Research Article

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Multi-response optimization of magnetic field assisted EDM through desirability function using response surface methodology

<https://doi.org/10.1515/jmbm-2020-0003>

Received Nov 25, 2019; accepted Feb 17, 2020

Abstract: Magnetic field assisted electrical discharge machining (MFAEDM) is the modification of in conventional EDM process by use of magnetic field on EN-31. This article explain the application of response surface methodology to analyzes the effect of various process parameters such as Ton, Toff and Ip on performance measures such as material removal rate (MRR), electrode wear rate (EWR) and overcut (OC). Analysis of variance was used to check the adequacy of response surface model and significance of process parameters on performance measures. Multi-objective desirability function has been applied to obtain the optimal process parameter settings. Thereafter, machined surface of EN-31 characterized through SEM and EDX. The novelty of this paper is to improve the strategies for flushing the debris which remain clogged in standard EDM in-between machining gap that will interrupts the regular discharge conditions and reduces cutting rate as well as deteriorate the surface characteristics.

Keywords: Magnetic field assisted electrical discharge machining (MFAEDM), material removal rate, electrode wear rate, overcut, material transfer mechanism, surface morphology, EDX

1 Introduction

In previous years, several researchers focused their interest in modification of standard EDM with different hybrid techniques like powder mixed, electro discharge chemical machining, electro discharge grinding, electro-discharge milling and wire cut EDM. In standard EDM we have ob-

served the low MRR and surface quality. The standard EDM is known for tool and die making machine in which a series of discharges occurs having temperature in the range of 10000°C to 12,000°C between tool and work-piece. The tool and workpiece are immersed in dielectric kerosene and machined debris also washed away by dielectric [1]. There is no physical contact between tool and work piece which may produce no mechanical cutting forces, stresses, chatter and vibration problems, as it is well-known in conventional machining [2]. In conventional EDM enormous amount of debris clogged in the machining gap which results in low machining efficiency and surface roughness. Several authors utilized their hard work on magnetic force intensity applications to encourage the manufacturing technique and their effects of magnetic force process were confirmed from experimental findings. Makenzi *et al.* [3] was perceived that the surface roughness of mild steel improved with magnetic force assisted EDM. Yan *et al.* [4] performed to develop the quality of EDM surface through magnetic abrasive finishing process. Singh and Shan [5] applied the magnetic field around the work material in abrasive flow machining process and results showed that the surface integrities improved of both internal and external components. Cetin *et al.* [6] proposed a debris segregation model to assess and simulate the debris attentiveness in the machining zone area. Kremer *et al.* [7] developed the hybrid EDM assisted with ultrasonic vibration to improve the material removal rate. Lin *et al.* [8] studied the machining features of Ti-6Al-4V alloy by hybrid setup of EDM with USM. The experimental results indicated to reduce the recast layer thickness and also increase the machining efficiency. Lin and Lee [9] experimental investigation of machining parameters and also optimize the material removal rate, electrode wear rate and surface roughness through Taguchi and grey relation analysis of magnetic-force-assisted EDM. Cao *et al.* [10] perceived that magnetic-force-assisted EDM also finds the application for machining of non-ferromagnetic materials. The MRR of magnetic-force-assisted EDM increases rapidly with the discharge current and pulse duration. Bhattacharya *et al.* [11] found

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that with effective utilization of external magnetic field enhanced the material removal rate by expelling material from work piece inter-zone. Joshi *et al.* [12] observed that magnetic field develops the higher ionization and plasma confinement in dry EDM which was performed in pulsating magnetic field. Chattopadhyay *et al.* [13] investigated on reverse polarity of magnetic field that influences the rotary EDM parameters that affecting the surface roughness. Wang *et al.* [14] exposed the magnetic abrasive finishing for inner surface finishing of tubing. Wang *et al.* [15] exposed the comparative analysis of dielectric for EDM of titanium alloy. They achieved the highest material removal rate, a low electrode wear rate, fewer cracks, and better surface roughness in distilled water as compared to kerosene oil. Teimouri *et al.* [16] studied the hybrid rotary tool EDM assisted with magnetic field achieved low tool wear rate and overcut. Payal *et al.* [17] investigated the EDM surfaces of EN-31 tool steel. They found that for high discharge current, copper electrodes show highest MRR. Kumar *et al.* [18, 19] studied and optimize WEDM machining parameters and surface integrity by using response surface methodology. Lin *et al.* [20] investigated the magnetic force assisted EDM machining parameters and obtain the best optimal solution for output responses through Taguchi method. Peruri and Chaganti [21] review the magnetic assisted machining processes and their application in various fields.

Most of the work was explored to utilize the magnetic fields by single factor and performance measure variation and there is less work was reported on multi objective optimization using response surface methodology.

Based on the literature, novelty of the research work explores the paybacks of magnetic field assisted EDM (MFAEDM) were determined. Moreover, the essential EDM parameters such as Ton, Toff and Ip were varied to explore their effects on MRR, Electrode wear Rate (EWR) and Overcut (OC). The RSM based box-behnken design has been utilized to set level and their ranges to explore the above said performance characteristics. Analysis of variance has been utilized to validate the significance of process parameters and developed the empirical model for prediction of performance measures. Multi-objective desirability approach was carried out to optimize the machining parameters. Thereafter, surface characteristics were analyzed through morphology of machined samples by scanning electron microscope and EDX. The main objectives of applying a magnetic field involve:

1. To improve the strategies for flushing the debris which remain clogged in the inter-electrode gap that will interrupts the regular discharge conditions and

reduces metal removal rate as well as deteriorate the surface roughness.

2. The machining gap area creates the magnetic field to sweep away the suspended debris when magnets were attached to standard EDM.
3. To get deeper and more accurate sparking plasma channel.

2 Experimental details

In this investigation, the experiments were conducted on a 4-Axis numerical control EDM manufactured by Electronica India Ltd, Pune hybrid with magnetic field assistance of permanent magnets set-up as shown in Figure 1(a) and 1(b). The chemical arrangement of work material (EN-31) is taken as follows (wt. %): C=0.96, Si=0.226, Mn=0.410, Ph=0.015, Fe=96.96, Cr=1.22, S=0.024, Mo=0.019, Ni=0.068 and V=0.013. The rectangular form material having dimensions 100mm × 50mm × 3mm was utilized for machining. Kerosene oil is taken as the dielectric. A cylindrical copper having $\varnothing 5\text{mm}$ with 99.9% purity was used as the electrode. A neodymium magnet with a magnetic field intensity of 0.3 Tesla was used. To obtain better MRR positive polarity was chosen. The parameters which are kept fixed during experimentation as shown in Table 1. The optimal parametric combinations were predicted based on desirability approach and conformation tests were also performed according to design of experiment. The machined holes are systematically polished, cleaned and etched with solution of acetone, 2ml of HF acid (30%)+ 5ml of conc. of nitric acid with addition of deionized water. The investigation was further extended to examine the surface morphology in form of craters, cracks and recast layer.

Table 1: EDM fixed parameters

Machining Parameters	Units	Fixed operating conditions
Work-piece	-	EN31
Plates size	mm	100×50×3
Tool electrode	-	Copper
Work-piece Polarity	-	Positive
Electrode Polarity	-	Negative
Dielectric Fluid	-	Kerosene
Magnetic field Intensity	Tesla	0.3T

Figure 1: (a) Die sink EDM set-up; (b) Schematic diagram of magnetic Force assisted EDM

Figure 2: (a) Precision weight balance; (b) Profile projector; (c) Neodymium magnet

3 Experimental procedure and test equipment

Detailed procedure of conducting the experiments and recording the data as follows:

- Positive electrode polarity was selected while conducting the experiments. An initial weight of electrode and work piece is measured with Shimadzu make balance with model no. AUX 220 as shown in Figure 2 (a).

- Magnets are located at a distance 20mm from the work-piece in machining area as shown in Figure 1 (b) and 2(c).
- Set the parameters of the according to design of experiment.
- Cutting time for conduct of each experiment is noted by a stop watch.
- The MRR of work-piece material is calculated by following formula:

$$MRR = \frac{I_w - F_w}{M_t} \quad (1)$$

Table 2: Parameters and their levels of experimental design

S.No.	Symbols	Input parameters	Parameters Level			Units	Definition of parameters
			Low(-)	Medium(0)	High(+)		
1.	T_{on}	Pulse on Time	10	30	50	μs	Due to increase of pulse on time the discharge energy increases on electrode.
2.	T_{off}	Pulse off Time	10	30	50	μs	At low pulse off time results in an unstable process and less time available for de-ionization. As a result, the cutting rate also increases.
3.	I_p	Peak Current	2	6	9	A	Higher the peak current is the width of peak wider and wider which results larger size of craters on machined surface.

Where, I_w = Initial workpiece weight (g)

F_w = Final weight of work-piece (g)

C_t = Cutting time (min)

- The EWR of electrode is calculated by following formula:

$$EWR = \frac{I_e - F_e}{C_t} \quad (2)$$

Where, I_e = Initial electrode weight (g)

F_e = Final electrode weight (g)

C_t = Cutting time (min)

- Diameter of the hole is measured on a profile projector manufactured by Mitutoyo with model no. PJ-A3000 as shown in Figure 2b.
- A total of 17 experiments were proposed as per design of box-behnken design.

model was considered which is given as follows: [23–26].

$$Y = \beta_0 + \sum_{i=1}^k \beta_i x_i + \sum_{i=1}^k \beta_{ii} x_i^2 + \sum_{i < j} \beta_{ij} x_i x_j + \epsilon \quad (4)$$

Where

Y = Predicted Response

$x_n = i^{th}$ control parameter, $i=1,2,\dots,k$

β = regression coefficient

ϵ = chance error

k = number of parameters

The main objective of study was to explore the effects of Ton, Toff and Ip on MRR, EWR and OC. Table 2 shows the level of process parameters at which experimentation is to be carried out. These levels have been decided after detailed review of past work and pilot experimentation.

4 Experimental design

For multi objective problems and a response surface methodology is the good combination of experimental and statistical method in engineering applications. Empirical modeling was developing to fit the model between the response Y and independent parameters $x_1, x_2, x_3, \dots, x_n$ [22]. In general, the relationship is as follows:

$$Y = f(x_1, x_2, x_3, \dots, x_n) \quad (3)$$

Where

Y = output of the response

$x_n = i^{th}$ independent variables

In this research work there are three parameters were considered i.e. Ton, Toff and Ip. A polynomial quadratic

5 Results and discussion

5.1 Mathematical model and parametric effect on MRR

The adequacy of model and their interaction effects of parameters for the response MRR as shown in ANOVA Table 4. The model F value of 67.56 and p values is less than 0.05 implies that model is significant at 95% of confidence interval. It was observed that the factors A (Ton) and C (Ip) have a most significant effect on MRR because of major percentage of contribution i.e. 53.42% and 25.04%. The lack of fit F value of 1.07 implies that it is not significant compared to pure error. The determination of coefficient of “R-squared” 0.9886 and “Adj. R-squared” of 0.9473 which indicated that

Table 3: Experimental design and results

Run No.	Factors			Response variables		
	Ton (μs)	Toff (μs)	Ip (A)	MRR (mm ³ /min)	EWR (mm ³ /min)	OC (mm)
1.	30	30	6	14.66	0.26	0.33
2.	50	30	2	2.00	0.02	0.22
3.	30	10	2	3.39	0.06	0.11
4.	50	10	6	14.34	0.17	0.28
5.	10	30	2	1.73	0.01	0.16
6.	30	30	6	10.41	0.14	0.26
7.	50	30	9	8.10	0.11	0.32
8.	10	30	9	7.44	0.13	0.34
9.	30	30	6	8.58	0.13	0.33
10.	30	30	6	10.57	0.11	0.30
11.	10	50	6	6.40	0.13	0.31
12.	30	50	9	10.60	0.12	0.33
13.	30	10	9	8.53	0.22	0.24
14.	10	10	6	9.44	0.09	0.29
15.	30	50	2	1.88	0.02	0.33
16.	30	30	6	12.59	0.18	0.30
17.	50	50	6	8.96	0.15	0.26

Legend: T_{on} - Pulse on time, T_{off} - Pulse off time, I_p - Peak current, MRR - Material removal rate, EWR- Electrode wear rate, OC- Overcut

Table 4: ANOVA for response surface quadratic model for MRR

Source	SS	DOF	MS	F value	Prob>F	At95%CI	%Contribution
Model	186.87	9	20.76	67.56	<0.0001	significant	
A	100.45	1	100.45	326.85	<0.0001	significant	53.42
B	8.61	1	8.61	28.02	0.0011	significant	4.45
C	47.10	1	47.10	153.26	<0.0001	significant	25.04
A ²	10.83	1	10.83	35.23	0.0006	significant	5.75
C ²	12.19	1	12.19	39.16	0.0004	significant	6.48
AB	4.45	1	4.45	14.49	0.0067	significant	2.36
AC	2.91	1	2.91	9.47	0.0173	significant	1.54
BC	0.090	1	0.090	0.29	0.6052		0.047
Lack of fit	0.96	3	0.32	1.07	0.4569	Not significant	

R² = 0.9886

Adjusted R² = 0.9740

Predicated R² = 0.9092

Legend: CI- confidence interval, DOF-degree of freedom, MS- mean sum of squares, SS - Sum of squares.

predicted and experimental results had great perfect agreement. The empirical model equation for MRR is given by:

$$\begin{aligned}
 MRR = & +6.58209 - 0.20950 \times T_{on} - 0.2056 \times T_{off} \quad (5) \\
 & + 1.9198 \times I_p + 4.00875E - 003 \times T_{on}^2 - 0.13890 \\
 & \times I_p^2 + 2.63750E - 003 \times T_{on} \times T_{off} + 0.012186 \\
 & \times T_{on} \times I_p - 2.14286E - 003 \times T_{off} \times I_p
 \end{aligned}$$

It can be seen from the main effect plots as shown in Figure 3a-3c that the MRR increases significantly with effect

of Ton. It means that the number of sparks in unit time increases which increases in discharge energy. MRR is directly proportional to discharge energy. As a result material removal rate becomes faster with increase in Ton. When Toff increase, the number of discharges with in given period of time decreases. The MRR increases with increase of Ip. When Ip is low, large portion of energy is use to vaporize the metal so that the MRR is less at low current [27, 28]. MRR increase with Ip because at high current discharge

Figure 3: Main effect Plots for MRR (a) Ton Vs MRR; (b) Toff Vs MRR; (c) Ip Vs MRR

Figure 4: Interaction Plots for MRR (a) Ton Vs Toff; (b) Ton Vs Ip; (c) Toff Vs Ip

Table 5: The ANOVA for response surface quadratic model for EWR

Source	SS	DOF	MS	F value	Prob>F	At95%CI	%Contribution
Model	0.018	9	0.00198	35.52	<0.0001	Significant	
A	0.00692	1	0.00692	124.4	<0.0001	Significant	43.4
B	0.00186	1	0.00186	2.00	0.0007	significant	10.33
C	0.00396	1	0.00396	33.25	<0.0001	significant	22.00
A ²	0.00112	1	0.00112	70.78	0.029	significant	6.23
AB	0.00060	1	0.00060	20.05	0.0136	significant	3.35
AC	0.00275	1	0.00275	10.73	0.0002	significant	15.31
BC	0.00038	1	0.00038	49.26	0.0351	significant	2.11
Lack of fit	0.00031	3	0.00013	5.10	0.0748	Non significant	

$R^2 = 0.9786$

Adjusted $R^2 = 0.9510$

Predicated $R^2 = 0.7213$

Legend: CI- confidence interval, DOF- degree of freedom, MS - mean sum of squares, SS- Sum of squares.

energy is large. The interaction plots for the above said response as shown in Figure 4a-4c. It was observed that MRR increased from $1.73\text{mm}^3/\text{min}$ to $14.66\text{mm}^3/\text{min}$ with the increase Ton from $10\mu\text{s}$ to $50\mu\text{s}$ with simultaneous decrease of Toff from 50 to $10\mu\text{s}$. It was also observed MRR increasing from $1.73\text{mm}^3/\text{min}$ to $16.14\text{mm}^3/\text{min}$ with simultaneous increase of Ip and Ton. The same effect of MRR increased from $4.9\text{mm}^3/\text{min}$ to $12\text{mm}^3/\text{min}$. with simultaneous vary of Toff and Ip. It was observed that by simultaneous increasing of Ip and decreases of Toff the rate of discharge energy increases.

5.2 Mathematical model and parametric effect on EWR

By applying the multiple regression analysis on observed values, a predictive empirical relationship as presented in following equation that describe the correlation between response EWR and three parameters.

$$\begin{aligned} EWR = & +3.80714E - 003 + 5.06750E - 003 \times T_{on} \quad (6) \\ & - 1.64857E - 003 \times T_{off} + 0.016414 \times I_p \\ & - 4.08125E - 005 \times T_{on}^2 + 3.06250E - 005 \times T_{on} \\ & \times T_{off} - 3.75000E - 004 \times T_{on} \times I_p \\ & + 1.39286E - 004 \times T_{off} \times I_p \end{aligned}$$

To describe the significance and importance of developed quadratic model was observed in Table 5. From these observations the factors A, B, C and three interaction terms AB, AC and BC were found to be the significant for EWR.

The insignificant model terms are reduced by backward elimination method and improved the model. The

model F-value of 35.52 suggests that model is significant and “lack of fit F value” of 5.40 implies that it is not significant compared to pure error. There is only a 0.01% chance that a “Model F-value” this large could occur due to noise. The “R-squared” value of 0.9786 and other adequacy measures is reasonable agreement with the “Adj. R-squared” value of 0.9510. From Figures 5a-5c and 6a-6c it can observed that EWR is affecting by Ton, Toff and Ip. It appeared from these figures that EWR varies from $0.015\text{mm}^3/\text{min}$ to $0.26\text{mm}^3/\text{min}$ with the increase Ton by $10\mu\text{s}$ to $50\mu\text{s}$ and with parallel decrease of Toff by 50 to $10\mu\text{s}$.

5.3 Mathematical model and parametric effect on overcut (OC)

Overcut (OC) of the machined hole was measured by deducting the diameter of the tool electrode (D_{TE}) from the diameter of machined hole (D_{MH}) as given in follows:

$$OC = D_{MH} - D_{TE} \quad (7)$$

The profile of machined hole is not truly cylindrical but tapered because of debris movement and discharge occurring at the side surface in addition wear also occurs at the front end of the tool electrode [29]. From the ANOVA Table 6 the model F value of 28.16 implied that the model is significant for overcut. In this case A, B, C, C² and AC were the significant model terms. The “R-squared” value of 0.9356 and other adequacy measures is reasonable agreement with the “Adj. R-squared” value of 0.9614. This model indicated that predicted and experimental results had great perfect agreement be used to navigate the empir-

Figure 5: Main effect Plots for EWR (a) Ton Vs EWR; (b) Toff Vs EWR; (c) Ip Vs EWR

Figure 6: Interaction Plots for EWR (a) Ton Vs Toff; (b) Ton Vs Ip; (c) Toff Vs Ip

Figure 7: Main effect Plots for Overcut (a) Ton Vs OC; (b) Toff Vs OC; (c) Ip Vs OC

Table 6: ANOVA for response surface quadratic model for Overcut

Source	SS	DOF	MS	F value	Prob>F	At95%CI	%Contribution
Model	0.12	9	0.014	28.16	<0.0001	Significant	
A	0.024	1	0.024	50.12	0.0002	Significant	20.16
B	0.029	1	0.029	59.64	<0.0001	Significant	24.36
C	0.048	1	0.048	99.51	<0.0001	Significant	40.33
C ²	0.015	1	0.015	31.65	0.0008	Significant	12.60
AC	0.0030	1	0.0030	6.26	0.0408	Significant	2.54
Lack of fit	0.0021	3	0.0007	2.19	0.2321	Non Significant	

$R^2 = 0.9356$

Adjusted $R^2 = 0.9614$

Predicated $R^2 = 0.7716$

Legend: CI- confidence interval, DOF- degree of freedom, MS- mean sum of squares, SS- Sum of squares.

ical relation for the OC was modeled as follows:

$$\begin{aligned}
 \text{Overcut}(OC) = & -0.076638 + 2.88571E - 003 \times T_{on} \quad (8) \\
 & + 1.00000E - 004 \times T_{off} + 0.095531 \times I_p \\
 & - 4.91837E - 003 \times I_p^2 - 3.92857E - 004 \\
 & \times T_{on} \times I_p
 \end{aligned}$$

From Figures 7a-7c and 8a-8c it can be observed that overcut is affected by Ton, Toff and Ip. It appeared from these figures that overcut varies from 0.16mm to 0.38mm with simultaneous increase of Ton and decrease of Toff. It was also observed overcut increasing from 0.077mm to

0.363mm with simultaneous increase of Ip and Ton. It was observed that due to increase of Ip and Ton and low pulse off the overcut increases. Deeper and larger craters have been observed at workpiece profile. The debris makes the ridges and lumps due to high discharge energy as a result overcut increases.

Figure 8: Interaction Plots for Overcut (a) Ton Vs Toff; (b) Ton Vs Ip; (c) Toff Vs Ip

Table 7: Material migration in magnetic field assisted EDM

Sample No.	Control Factors			Material migration to machined samples (%)				
	Peak current (A)	Pulse on time (μ s)	Pulse off time (μ s)	C	O	Al	Cr	Fe
1	6	30	30	51.57	-	0.99	-	47.44
5	2	10	30	55.59	7.63	13.69	-	23.19
7	9	50	30	66.70	18.18	1.40	0.48	13.24
15	2	30	50	54.46	1.47	1.47	0.73	43.24

Table 8: Multi Response Optimization through desirability function

S.No	Ton (μ s)	Toff (μ s)	Ip A	MRR mm^3/min	EWR mm^3/min	OC mm	Desirability	
1.	10.00	10.00	3.18	8.26257	0.0776426	0.187511	0.563	Selected
2.	10.00	10.00	2.96	8.00717	0.0749302	0.174623	0.562	
3.	10.00	10.00	3.46	8.56604	0.0810366	0.203121	0.562	
4.	10.00	10.46	3.25	8.266166	0.0778832	0.190513	0.561	
5.	10.66	10.00	2.97	7.97396	0.0772984	0.176697	0.555	
6.	11.08	10.00	3.55	8.6059	0.0856173	0.210671	0.549	
7.	11.42	10.00	3.51	8.54028	0.0861661	0.208974	0.446	
8.	37.70	50.00	3.89	9.41468	0.110741	0.202916	0.417	
9.	36.04	50.00	4.03	9.13172	0.108261	0.20024	0.417	
10.	50.00	50.00	8.92	16.5946	0.135695	0.259337	0.359	
11.	50.00	50.00	8.62	16.5987	0.135733	0.266052	0.353	
12.	50.00	32.27	9.00	16.1374	0.134947	0.334371	0.300

Figure 9: SEM micrograph: Exp No. 1 at; $T_{on} = 30\mu s$; $T_{off} = 30\mu s$; $I_p = 6 A$

Figure 10: SEM micrograph: Exp No. 8 at $T_{on} = 30\mu s$; $T_{off} = 30\mu s$; $I_p = 9 A$

Figure 11: SEM micrograph: Exp No. 15 at $T_{on} = 30\mu s$; $T_{off} = 50\mu s$; $I_p = 2A$

Figure 12: SEM micrograph: Exp No. 1; at $T_{on} = 30\mu s$; $T_{off} = 30\mu s$; $I_p = 6A$

Figure 13: SEM micrograph: Exp No. 5; at $T_{on} = 10 \mu s$; $T_{off} = 30 \mu s$; $I_p = 2A$

Figure 14: SEM micrograph of optimal setting at $T_{on} = 10 \mu s$; $T_{off} = 10 \mu s$; $I_p = 4 A$

Figure 16: Ramp Graph showing desirability for MRR; EWR and Overcut

Table 9: Validation of Mathematical models with experimental data

Exp. No.	Experimental results			RSM model prediction			Prediction error(%)		
	MRR	EWR	OC	MRR	EWR	OC	MRR	EWR	OC
1.	8.50	0.080	0.190	8.26	0.077	0.187	2.8	3.7	1.5
2.	8.20	0.070	0.180	8.00	0.074	0.174	2.4	2.6	3.3

Figure 17: Bar Graph showing desirability for MRR; EWR and Overcut

Table 8 shows the composite desirability and the corresponding values of predicted responses obtained are also given. The current optimal process parameter settings are Ton of 10 μ s, Toff of 10 μ s, Ip of 4A and Figure 14 of SEM micrographs was observed with less number of cracks and craters. The three responses MRR, EWR and OC are

shown in Figures 16-18 with contour plots and optimized histograms.

8 Validation of experimental results

Prediction error in Table 9 has been calculated by the following formula.

$$\text{Prediction error} = \frac{\text{Experimental Result} - \text{Predicated Result}}{\text{Experimental Result}} \times 100 \quad (10)$$

In order to validate the developed models the confirmatory experiment was carried out and the obtained results are *i.e.* MRR=8.50 mm³/min, EWR=0.077 mm³/min and OC=0.190 mm, respectively. Table 9 shows the error percentage between experimental and predicted values for MRR, EWR and OC lies within 2.8%, 3.7% and 1.5%, respectively.

Figure 18: Graph between Ton and Toff for desirability

9 Conclusion

In this study, the influence of process parameters on MRR, EWR and OC while drilling of EN31 by MFAEDM technique have been examined. From the experimental investigations, the following conclusions were drawn:

1. MRR increasing from $1.73\text{mm}^3/\text{min}$ to $16.14\text{mm}^3/\text{min}$ with simultaneous increase of I_p and Ton. The magnetic field produces significant effect on MRR at high Ton and I_p . The debris was driven off quickly and reduces the abnormal discharge.
2. EWR varies from $0.015\text{mm}^3/\text{min}$ to $0.26\text{mm}^3/\text{min}$ with the increase Ton by $10\mu\text{s}$ to $50\mu\text{s}$ with parallel decrease of Toff by 50 to $10\mu\text{s}$. The minimum EWR $0.012\text{mm}^3/\text{min}$ was obtained when the parameters were set at Ton is $10\mu\text{s}$, Toff is $30\mu\text{s}$ and I_p is 2A with magnetic field.
3. It was observed that drilled hole has lower overcut with value of 0.11mm at lower I_p 2A .
4. The optimized value of MRR, EWR and OC are $8.26\text{mm}^3/\text{min}$, $0.077\text{mm}^3/\text{min}$ and 0.187mm with desirability 0.563 was obtained. The optimal setting of parameters at Ton, Toff and I_p are $10\mu\text{s}$, $10\mu\text{s}$ and 3.18A respectively with magnetic field of 0.3T .

5. The confirmation tests showed that the error between experimental and predicted values of MRR, EWR and OC are 2.8% and 3.7% , 1.5% respectively.
6. The drilled hole surface with high Ton, I_p and low Toff observed with craters, micro-cracks, spherical deposits and recast layer. The material migration also observed through EDX showing with copper and work material elements.

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