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Experimental Investigation of Electro Discharge Machining on NIMONIC 80A through Response Surface Methodology

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Electro discharge machining (EDM) is one of the most popular advancement machining process for machining of conductive hard material. In the present study, effect of machining parameters such as Current (A), Pulse ON time (T_{on}) and Pulse OFF time (T_{off}) on EDM process of NIMONIC 80A and their machining characteristics are Material Removal Rate (MRR), Tool Wear Rate and Surface Roughness (SR). The Box-Bhenken Design (BBD) of Response Surface Methodology (RSM) used to design and analysis of this experiment. In this research ANOVA results shows that Current and Pulse ON time is the most significant factors for material removal rate. The Current is only significant for tool wear rate and surface roughness. The optimization process is conducted for the experiment and the results shows that optimise parameters are current (3A), pulse on time 900µs and pulse off time 30µs.

***Keywords*:** Electro discharge machining (EDM), NIMONIC 80A, Box-Bhenken Design and Response Surface Methodology.

1. Introduction

The applications of a NIMONIC 80A is mostly used in gas turbine components (viz. blades, rings and discs), automobile exhaust valves, die-casting inserts and core, nuclear boiler tube supports and bolts. It belongs to a family of a nickel-based high temperature low creep and high performance super alloy, These super alloys contain the properties such as high strength, high hardness, low thermal diffusivity, presence of highly abrasive carbide particles and high tendency to welding to the tool and forming built-up edge by making them particularly difficult-to-machine. So, conventional machining methods of nickel-based super alloy become more difficult than conventional materials. To overcome these inferences, unconventional machining methods like Electro discharge machining, Electro chemical machining, Laser beam machining and Abrasive water jet machining became an attractive alternative.

EDM is an electro-thermal process whereas the material removed from the parent metal by the repetitive sparks. S V Gowthaman et al. [1] examined the effect of parameters (Pulse ON time, Pulse OFF time, Discharge current and gap voltage) on electrical discharge machining of MONEL super alloy with copper electrode. The MRR and Ra are dependent parameters. They reported that ANOVA results discharge current is the most significant parameter for MRR and Ra. Discharge current increases with increasing MRR and Ra". Chandramouli S et al. [2] "studied the electrical discharge machining of 17-4 PH steel using taguchi method of input parameters are current, pulse on time, pulse off time and tool life time. The MRR and Ra are output parameters. The current and pulse on time increases with increasing MRR and Ra". V Vikram Reddy et al. [3] "investigated the machining parameters such as current, pulse on time and pulse off time on electrical discharge machining of aluminium alloy 6082 and the machining characteristics are such as MRR, TWR and SR. This research shows that current and pulse on time increases leads to increasing MRR, TWR and SR and decreasing due to increase of pulse off time". Amitesh Goswami et al. [4] " studied wire-cut EDM of NIMONIC 80A alloy with independent parameters (peak current, pulse on time and pulse off time) using taguchi's rodust design methodology. The MRR and SR are dependent parameters. This investigation shows the current and pulse on time as most significant parameters". Sourbh sinha et al. [5] "investigated the different machining parameters(current, voltage and pulse on time) for the electrical discharge machining (EDM) process on Incoloy 800HT with machining characteristics MRR and TWR. This experiment is designed Box-Bhenken design response surface methodology. That results show that current is most significant parameter, as current increases, MRR, TWR increases. V Muthukumar et al. [6] "studied the ROC in die-sink electrical discharge machine process for INCOLOY 800 with copper electrode and their input parameters such as current, pulse on time, pulse off time and voltage. Central composite design of RSM is used to model and analysis the experiments. The research shows that current and voltage are the most significant parameters for ROC". Neelesh singh et al. [7] "investigated that Inconel 601 in EDM with machining characteristics of Material removal rate and surface roughness with input parameters such ad peak current, gap voltage and pulse on time. Experiments are designed Box-Bhenken Design of RSM. They reported that MRR and Ra increases with increasing current.

From the literature review, I understood that a few research work done on NIMONIC 80A of EDM. This Research studies that machining parameters such as current (A), Pulse ON time and Pulse OFF time on EDM of NIMONIC 80A and response characteristics such as MRR, TWR and SR. Experiments are designed and analysis conducted on Box-Bhenken Design of Response surface methodology.

2. Materials and Method

2. 1. Materials

NIMONIC 80A is a work piece material chosen from the present experiment; the chemical composition is shown in the Table. 1 and its dimensions of work piece is thickness 6mm and length and breadth is 15mm. The copper is chosen as electrode material and its dimensions are 10mm diameter and 50mm length. ARD ARTM30D Die-sink EDM machine tool is used to conducted the experiments and commercial grade "EDM oil" is used as dielectric oil. Machining time taken as 10min. The setting of electrode and work piece on EDM machine tool and machined samples are shown in the Fig. 1.

Table. 1. Chemical composition of NIMONIC 80A

Elements	C	Si	Mn	Cu	S	Cr	Fe	Ti	Al	Co	Ni
%	0.0318	0.363	0.053	0.0403	0.002	20.03	2.268	2.63	1.387	0.4013	Bal

Fig. 1. The setting of electrode and work piece on EDM machine tool and machined samples

2. 2. Design of Experiments

Experiments is designed on the Box-Bhenken design (BBD) of experiment technique with three machining parameters such as Current, Pulse ON time and Pulse OFF time and their levels are shown in the Table. 2. All the experiments are designed Box-Bhenken Design of Response Surface

Methodology in Stat-Ease Design Expert software 11. The BBD layout with experimental results is shown in Table. 3.

Table. 2. Machining parameters and their levels

Factors	Units	Levels		
		Low (-1)	**Medium (0)**	**High (1)**
Current	**A**	3	9	15
Pulse ON time (T_{on})	**µs**	300	600	900
Pulse OFF time (T_{off})	**µs**	30	60	90

The material removal rate and tool wear rate are calculated by using the following equation [1] [2]. Both can be measured with the CONTECH analytical balance. The TAYOR HABSON surtronic 3+ surface roughness tester is used to measured the surface roughness.

MRR was calculated as

$$MRR = \frac{W_{wb} - W_{wa}}{t} \text{ (gm/min)} \tag{1}$$

W_{wb} is weight of work piece before machining, W_{wa} is a weight of work piece after machining and t is machining time.

TWR was calculated as

$$TWR = \frac{W_{tb} - W_{ta}}{t} \text{ (gm/min)} \tag{2}$$

W_{tb} is weight of tool before machining, W_{ta} is a weight of tool after machining and t is machining time.

Table. 3.The BBD layout with experimental results

STD	INPUT PARAMETERS			OUTPUT PARAMETERS		
	CURRENT (A)	**T_{on} (µs)**	**T_{off} (us)**	**MRR (gm/min)**	**TWR (gm/min)**	**SR (µm)**
1	3	300	60	0.00251	0.00066	1
2	15	300	60	0.29843	0.00274	7.5
3	3	900	60	0.00205	0.00062	1.4
4	15	900	60	0.34988	0.00279	7.4
5	3	600	30	0.00221	0.00074	1.2
6	15	600	30	0.30673	0.00225	6.8
7	3	600	90	0.00211	0.00147	1.2
8	15	600	90	0.2253	0.00238	8.1
9	9	300	30	0.09691	0.00082	5.6
10	9	900	30	0.04035	0.00086	5
11	9	300	90	0.06554	0.00215	5.8
12	9	900	90	0.04906	0.00194	4
13	9	600	60	0.06608	0.00157	4.8
14	9	600	60	0.07427	0.00152	5.5
15	9	600	60	0.06998	0.00172	5.2
16	9	600	60	0.06705	0.00192	5.6
17	9	600	60	0.05517	0.00068	3.8

3. Results and Analysis

The Stat-Ease Design Expert 11 Software is used to analyse the experimental machining characteristics are shown in Table. 3. ANOVA is performed, to check the goodness and suitability of fitness of the model and the model adequacy examination comprises: the test for significance of the regression model, test for significance on model coefficients, and test for lack of fitness.

3.1 Material Removal Rate

For the MRR analysis, the quadratic model for statistical analysis of MRR is recommended by the fitness test summary. The results of MRR are shown in ANOVA Table. 4 and Other ANOVA parameters are shown in Table. 5.

Table. 4. ANOVA for MRR model

Source	**Sum of squares**	**Dof**	**Mean**	**F-value**	**p-value**	
Model	1000.21	9	111.13	2580.47	<0.0001	Significant
A-CURRENT	753.78	1	753.78	17502.39	<0.0001	
B-T_{on}	2.38	1	2.38	55.20	0.0001	
C-T_{off}	0.1326	1	0.1326	3.08	0.1228	
AB	1.28	1	1.28	29.81	0.0009	
AC	0.0097	1	0.0097	0.2254	0.6494	
BC	0.3349	1	0.3349	7.78	0.0270	
A^2	239.56	1	239.56	5562.40	<0.0001	
B^2	0.0077	1	0.0077	0.1791	0.6849	
C^2	0.3888	1	0.3888	9.03	0.0198	
Residual	0.3015	7	0.0431			
Lack of Fit	0.1050	3	0.0350	0.7121	0.5937	not significant
Pure Error	0.1965	4	0.0491			
Cor Total	1000.51	16				

Table 5. Other ANOVA parameters

R^2	0.9997	Predicted R^2	0.9980
Adjusted R^2	0.9993	Adeq Precision	129.090

The non–significant terms are eliminated by the backward elimination process in arrange to adjust the fitted ANOVA for MRR. Regression equation obtained for the MRR is shown below.

$$\frac{1}{SQUARE\ ROOT\ (MRR)} = 32.40230 - 5.19928 \times \mathrm{CURRENT} + 0.006579 \times \mathrm{T_{on}} - 0.016653 \times \mathrm{T_{off}} - 0.000315 \times \mathrm{CURRENT} \times \mathrm{T_{on}} - 0.000032 \times \mathrm{T_{on}} \times \mathrm{T_{off}} + 0.209462 \times \mathrm{CURRENT}^2 + 0.000335 \times \mathrm{T_{off}}^2 \quad (3)$$

3. 2. Influences of machining parameters on Material Removal Rate

Fig. 2. has shown that effect of current on material removal rate for a constant T_{on} (600μs) and T_{off} (60μs). It shows that with current increase, material removal rate also linearly increases. Increase in the current, spark discharge is increased, gives to the action of melting, vaporisation and

advancement of large impulsive force in the spark gap. Hence, results MRR linearly increases. Fig. 3. has shown that effect of Pulse ON time on material removal rate for a constant current (15A) and T_{off} (90µs). It shows that with Pulse ON time increase, material removal rate also linearly increases. This may be happened due to the fact that increase in pulse on time, increases energy input per spark and therefore results in high erosion at the machining zone and creates larger craters of relatively higher depth. So, results increase in MRR. Fig. 4. has Shown that effect of pulse off time on material removal rate for a constant current (9A) and T_{on} (600µs). It shows that with Pulse OFF time increase, material removal rate also linearly increases. This may happen due to fact that increase in pulse off time causes the plasma channel to become decreases, which reduces the positive ions on the work surface. Hence results MRR linearly decreases.

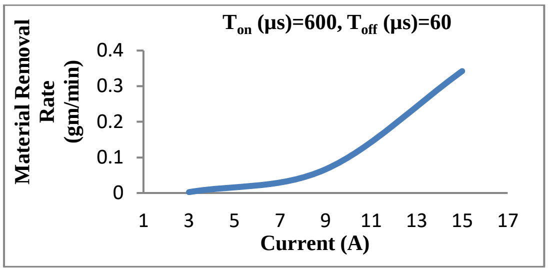


Fig. 2. Effect of current on material removal rate

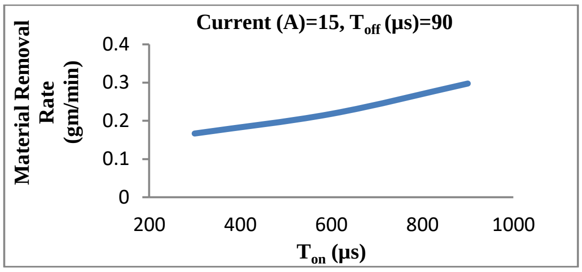


Fig. 3. Effect of T_{on} on material removal rate

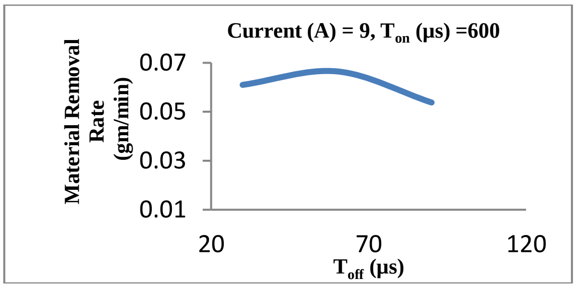
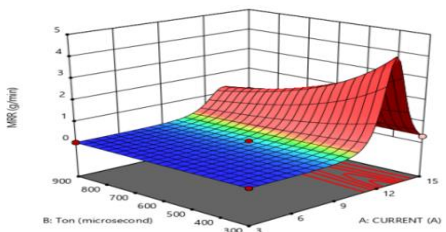


Fig. 4. Effect of T_{off} on material removal rate

Fig.5. has shown that the influence of current (A) and T_{on} (µs) on MRR (gm/min). Maximum MRR occurs for a maximum level of current and maximum level of pulse on time (T_{on}). Fig. 6. has shown the influences of pulse on time (T_{on}) and pulse off time (T_{off}) on material removal rate. It can be observed that slightly maximum material removal rate for a maximum level of pulse on time (T_{on}).



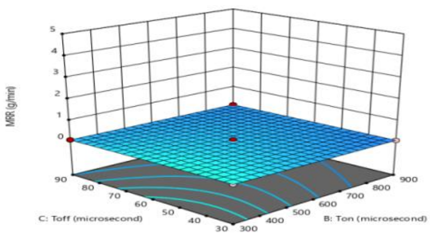


Fig. 5. 3D plots for MRR Vs current and T_{on} (µs) Fig. 6. 3D plot for MRR Vs T_{on} (µs) and T_{off} (µs)

3.3. Tool Wear Rate

For the TWR analysis, the quadratic model for statistical analysis of TWR is recommended by the fitness test summary. The results of TWR are shown in ANOVA Table. 6 and Other ANOVA parameters are shown in Table. 7.

Table. 6. ANOVA for TWR model

Source	Sum of Squares	DOF	Mean	F-value	p-value	
Model	5.941E-06	3	1.980E-06	12.08	0.0006	Significant
A-CURRENT	4.498E-06	1	4.498E-06	27.44	0.0002	
B-T_{on}	8.253E-12	1	8.253E-12	0.0001	0.9945	
C-T_{off}	1.337E-06	1	1.337E-06	8.15	0.0145	
Residual	1.967E-06	12	1.639E-07			
Lack of Fit	1.066E-06	8	1.333E-07	0.5917	0.7556	Non-significant
Pure Error	9.009E-07	4	2.252E-07			
Cor Total	7.908E-06	15				

Table. 7. Other ANOVA parameters

R^2	0.7513	Predicted R^2	0.5729
Adjusted R^2	0.6891	Adeq Precision	12.0892

Regression equation obtained for the TWR is shown below

$$\mathrm{TWR} = -0.000450 + 0.000136 \times \mathrm{CURRENT} - 3.67908\mathrm{E}-09 \times \mathrm{Ton} + 0.000014 \times \mathrm{Toff} \quad (4)$$

3.4. Influences of machining parameters on Tool Wear Rate

Fig. 7. has shown that the effect of current on tool wear rate is constant in T_{on} (600μs) and T_{off} (60μs). It shows that when current increases, tool wear rate also linearly increases. Increase in the current, discharges energy increases then melting and vaporization of material from the electrode. So, TWR increases. . Fig. 8. has shown that the effect of Pulse ON time on tool wear rate for a constant current (9A) and T_{off} (90μs). It shows that when Pulse ON time increase there is no variation in tool wear rate. This may be happened due to the reason that pulse on time increases there is an increasing possibility deposition of carbon on the tool, which results no variation on the tool wear rate by increasing pulse on time. Fig. 9. has Shown that the effect of pulse off time on material removal rate for a constant current (9A) and T_{on} (600μs). It shows that with Pulse OFF time increase, tool wear rate also linearly increases. This may be due to the reason that increases in the pulse off time, energy per spark decreases therefore flushing time also increases. Flushing to clear the debris on the tool surface results increases in TWR.

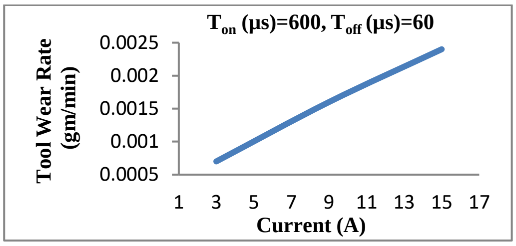


Fig. 7. Effect of current on tool wear rate

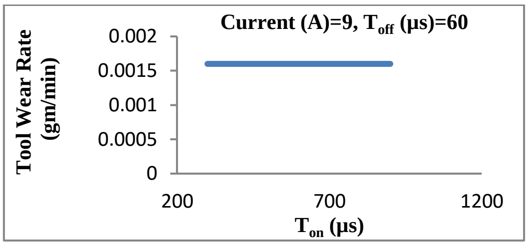


Fig. 8. Effect of T_{on} on tool wear rate

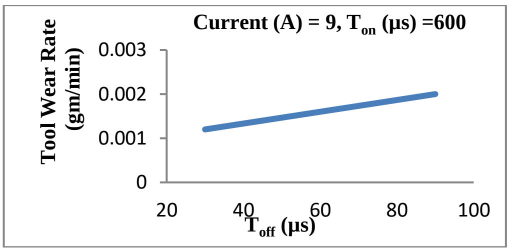


Fig. 9. Effect of T_{off} on tool wear rate

3.4 Surface Roughness

For the SR analysis, the linear model for statistical analysis of SR is recommended by the fitness test summary. The results of SR are shown in ANOVA Table. 8 and Other ANOVA parameters are shown in Table. 9.

Table. 8. ANOVA for surface roughness model

Source	**Sum of squares**	**Dof**	**Mean**	**F-value**	**p-value**	
Model	78.71	3	26.24	51.74		Significant
A-CURRENT	78.13	1	78.13	154.06		
B-T_{on}	0.5512	1	0.5512	1.09	0.3161	
C-T_{off}	0.0313	1	0.0313	0.0616	0.8078	
Residual	6.59	13	0.5071			
Lack of Fit	4.46	9	0.4961	0.9324	0.5755	Non significant
Pure Error	2.13	4	0.5320			
Cor Total	85.30	16				

Table. 9. Other ANOVA parameters

R^2	0.92271	Predicted R^2	0.86671
Adjusted R^2	0.90488	Adeq Precision	19.6133

Regression equations in terms of actual values

$$\mathrm{SR} = +0.412500 + 0.520833 \times \mathrm{CURRENT} - 0.000875 \times \mathrm{Ton} + 0.002083 \times \mathrm{Toff}$$

(5)

3. 5. Influences of machining parameters on Surface Roughness

Fig. 10. has shown that effect of current on surface roughness for a constant T_{on} (600μs) and T_{off} (60μs). It shows that with current increase, surface roughness also linearly increases. Increase in the current, the discharge energy increases to generation of violent sparks and impulse force. So, deeper and larger craters are formed on the surface of work piece and after sparking debris are not properly washed out on the surface of the work piece. The residues are staying behind at carter edge to form rough surface. Hence, results SR linearly increases. Fig. 11. has Shown that effect of Pulse ON time on surface roughness for a constant current (9A) and T_{off} (60μs). It shows that with Pulse ON time increase, surface roughness linearly decreases. This may be happened due to the increase in pulse on time, the more material gets melted on surface of the work piece. Here proper flushing is done due to T_{off} taken as 60μs. So, flushing can clear the debris of surface of the work piece when proper arcing can takes place. Hence, results higher T_{on} value decreases the surface roughness. Fig. 12. has Shown that effect of pulse off time on surface roughness for a constant current (9A) and T_{on} (600μs). It shows that with Pulse OFF time increase, surface roughness increases. This may happen due to that increase in the Pulse OFF time, energy per spark decreases. Therefore, the resolidfied of recast layer was formed on the machined surface of the work piece during cooling periods. Hence, results surface roughness increases.

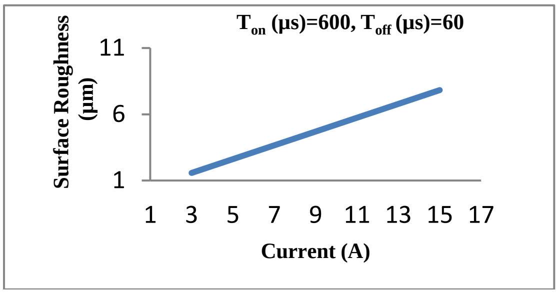


Fig. 10. Effect of current on surface roughness

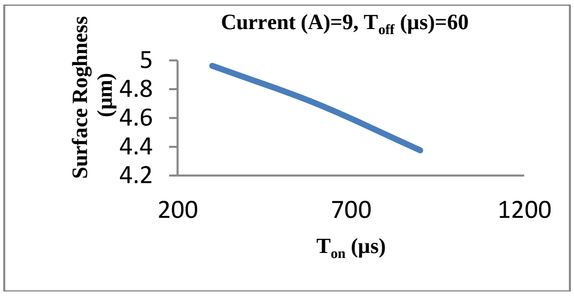


Fig. 11. Effect of T_{on} on surface roughness

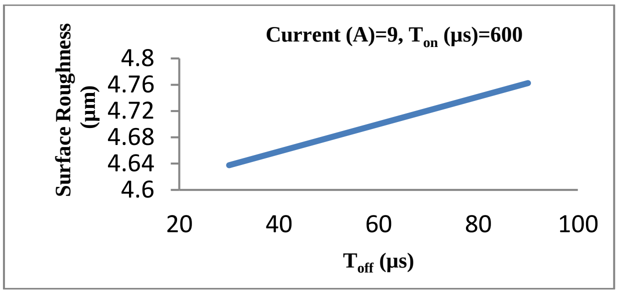


Fig. 12. Effect of T_{off} on surface roughness

4. Optimization

Design Expert software was given desirability value. The optimise parameters where the maximum value of MRR and Minimum value of TWR and SR is Current **3A**, Pulse ON time **900µs** and Pulse OFF time **30µs** with desirability value is **0.980.**

4.1 Confirmation test

The confirmation test is performed by conducting set of experiments. Table.10. shows that the predicated and the experimental values are within the acceptable range. Hence, this model can be used for predication of MRR, TWR and SR at 95% level of confidence.

Response	**Predicated mean**	**Predicated medium**	**Std.dev**	**N**	**95% PI low**	**Data mean**	**95% PI high**
MRR	0.00194193	0.00194193	3.22118E-05	2	0.001853	0.001959	0.002035
TWR	0.000362	0.000362	0.0004048	2	-0.0005507	0.000685	0.0012756
SR	1.25	1.25	0.71212	2	-0.236593	1.250	2.73667

5. Conclusions

The following conclusions are noted as per the experimental study.

1. The ANOVA results shows the Current and Pulse ON time is the most significant parameters of MRR and Current is the most significant parameters of TWR and SR.
2. MRR increases with the Current and Pulse ON time increase and MRR decreases with increase in Pulse OFF time.
3. TWR increases with the Current and Pulse OFF time increase and there is no variation in Pulse OFF time.
4. SR increases with increase the Current and Pulse OFF time and SR decreases with increase in Pulse OFF time.
5. The optimise parameters where the maximum value of MRR and Minimum value of TWR and SR is Current **3A**, Pulse ON time **900µs** and Pulse OFF time **30µs** with desirability value is **0.980**.

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