0.2167	0.4067	0.4933
2	0.5167	0.5067	0.4733
3	0.7367	0.5567	0.5033
Delta	0.5200	0.1500	0.0300
Rank	1	2	3

TABLE 13: RESPONSE TABLE FOR S/N RATIOS OF TWR

Level	I(A)	T_{on}(µs)	T_{off}(µs)
1	14.074	9.927	8.638
2	5.798	6.997	7.555
3	2.673	5.621	6.352
Delta	11.400	4.306	2.286
Rank	1	2	3

Smaller the better Here according to the ranks, the effects of various input factors on TWR in sequence are peak current, pulse on time and pulse of time. Table 14 presents the ANOVA for TWR at 95% confidence level. The data presented in the ANOVA reveals the significance of input parameters on TWR which is as follows. The peak current, and pulse on time are significant factors affecting the TWR since respective F values are higher than theF_{cr} .Where as pulse off time has not significant effect on TWR.

TABLE 14: ANOVA FOR TWR USING ADJUSTED SS FOR TESTS

Source	DF	Seq SS	Adj SS	Adj MS	F	P
I(A)	2	0.408800	0.408800	0.204400	107.58	0.009
T_{on}(µs)	2	0.035000	0.035000	0.017500	9.21	0.098
T_{off}(µs)	2	0.001400	0.001400	0.000700	0.37	0.731
Error	2	0.003800	0.003800	0.001900		
Total	8	0.449000				

S = 0.0435890   R-Sq = 99.15%   R-Sq (adj) = 96.61%

Empirical expressions have been developed to evaluate the relationship between input and output parameters. The experimental values of TWR have been used to construct the empirical expressions. Hence regression analysis was done to find out the empirical model to represent functional relationship between dependent output parameter with the input parameters. Further mathematical model has been developed using non-linear regression analysis to predict the TWR values. Table 15 shows the regression coefficients of the model. The regression equation is

$$\begin{aligned}\mathrm{TWR} = -0.306806\ &+ 0.052500\,\mathrm{I} + 0.003500\mathrm{T_{on}} \\ &- 0.003444\ \mathrm{T_{off}} - 0.000625\ \mathrm{I}^2 \\ &- 0.000010\mathrm{T_{on}^2} \\ &+ 0.000028\mathrm{T_{off}^2} \ldots\ldots\ldots\ldots\ldots\ldots (4)\end{aligned}$$

The predicted values of TWR using regression Equation (4), and corresponding residuals and percentage of error are presented in the Table 16

TABLE 15: ESTIMATED REGRESSION COEFFICIENTS FOR TWR

Term	Coef	SE Coef	T	P
Constant	-0.306806	0.201876	-1.520	0.268
I(A)	0.052500	0.015571	3.372	0.078
Ton(µs)	0.003500	0.002491	1.405	0.295
Toff(µs)	-0.003444	0.004491	-0.767	0.523
I(A)*I(A)	-0.000625	0.000482	-1.298	0.324
Ton(µs)*Ton(µs)	-0.000010	0.000012	-0.811	0.502
Toff(µs)*Toff(µs)	0.000028	0.000034	0.811	0.502

S = 0.0435890 PRESS = 0.07695
R-Sq = 99.15% R-Sq (pred) = 82.86% R-Sq (adj) = 96.61%

TABLE 16: EXPERIMENTAL RESULTS AND PREDICTED VALUES USING REGRESSION MODEL OF TWR

Ex.no.	I (A)	T_{on} (µs)	T_{off} (µs)	Experimental TWR (mm³/min)	Predicted TWR (mm³/min)	residual
1	8	50	35	0.11	0.136667	-0.0266667
2	8	100	65	0.22	0.216667	0.0033333
3	8	150	95	0.32	0.296667	0.0233333
4	16	50	65	0.44	0.416667	0.0233333
5	16	100	95	0.52	0.546667	-0.0266667
6	16	150	35	0.59	0.586667	0.0033333
7	24	50	95	0.67	0.666667	0.0033333
8	24	100	35	0.78	0.756667	0.0233333
9	24	150	65	0.76	0.786667	-0.0266667

The values of R^2(99.15%) and R^2_{adj}(96.61%) of the model are in the acceptable range of variability in predicting TWR values. Further, percentage errors in predicting TWR values were calculated and are in acceptable range. Hence the model is adequate in predicting the TWR values.

3.3 Effect of Process Parameters on SR

The average values of SR for each trial and their respective S/N ratio values are presented in Table 6. Figure 6 presents main effects plot for means of SR. Figure 7 shows main effects plot for S/N ratios of SR.

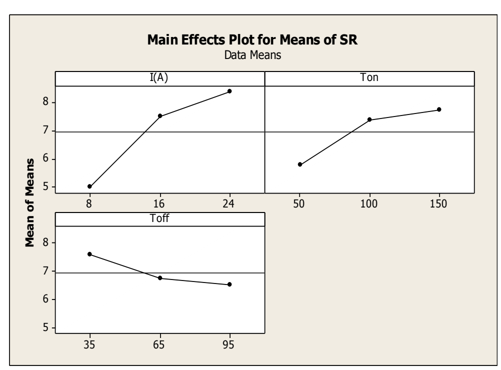

Figure 6: Effect of process parameters on mean data of SR

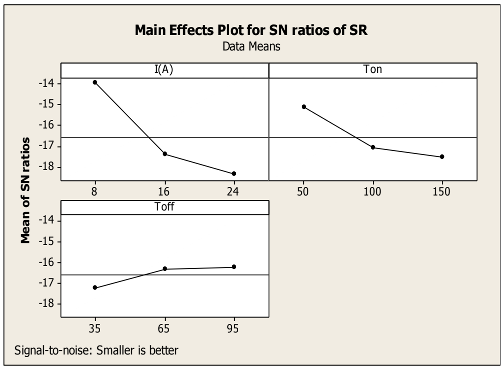

Figure 7: Effect of process parameters on S/N ratio data of SR

Further it is observed from the Figures 6 and 7 that there is increase in surface roughness with increase in peak current. This can be attributed to the fact that increase in peak current causes increase in spark energy resulting in the formation of deeper and larger craters result in increase in surface roughness. It is also noticed that surface roughness increases with the increase in pulse on time. The spark energy and time of transferring energy in to the work piece increases with increase in pulse on time. This phenomenon leads to increase in formation of molten pool resulting in deeper and larger craters which again results in increase in SR [11]. However decrease in surface roughness value is observed with increasing in pulse off time. This may be due to proper removal of debris from the discharge channel.

Since it is always desirable to minimize the SR smaller the better option is selected. From Figure 7 noticed that minimum SR value is attained when peak current at 8 A (level 1), pulse on time at 50μs (level 1) and pulse off time at 95μs (Level 3). Further optimum surface roughness value is calculated as 3.393μm and corresponding S/N ratio is-12.161. Table 17 shows response Table for means of SR. Table 18 presents response Table for S/N ratios for SR.

TABLE 17: RESPONSE TABLE FOR MEANS OF SR

Level	I(A)	T_{on}(μs)	T_{off}(μs)
1	5.005	5.777	7.600
2	7.497	7.376	6.750
3	8.381	7.730	6.583
Delta	3.376	1.953	1.067
Rank	1	2	3

TABLE 18: RESPONSE TABLE FOR S/N RATIOS OF SR

Level	I(A)	T_{on}(μs)	T_{off}(μs)
1	**-13.98**	**-15.14**	-17.22
2	-17.40	-17.08	-16.22
3	-18.36	-17.52	**-16.20**
Delta	4.39	2.38	1.01
Rank	1	2	3

Smaller the better

Here according to ranks, the effects of various input factors on SR in sequence of its effect are pulse on time peak current, and pulse off time. Table 19 represents the ANOVA for SR at 95% confidence level.

TABLE 19: ANOVA FOR SR, USING ADJUSTED SS FOR TESTS

Source	DF	Seq SS	Adj SS	Adj MS	F	P
I(A)	2	18.3906	18.3906	9.1953	99.43	0.010
Ton	2	6.4949	6.4949	3.2474	35.12	0.028
Toff	2	1.9060	1.9060	0.9530	10.31	0.088
Error	2	0.1850	0.1850	0.0925		
Total	8	26.9765				

S = 0.0435890 R-Sq = 99.15% R-Sq (adj) = 96.61%

The data presented in the ANOVA reveals the significance of input parameters on SR which is as follows. The pulse on time, peak current, and pulse off time are significant factors affecting the SR since respective F values are higher than the F_{cr} .

Empirical expressions have been developed to evaluate the relationship between input and output parameters. The experimental values of SR have been used to construct the empirical expressions. Hence regression analysis was done to find out the empirical model to represent functional relationship between dependent output parameter with the input parameters. Further mathematical model has been developed using non-linear regression analysis to predict the SR values. Table 20 shows the regression coefficients of the model. The regression equation is

$$\begin{aligned} SR = -0.694250 + 0.613260I + 0.069279\ T_{on} \\ - 0.063422\ T_{off} - 0.012570I^2 \\ - 0.000249T_{on}^2 \\ + 0.000351T_{off}^2 \ \ldots\ldots\ldots\ldots\ldots\ldots (5) \end{aligned}$$

The predicted values of SR using regression Equation (5), and corresponding residuals and % error are presented in the Table 21

TABLE 20: ESTIMATED REGRESSION COEFFICIENTS FOR SR

Term	Coef	SE Coef	T	P
Constant	-0.694250	1.40853	-0.493	0.671
I(A)	0.613260	0.10864	5.645	0.030
Ton(µs)	0.069279	0.01738	3.986	0.058
Toff(µs)	-0.063422	0.03134	-2.024	0.180
I(A)*I(A)	-0.012570	0.00336	-3.741	0.065
Ton(µs)*Ton(µs)	-0.000249	0.00009	-2.892	0.102
Toff(µs)*Toff(µs)	0.000351	0.00024	1.469	0.279

S = 0.304129 PRESS = 3.74602
R-Sq = 99.31% R-Sq(pred) = 86.11% R-Sq(adj) = 97.26%

TABLE 21: EXPERIMENTAL RESULTS AND PREDICTED VALUES USING REGRESSION MODEL OF SR

Exp.No	I (A)	T_{on} (µs)	T_{off} (µs)	Experimental SR (mm³/min)	predicted SR (mm³/min)	residual
1	8	50	35	4.65300	4.45975	0.19325
2	8	100	65	5.05900	5.20875	-0.14975
3	8	150	95	5.30250	5.34600	-0.04350
4	16	50	65	6.05950	6.10300	-0.04350
5	16	100	95	7.67725	7.48400	0.19325
6	16	150	35	8.75550	8.90525	-0.14975
7	24	50	95	6.61950	6.76925	-0.14975
8	24	100	35	9.39075	9.43425	-0.04350
9	24	150	65	9.13275	8.93950	0.19325

The values of R^2(99.31%) and R^2_{adj}(97.26%) of the model are in the acceptable range of variability in predicting SR values. Further, percentage errors in predicting SR values were calculated and are in acceptable range. Hence the model is adequate in predicting the SR values.

4. CONFIRMATION EXPERIMENTS

To verify the predicted optimal values of responses such as MRR, TWR, and SR three confirmation experiments were conducted at their optimal parametric settings .The data from the confirmation experiments and their comparisons with respective predicted values and the deviation of predicted results from experimental results were calculated as percentage error and are presented in Table 22.

$$\%error = \frac{experimentalvalue - predictedvalue}{experimentalvalue} \times 100 \ldots\ldots\ldots (6)$$

TABLE 22: CONFIRMATION OF EXPERIMENTS AT OPTIMAL CONDITIONS (DIELECTRIC ONLY)

S.No.	Optimum parameters			Response	Experimental value	Predicted value	%error
	I (A)	T_{on} (µs)	T_{off} (µs)				
1	24	150	35	Max.MRR (mm³/min)	15.33	14.88	2.93
2	8	50	95	Min.SR (µm)	3.50	3.39	3.14
3	8	50	35	Min.TWR (mm³/min)	0.11	0.13	18.18

5. CONCLUSIONS

The following conclusions are derived from the work:

1. All the chosen responses namely MRR, TWR, and SR are increased with increase in peak current and pulse on time. However MRR and SR decrease with increase in pulse off time.
2. Optimal combination of process parameters when peak current is at 24A (level 3), pulse on time is at 150µs (level 3) and pulse off time is at 35µs (level 1), provide maximum MRR. Optimum value of MRR is calculated as 14.88(mm³/min) and corresponding S/N ratio is 24.4453. Whereas minimum TWR value was achieved when peak current was at 8A (level 1), pulse on time at 50µs (level 1) and pulse of time at 35µs (Level1). Further optimum TWR value was calculated as 0.136mm³/min and corresponding S/N

ratio is 17.608. However minimum SR value is attained when peak current at 8 A (level 1), pulse on time at 50µs (level 1) and pulse off time at 95µs (Level 3). Further optimum surface roughness value is calculated as 3.393µm and corresponding S/N ratio is-12.161.

3. Peak current pulse on time and pulse off time are significant parameters affecting MRR, TWR and SR. However pulse off time has no significant effect on TWR.

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