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Mathematical Modeling and Analysis of Influence of Process Parameters on MRR during EDM of Stainless Steel 304

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Abstract: *The present work aims to investigate the influence of process parameters such as peak current, pulse on time and pulse off time on material removal rate (MRR) in electrical discharge machining (EDM) of Stainless Steel 304 material. Optimal combination of process parameters to get maximum MRR was achieved using Taguchi method. Analysis of variance (ANOVA) has been performed to find the significant effect of parameters on MRR and results revealed that process parameters such as Peak current, pulse on time and pulse off time are having significant affect on MRR. Further regression analysis has been performed and developed second order full quadratic mathematical model to establish relationship between MRR and process parameters. The values of R^2 (98.44%) and R^2_{adj} (97.61%) of the model are in the acceptable range of variability in predicting response values. Also the interactional effects among the process parameters were studied and observed that peak current and pulse on time as well as peak current and pulse off time are significantly intersecting each other.*

Key Words: *Electrical Discharge Machining, Peak Current, Pulse on Time, Pulse off Time, Material Removal Rate, Taguchi Method, ANOVA, Regression Analysis*

I. Introduction

Electrical discharge machining (EDM) is widely used advanced manufacturing processes in industry for machining electrically conductive materials such as metals, metallic alloys, graphite, or even some conductive ceramic materials, irrespective of their hardness. It is extensively used in the manufacture of mould, die, automotive, aerospace and surgical components [2]. In this process removing of material from workpiece through successive electrical discharges occurring between an electrode and a workpiece. This electric sparking process is carried out in a dielectric liquid or in gas. The desirable properties of dielectric are low-viscosity, high dielectric strength, quick recovery after breakdown, effective quenching/cooling and flushing ability. Spark is initiated at the peak between the contacting surfaces of electrode and workpiece and exists only momentarily. Metal as well as dielectric will evaporate at this intense localized heat. The influence of process parameters such as discharge current, gap voltage, pulse-on time and duty cycle on performance characteristics material removal rate, electrode wear rate and surface roughness was reported during RDM of Ti–6Al–4V alloy[12]. The effect of process parameters namely peak current, pulse on time, duty factor and supply voltage on material removal rate electrical discharge machining process using response surface methodology have been investigated. Experiments were conducted on EN31 tool steel with electrolyte copper as electrode [11]. Taguchi-grey relational approach based multi response optimization techniques were applied to maximize material removal rate and to minimize surface roughness in electrical discharge machining of AISI 202 stainless steel using brass has been used as tool electrode with kerosene as the dielectric medium [7]. Electrical process parameters such as gap voltage, peak current and duty factor have been used as input parameters. The effects of each process parameter on the responses were studied individually using the signal to noise ratio graphs and it was noticed that the responses such as MRR and SR are mainly influenced by current followed by voltage, electrode rotation and spark gap. Grey relational analysis (GRA) was used for simultaneous multi-response optimization of the responses [3]. Investigated the influence of optimal set of process parameters such as current, pulse on time and pulse on time in EDM process to identify the variations in three performance characteristics such as material removal rate , tool wear rate, and surface roughness during EDM of Mild Steel IS2026 using copper electrode [5]. Optimization of performance characteristics in unidirectional glass fiber reinforced plastic composites using Taguchi method and Grey relational analysis was studied [4]. The influence of process parameters namely pulse on time, duty cycle, discharge current and gap voltage on Tool Overcut during die sinking EDM of SS304 was studied and it was found that duty cycle has most significant followed by discharge current and pulse on time on tool over cut. Whereas gap voltage has least effect on Tool overcut [8]. The individual effect of process parameters such as peak current and pulse duration on performance characteristics namely MRR, TWR and SR have been explored. Experiments were conducted with PH17-4 stainless steel as work material and electrolyte copper as electrode [10]. Conducted an experiments to examine the effect of process parameters such as peak current, pulse on time and pulse off time on performance characteristics related to surface integrity such as surface roughness, white layer thickness and surface crack density during electrical discharge machining of RENE80 nickel super alloy [9]. The use of Taguchi method was reported to optimize the machining parameters such as current, pulse-on-time and pulse-off-time for EDM of tungsten carbide considering individual responses namely MRR, EWR and SR [6]. Optimization of machining parameters (Pulse on time, Pulse off time and peak current) of the Electric Discharge Machining on EN 31 tool steel with copper as an electrode was done considering the Material Removal Rate as response using the Taguchi method [1].

From the literature survey it was noticed that less work has been reported on electrical discharge machining of SS304 material. SS304 material is commonly used in gas turbines, piping, nuclear reactors, pumps, and tooling. It is difficult to machining this material with conventional machining processes owing to its high hardness. Hence it is necessary to explore the machinability characteristics of SS304 material during EDM process. Hence the present work aims to investigate the influence of process parameters on MRR during EDM of SS304 material. Analysis of variance (ANOVA) has been performed to find the significance of machining parameters. Taguchi method (using of S/N ratios) was used to obtain optimal combination of process parameters. Further regression analysis has been performed to establish relationship between MRR and machining parameters and mathematical model was developed to predict MRR using RSM approach.

II. Design of Experiments, Experimental Set Up and Procedures

Experiments were conducted by choosing stainless steel 304 as work material and, electrolyte copper of diameter ø14mm and length 60 mm was used as tool electrode. The chosen work material bar was cut into specimens with dimensions of $100 \times 18 \times 8$ mm^3 using wire-cut EDM. The chemical composition and mechanical properties of stainless steel 304 are shown in Table 1 and Table 2 respectively. The physical properties of tool electrode are presented in Table3. In the present study, three process parameters such as peak current, pulse on time and pulse off time and each parameter at three levels were considered. The total numbers of experiments to be conducted are 3^3=27. Each experiment was repeated two times to minimize the experimental errors. Trial experiments were conducted using one factor-at-a-time approach to select range of chosen process parameters. The working range of the selected process parameters and their levels is shown in Table 4. Experiments were carried out on EDM machine model MOLD MASTERS605 using commercial EDM oil grade SAE240 as dielectric fluid with side flushing. The experimental set up is shown in Figure 1. Machining time considered for conducting each experiment is 5 min. The experimental conditions are given in Table 5. The experiments were conducted as per the Orthogonal Array shown in Table 6,

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

Table 2: Mechanical properties of stainless steel 304

Density	7.8 (g/cm³)
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

Table 3: Physical properties of electrolyte copper

Density	8.95 (g/cm³)
Specific capacity	383 (J/kg °C)
Thermal conductivity	394 (W/m °C)
Electrical resistivity	1.673×10¯8 Ω m
Melting point	1083°C

Table 4: 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

Table 5: Experimental conditions

Working conditions	Description
Work piece	Stainless Steel (304) (100mm×18mm×8mm)
Electrode	Electrolyte copper Ø 14mm and length 60 mm
Dielectric	Commercial EDM Oil grade SAE 240
Flushing	Side flushing with pressure 0.5MPa
Polarity	Normal
Supply voltage	240 V
Machining time	5 minutes

Figure1: Experimental set up

Material removal rate (MRR), was selected to estimate machining performance. For weighing the work pieces before machining and after machining digital weighing balance (citizen) (capacity up to 300 grams and resolution of 0.1gms) was used. Then the material removal rate (MRR) is calculated with equation (1).

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

Where ΔW is the weight difference of work piece before and after machining (g), ρ_w is density of work material (g/mm³), and t is machining time in minutes.

Taguchi method is used to determine suitable combination of process parameters for obtaining maximum MRR. The experimental MRR values are further transformed into a S/N ratios. The characteristic MRR is chosen as “higher-the-better” characteristic. Taguchi method uses the S/N ratio to measure the quality characteristic deviating from the desired value. The S/N ratio η is defined as

$$\eta = -10\log(MSD) \quad \dots\dots\dots (2)$$

$$MSD_{MRR} = \frac{1}{m}\sum_{i=1}^{m}\frac{1}{MRR_i^2} \quad \dots\dots\dots (3)$$

After calculation of S/N ratio, the effect of each machining parameter at different levels was separated. The mean S/N ratio for each process parameter at each level was calculated by averaging the S/N ratios for the experiments at the same level for that particular parameter. Mean of means response tables and mean of means graphs for MRR were prepared. The analysis of variance (ANOVA) has been applied to find out the significance of parameters and the p value was used to determine whether the process parameter has significant effect or not on the response MRR. The parameter has significant effect if value of p is less than 0.05 i.e. α = 0.05 (95% Confidence Level).

Table 6: Experimental layout using an L_{27} (OA)

S.No	A	B	C
	Peak current	Pulse on time	Pulse off time
1	1	1	1
2	1	1	2
3	1	1	3
4	1	2	1
5	1	2	2
6	1	2	3
7	1	3	1
8	1	3	2
9	1	3	3
10	2	1	1
11	2	1	2
12	2	1	3
13	2	2	1
14	2	2	2
15	2	2	3
16	2	3	1
17	2	3	2
18	2	3	3
19	3	1	1
20	3	1	2
21	3	1	3
22	3	2	1
23	3	2	2
24	3	2	3
25	3	3	1
26	3	3	2
27	3	3	3

Table7: Average experimental results and S/N ratios of MRR

Ex.No	Process parameters			Response (MRR)	
	I (A)	Ton (μs)	Toff (μs)	Mean (mm^3/min)	S/N ratio (dB)
1	8	50	35	2.0177	6.0969
2	8	50	65	1.3871	2.8424
3	8	50	95	0.3783	-8.443
4	8	100	35	1.5132	3.5982
5	8	100	65	1.261	2.0145
6	8	100	95	1.1349	1.0994
7	8	150	35	2.1438	6.6235
8	8	150	65	1.0088	0.0763
9	8	150	95	0.5044	-5.9443
10	16	50	35	4.2875	12.6441
11	16	50	65	1.7654	4.9371
12	16	50	95	2.5221	8.0351
13	16	100	35	7.1879	17.132
14	16	100	65	5.0441	14.0557
15	16	100	95	4.7919	13.6102
16	16	150	35	7.9445	18.0013
17	16	150	65	6.053	15.6394
18	16	150	95	5.6747	15.0788
19	24	50	35	7.8184	17.8624
20	24	50	65	6.4313	16.1659
21	24	50	95	4.7919	13.6102
22	24	100	35	14.5019	23.2285
23	24	100	65	10.3405	20.2908
24	24	100	95	8.3228	18.4054
25	24	150	35	15.3846	23.7417
26	24	150	65	12.4842	21.9272
27	24	150	95	12.3581	21.8391

III. Results and Discussions

3.1. Effect of Process Parameters on Material Removal Rate:

The average values of MRR for each trial (run) and respective S/N ratio values are presented in Table 7. 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 can be used to compare the magnitudes of the various main effects and compare the relative strengths of the effects across factors. However it is essential to proceed to estimate significance of parameters using ANOVA Table. From Figures 2 and 3 it has been observed that MRR increases with increasing in peak current.

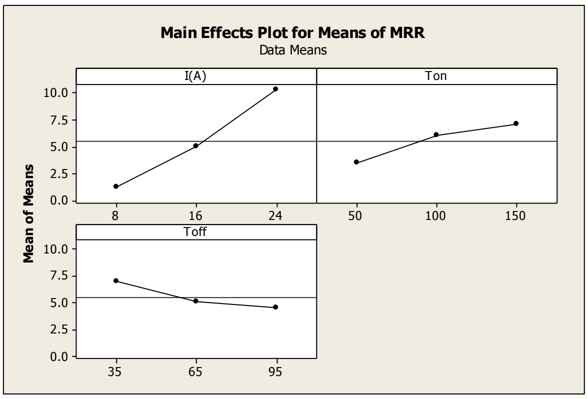

Figure 2: Effect of process parameters on mean data of MRR

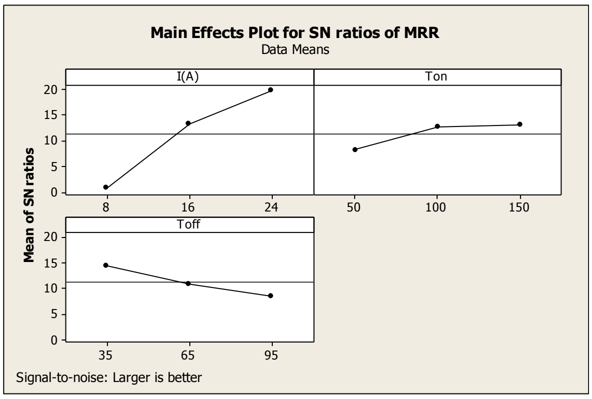

Figure 3: Effect of process parameters on S/N Ratios of MRR

The increase in peak current causes increase in discharge energy resulting increased in current density. This quickly over heats the work piece that increases MRR with peak current. Further discharge strikes intensively over work piece surface with increase in current. This creates an impact force on the molten material in the molten puddle and ejection of more material out of the crater. However MRR increases with increase in pulse on time. The spark energy in the discharge channel and the period of transferring this energy in to the electrodes increases with increase in pulse on time. This occurrence leads to formation of bigger craters resulting increase in MRR (V.V Reddy et al, 2014). It was also noticed that 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 shows 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), give maximum MRR. At optimal parametric setting MRR value was calculated as 15.6789 (mm^3/min) and corresponding S/N ratio is 24.5031. Table 8 shows response Table for means of MRR. Table 9 presents response Table for S/N ratios for MRR.

The rank corresponds to the level of effect of input parameters 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. Table 10 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 p values are less than α value i.e., 0.05.

Table 8: Response Table for Means of MRR

Level	I(A)	Ton	Toff
1	1.261	3.489	6.978
2	5.03	6.011	5.086
3	10.27	7.062	4.498
Δ	9.009	3.573	2.48
Rank	1	2	3

Table 9: Response Table for S/N Ratios of MRR

Level	I(A)	Ton	Toff
1	0.8849	8.1946	14.3254
2	13.2371	12.6039	10.8833
3	19.6746	12.9981	8.5879
Δ	18.7897	4.8036	5.7375
Rank	1	3	2

Larger the better

Table 10: Analysis of Variance for MRR, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
I(A)	2	368.508	368.508	184.254	70.87	0
Ton	2	60.693	60.693	30.346	11.67	0
Toff	2	30.225	30.225	15.112	5.81	0.01
Error	20	51.996	51.996	2.6		
Total	26	511.421				

S = 1.61239 R-Sq = 89.83% R-Sq(adj) = 86.78%

3.2 Mathematical model to predict MRR

RSM is a collection of mathematical and statistical technique that is useful for modeling and analysis of problems in which output is influenced by several input variables. The objective is to find the correlation between output and input variables are investigated. The second-order model is generally used when the output function is not known or non-linear and the same is adopted. The following second-order model explains the behavior of the system.

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \sum_{i,j=1, i \neq j} \beta_{i,j} X_i X_j + \epsilon \quad \ldots\ldots\ldots (4)$$

Where Y is the corresponding response X_i is the input variables, X_{ii}^2 and $X_i X_j$ are the squares and interaction terms, respectively, of these input variables. The unknown regression coefficients are β_o, β_i, β_{ii} and β_{ij} and the error in the model is depicted as ϵ. It also confirms that this model provides an explanation of the relationship between the Independent factors and the response or output for MRR. The second order response surface representing the MRR can be expressed as a function of process parameters such as peak current, pulse on time and pulse off time. The relationship between the MRR and process parameters can be expressed as follows

$$MRR = \beta_0 + \beta_1(I) + \beta_2(T_{on}) + \beta_3(T_{off}) + \beta_4(I\,T_{on}) + \beta_5(T_{on} T_{off}) + \beta_6(I\,T_{off}) + \beta_7(I^2) + \beta_8(T_{on}^2) + \beta_9(T_{off}^2) \quad \ldots\ldots\ldots (5)$$

The coefficients of regression Equation 5 are estimated from experimental data using Minitab14 a statistical software package. The response surface models are developed, which are used to predict the results by iso-response contour plot and 3D response surface plots to study the main effect of the variables and the mutual interactions between the variables of the responses.

Table 11: R^2 and R^2_{adj} test for MRR regression model.

Degree of model	R^2(%)	R^2_{adj}(%)
Linear	88.07	86.51
Linear + square	89.83	86.78
Linear + interaction	96.67	95.67
Full quadratic	98.44	97.61

To decide the degree of the regression model, the values of the coefficient of determination (R^2) and adjusted R^2-statistic (R^2adj) are estimated, compared and summarized in Table 11 for various models. It is observed from the Table 11 that full quadratic model is the best among all the models, where R^2 = 98.44% indicates that 98.44% of total variation in the response is explained by predictors or factors in the model. However, R^2adj is 97.61% which accounts for the number of predictors in the model describe the significance of the relationship. Therefore, the full quadratic model is considered for further analysis in this study.

Table 12: Estimated Regression Coefficients for MRR

Term	Coef	SE Coef	T	P
Constant	2.07428	2.33758	0.887	0.387
I(A)	-0.0552	0.15919	-0.347	0.733
Ton	0.02536	0.02547	0.996	0.333
Toff	-0.085	0.04488	-1.894	0.075
I(A) x I(A)	0.01149	0.00438	2.627	0.018
Ton xTon	-0.00029	0.00011	-2.627	0.018
Toff xToff	0.00072	0.00031	2.327	0.033
I(A) xTon	0.00444	0.0005	8.969	0
I(A) x Toff	-0.00298	0.00083	-3.609	0.002
Ton x Toff	-0.00003	0.00013	-0.212	0.834

S = 0.685958 PRESS = 20.7793 R^2 = 98.44% R^2(pred) = 95.94% R^2(adj) = 97.61%

Table 12 represents the regression coefficients and its significance in the model. The columns in the table correspond to the terms, the value of the coefficients (Coef.), and the standard error of the coefficient (SE Coef), t-statistic and p-value to decide whether to reject or fail to reject the null hypothesis. To check the adequacy of the model, with a confidence level of 95%, the p-value of the statistically significant term should be less than 0.05. The values of R^2 and R^2adj are 98.44%and 97.61% respectively of full quadratic model exhibiting significance of relationship between the output and process parameters and the terms included in the satisfactory model are I, T_{on}, $T_{off,}$ I^2, $T_{on}{}^2$, $T_{off}{}^2$, $I\times T_{on,}$ $T_{on}\times T_{off}$, $I\times T_{off.}$. Analysis of variance (ANOVA) is used to check the adequacy of the second-order model, which includes test for significance of the regression model, model coefficients and test for lack-of- fit. ANOVA of the model is shown in Table 13. This consists of two sources of variation, such as regression and residual error. The regression error consists of variation due to the terms in the model (sum of linear, square and interaction terms). Residual error consists of the lack of fit and pure error.

Table 13: Analysis of Variance for MRR

Source	DF	Seq SS	Adj ss	Adj MS	F	P
Regression	9	503.422	503.422	55.9358	118.88	0
Linear	3	450.385	2.387	0.7956	1.69	0.207
I(A)	1	365.261	0.057	0.0565	0.12	0.733
Ton	1	57.446	0.467	0.4665	0.99	0.333
Toff	1	27.678	1.688	1.6883	3.59	0.075
Square	3	9.04	9.04	3.0134	6.4	0.004
I(A)* I(A)	1	3.247	3.247	3.2467	6.9	0.018
Ton*Ton	1	3.247	3.247	3.2467	6.9	0.018
Toff*Toff	1	2.547	2.547	2.547	5.41	0.033
Interaction	3	43.997	43.997	14.6657	31.17	0
I(A)*Ton	1	37.848	37.848	37.8483	80.44	0
I(A)*Toff	1	6.128	6.128	6.1276	13.02	0.002
Ton*Toff	1	0.021	0.021	0.0212	0.05	0.834
Residual Error	17	7.999	7.999	0.4705		
Total	26	511.421				

S = 0.685958 PRESS = 20.7793 R-Sq = 98.44% R-Sq (pred) = 95.94% R-Sq(adj) = 97.61%

The Table 13 depicts the sources of variation, degree of freedom (DF), sequential sum square error (Seq SS), adjusted sum square error (Adj SS), adjusted mean square error (Adj MS), F statistic and the p-values in columns. The p-value of regression model and its all square and interaction terms have p-value less than 0.05, hence they are statistically significant at 95% confidence and thus the model adequately represent the experimental data. Further mathematical model developed to predict MRR is

$$MRR = 2.07428 - 0.05517\,\mathrm{I} + 0.02536\,\mathrm{T_{on}} - 0.08500\mathrm{T_{off}} + 0.01149\,\mathrm{I}^2 - 0.00029\ \mathrm{T_{on}^2} + 0.00072\,\mathrm{T_{off}^2} + 0.00444\,\mathrm{I}\,\mathrm{T_{on}} - 0.00298\ \mathrm{I}\,\mathrm{T_{off}} - 0.00003\,\mathrm{T_{on}}\,\mathrm{T_{off}}\ \ldots\ldots(6)$$

Table14 presents the process parameters for each run order, along with the experimental values of MRR, the predicted values of MRR and the residues. The predicted values of MRR obtained using Equation 6 are close to the experimental values confirming the adequacy of the model. Normal probability plot (Figure4) depicts that the residuals are almost falling on a straight line, which indicates that the residues are normally distributed. The histogram plot (Figure4) shows the symmetry of the residues. It is in the form of Gaussian distribution (bell shape), and the residues are distributed with mean zero. In addition, the plot of the residues verse run order illustrates that there is no noticeable pattern or unusual structure present in the data as depicted in Figure4. The residues, which lies in the range of -0.79865 to 1.569 are scattered randomly about zero, i.e., the errors have a constant variance (Table 14). Further experimental values are compared with the predicted values in Figure4. It was observed that the regression model is fairly well fitted with the experimental values.

Table14: Process Parameters, Predicted MRR and Residues.

Expt No	Process parameters			Response (MRR) (mm^3/min)		
	I (A)	Ton (µs)	Toff (µs)	Experimental	predicted	residual
1	8	50	35	2.0177	1.7059	0.31176
2	8	50	65	1.3871	0.571	0.81617
3	8	50	95	0.3783	0.7391	-0.3608
4	8	100	35	1.5132	2.494	-0.9808
5	8	100	65	1.261	1.3171	-0.0561
6	8	100	95	1.1349	1.4432	-0.3083
7	8	150	35	2.1438	1.811	0.33277
8	8	150	65	1.0088	0.592	0.41684
9	8	150	95	0.5044	0.6761	-0.1716
10	16	50	35	4.2875	4.4136	-0.1261
11	16	50	65	1.7654	2.5641	-0.7987
12	16	50	95	2.5221	2.0177	0.50441
13	16	100	35	7.1879	6.9777	0.21017
14	16	100	65	5.0441	5.0862	-0.042
15	16	100	95	4.7919	4.4977	0.29424
16	16	150	35	7.9445	8.0706	-0.1261
17	16	150	65	6.053	6.137	-0.0841
18	16	150	95	5.6747	5.5065	0.16814
19	24	50	35	7.8184	8.5925	-0.7741
20	24	50	65	6.4313	6.0284	0.40283
21	24	50	95	4.7919	4.7674	0.02452
22	24	100	35	14.5019	12.9326	1.56928
23	24	100	65	10.3405	10.3265	0.01401
24	24	100	95	8.3228	9.0234	-0.7006
25	24	150	35	15.3846	15.8015	-0.4168
26	24	150	65	12.4842	13.1533	-0.6691
27	24	150	95	12.3581	11.8082	0.54995

Figure 5 presents interaction plot for means of MRR. It was noticed from the Figure 5 that I, and T_{on} as well as I, and T_{off} are intersecting each other significantly at a confidence level of 95%, .The same observation was made from Table 13.

Figure 6(a) and (b) represents contour plot and surface plot respectively for MRR in relation to process parameters of I and Ton keeping T_{off} remains constant at 65 µs. It was seen from the Figure 6 that, significant increase in MRR with increase in I for any value of Ton. However it was also observed that MRR increases sharply with increase in Ton. The effect of I and T_{off} on the estimated contour and surface plots of MRR is shown in Figure 7(a) and (b), respectively, keeping T_{on} remains constant at 100µs. It can be noted that, when I increases MRR is increasing, however, MRR decreases with increase in T_{off},. Figure 8 (a) and (b) represent contour and surface plots of MRR as a function of T_{on} and T_{off} keeping I remains constant at 16 A. The lowest possible MRR value occurred at smaller T_{on} and at higher T_{off} values. Further it can be concluded that I, and T_{on}

are directly proportional to the MRR, whereas T_{off} is inversely proportional to the MRR for the given range of experiments conducted for this test.

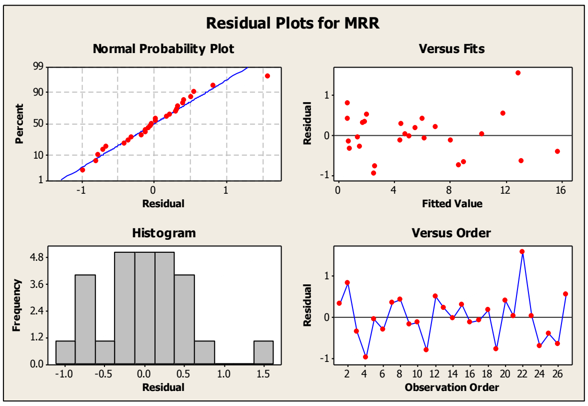

Figure 4: Residual plots for MRR

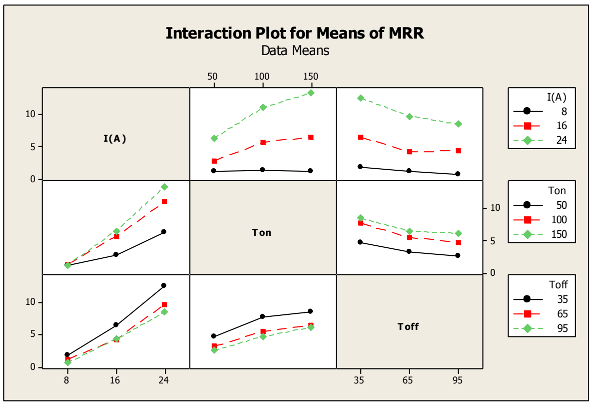

Figure 5: Interaction plot for Means of MRR

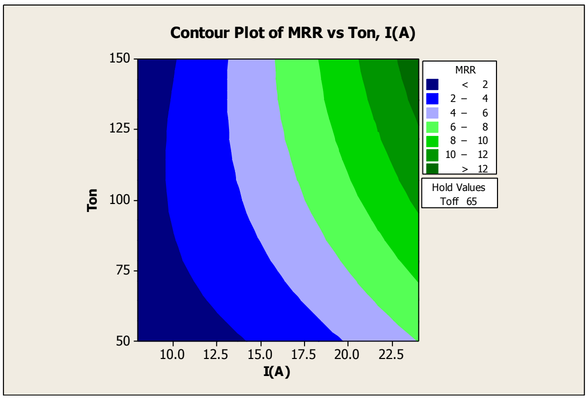

Figure 6 (a) Contour plot of MRR vs Ton, I(A)

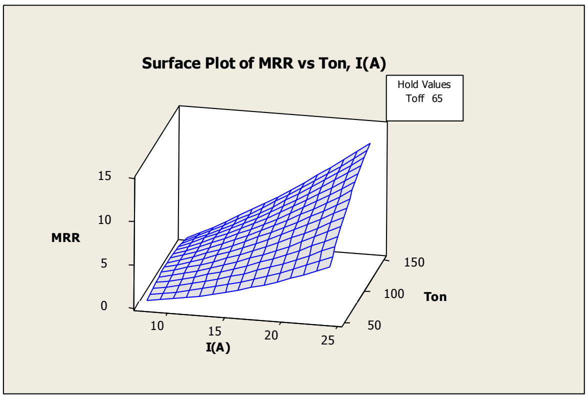

Figure 6 (b) Surface plot of MRR vs Ton, I(A)

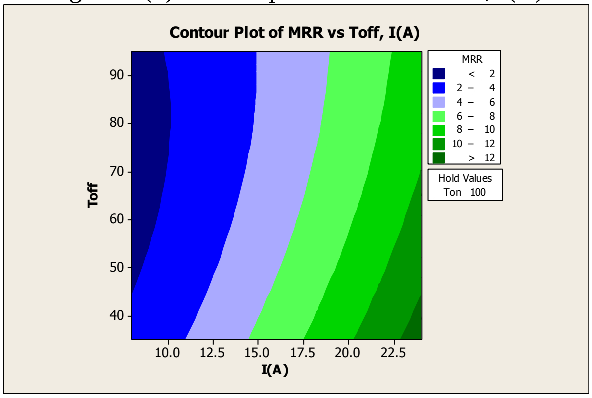

Figure 7(a) Contour plot of MRR vs Toff, I(A)

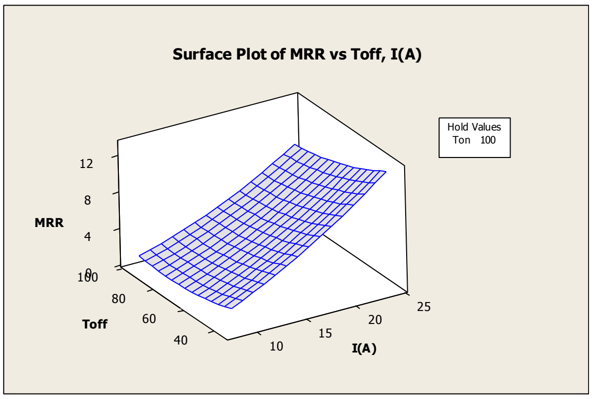

Figure 7(b) Surface plot of MRR vs Toff, I(A)

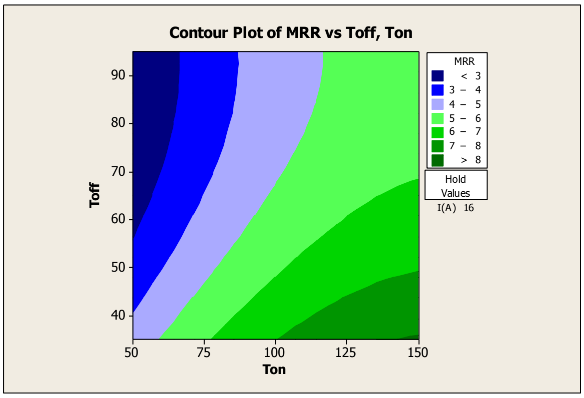

Figure 8(a) Contour Plot of MRR vs Toff, Ton

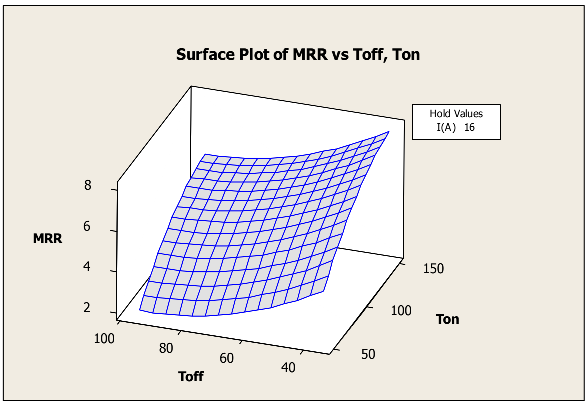

Figure 8(b) Surface Plot of MRR vs Toff, Ton

3.3. Confirmation Experiment

To verify the predicted value of MRR confirmation experiment was conducted at their optimal parametric setting. The deviation of predicted value from experimental value was calculated as percentage error and is presented in Table 15.

$$\%error = \frac{experimentalvalue - predictedvalue}{experimentalvalue} \times 100 \dots\dots\dots (7)$$

Table 15: 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)	15.3846	15.6789	1.91

IV. Conclusions

The following conclusions have been arrived during the present work:

1. Stainless Steel 304 can easily be machined on EDM with reasonable speed and surface finish. It is difficult to machine Stainless Steel 304 on conventional machining because of shorter tool life and severe surface damage due to its high hardness and strength.
2. MRR is increased with increase in peak current and pulse on time. However MRR decreases with increase in pulse off time.
3. Further optimal combination of process parameters are: I is at 24A, T_{on} is at 150µs and T_{off} is at 35 µs yield maximum MRR (15.6789 mm³/min), Confirmation experiment was conducted at respective optimal parametric setting corresponding MRR value 15.3846 mm³/min and percentage error was found to be 1.91%.
4. The analysis of variance reveals that process parameters such as Peak current, pulse on time and pulse off time are having significant affect on MRR.
5. Regression analysis has been performed and developed second order full quadratic mathematical model to establish relationship between MRR and process parameters (I, Ton and Toff). The values of R^2 and R^2_{adj} of the model are in the acceptable range of variability in predicting response values. The predicted values of MRR using regression equation, corresponding residuals and percentage error were calculated. The percentage error in predicting MRR is less than 5% hence the mathematical model given below is adequate in predicting the MRR values.

$$MRR = 2.07428 - 0.05517\,\mathrm{I} + 0.02536\,\mathrm{T_{on}} - 0.08500\mathrm{T_{off}} + 0.01149\,\mathrm{I}^2 - 0.00029\ \mathrm{T_{on}^2} + 0.00072\,\mathrm{T_{off}^2} + 0.00444\,\mathrm{I\,T_{on}} - 0.00298\ \mathrm{I\,T_{off}} - 0.00003\,\mathrm{T_{on}\,T_{off}}\ \dots\dots (6)$$

6. The interactional effects among the process parameters were studied and observed I, and T_{on} as well as I, and T_{off} are intersecting each other significantly at a confidence level of 95%, .The significance of interactional terms are verified with ANOVA and these terms were included in the regression model.

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