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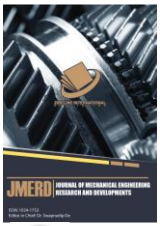

RESEARCH ARTICLE

MULTI RESPONSE OPTIMIZATION OF EDM PROCESS PARAMETERS FOR INCONEL X-750 USING MOORA

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ABSTRACT

Electrical discharge machining (EDM) is used extensively to machine hard to cut materials like nickel, titanium and super alloys with higher dimensional accuracy and surface finish. In this present study, a multi response optimization on the basis of ratio analysis (MOORA) is proposed for finding optimum process parameter of Electrical Discharge machining (EDM) during machining of Inconel X-750 material which is used mostly in thermal erosion process like nuclear plants, aerospace industry. In this study, response surface methodology (RSM) with Box-Behnken approach has been utilized for selecting the appropriate process parameters by using three level four factor (discharge current (Ip), voltage (V), pulse on time (Ton) and pulse off time (Toff)) using tungsten copper electrode (W-Cu). The machining responses considered are material removal rate (MRR), surface roughness (SR) and tool wear rate (TWR). The satisfactoriness of developed mathematical model has been tested with the use of analysis of variance (ANOVA). Further mathematical equations are generated using the statistical software MINITAB 17. The experimental data used for adequate regression model to optimize the process using MOORA. Further the surface characteristics of the machined surface are identified using scanning electron microscope (SEM) and elements with their peak values are revealed with EDX analysis.

KEYWORDS

Inconel X-750, tungsten-copper electrode, RSM, multi response optimization, MOORA

1. INTRODUCTION

In manufacturing industries there is a tremendous change in the development of emerging materials like Hastelloy, Titanium, Inconel, Nimonics, carbides, composites and super alloys. These materials are widely used in various applications like automobile, aerospace missiles and nuclear industry. INCONEL is a family of austenite nickel-chromium-based super alloys. Inconel X-750 is a precipitation harden able material having excellent properties like good corrosion resistance, mechanical strength and high temperature resistance. In conventional machining process it is very difficult to cut materials particularly with contour and complex shapes along with tight tolerance and good surface finish. It is very difficult to machine tungsten, hardened steel, titanium, High strength super alloys, and super alloys like Inconel X 750 Due to that cause of difficult in conventional machining selected one of the un-conventional machining processes named as EDM to cut the Inconel X-750 material. EDM is a one of the promising un-conventional machining processes having characteristics like reducing the machining stress, work hardening and metallurgical damage. In EDM machining phenomenon was an interrupted electric spark discharge occurs between the electrode (cathode) and the work piece (anode). In order to generate the spark between the electrode and work piece is kept under electrical conductivity. It uses electricity as energy source and electrically conductive materials as a tool. In EDM direct contact between the tool electrode and work piece is avoided to eliminate the mechanical stresses, vibration effects while machining.

The thermoelectric energy is produced between electrode and work piece which is immersed in dielectric fluid with conduction of electric current to erode the work piece material. A pulse discharge gap of 0.3 mm is maintained between the work piece and the electrode to remove the unwanted material from the parent metal through melting and Vaporizing. One of the drawbacks of EDM is lower rate of MRR and higher rate of TWR was occurred while machining with copper, brass, graphite electrodes. So that, tungsten–copper (W-Cu) electrode was considered to analyze the performance of EDM in terms of material removal rate (MRR), surface finish (SR) and tool wear rate (TWR). W-Cu was selected as an electrode because of its high thermal conductivity, low thermal expansion coefficient and high melting point at elevated temperature. The copper properties in this aforesaid tool responsible for high thermal conductivity, where tungsten provides spark erosion characteristics. The mixture of copper and tungsten gives good tool wear resistance properties to increase machining conditions. The selection of process parameters plays an important role in machining. The process parameters with their levels are selected based on number of trial experiments. The proper selection of parameters gives the better results of machining. It has been noticed that most of the authors focused on reducing the surface roughness and increasing the material removal rate using different materials like copper, graphite, brass. However, very few authors have been experimental investigated on Inconel X-750 with W-Cu electrode. This research work offers new insights into the performance of die sinking EDM of Inconel X750 using W-Cu electrode. RSM Box behnken DOE is used to find the effect of process parameters. The ANOVA results identified the best process parameters and also developed the mathematical equations on selected performance characteristics. Multi response optimization using MOORA was used to find the optimum values of process parameters. Experiments are planned and conducted using RSM box behnken

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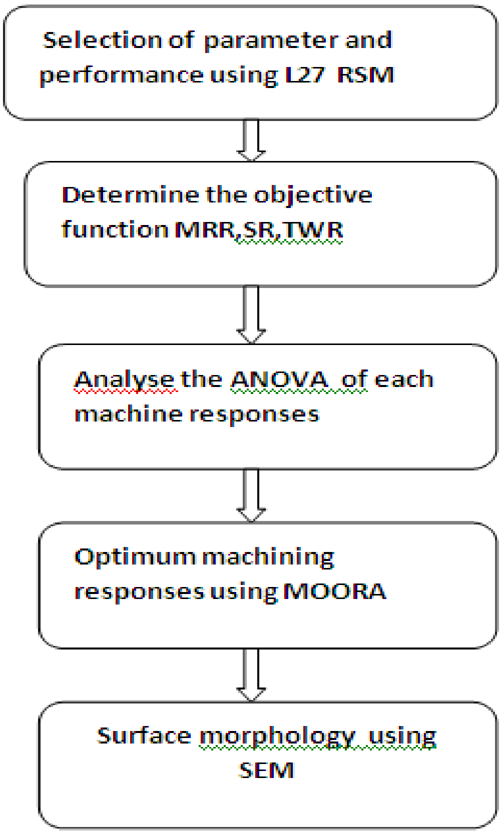
approach. Discharge current (Ip), voltage (V), pulse on time (Ton) and pulse off time (Toff) are considered as input parameters to analyze the effect of output responses MRR, SR and TWR. ANOVA test is used to determine the influence of process parameters on the responses like MRR, SR, TWR.

2. OBJECTIVE

The main objective of this research work is to find the optimum process parameters using multi response optimization technique MOORA. The effect of process parameters for the three output responses and their optimum values are calculated using ANOVA analysis. Surface characteristics of the machined component is identified at maximum MRR and at minimum SR using scanning electron microscope (SEM). EDX analysis is done to find out the chemical composition of the work piece material at different locations.

3. Methodology



3. LITERATURE

Sarat kumar sahoo et al. investigated the experimental analysis of wire edm process parameters for high carbon high chromium steel. They adopted MOORA method for conducting multi response optimization. The ouput parameters considered are material removal rate, surface roughness, and kerf width of the high-carbon and high-chromium steel. They concluded that the MOORA method is a very efficient technique for complex multi-objective optimization problems [1]. Himadrimajumder et al. optimized the performance responses of WEDM using multi objective optimization on the basis of ratio analysis (MOORA) coupled with principal component analysis (PCA). The performance responses selected in this study are average cutting speed, average Kerf width and average surface roughness (Ra). They conducted Confirmation test which reveals that MOORA coupled with PCA was a best methodology to decide available cutting parameters for a desired response quality for WEDM of titanium grade 6 [2]. Patel et al. utilized a multi objective optimization technique Analytic Hierarchy Process (AHP) and MOORA to optimize the output responses in WEDM for EN31 alloy steel [3]. A.Jaiswal et al.done multi response optimization of wire edm process parameters using MOORA. They conducted the experiments on D3 die steel with brass wire by considering the four input process parameters like pulse-on-time, pulse-off-time, servo voltage and wire tension. The output responses considered are cutting and surface roughness. The experiments are designed using Taguchi approach. Multi objective optimization using ratio analysis (MOORA) is applied for obtaining higher cutting speed and lower surface roughness [4].

Neeleshsingh et al.studied the machining characteristics of Inconel 601 in edm using RSM. They investigated the effect of material removal rate (MRR) and surface roughness (SR, Ra) with different input variables which are gap voltage (Vg), peak current (Ip) and pulse on time (Ton).The experiments are carried out using RSM Box-Behnken Design (BBD).ANOVA is used to find the effect of input parameters on their output responses and to analyse the significant of the derived model [5].Mandeep kumar et al. investigated multi response optimization in WEDM of Inconel X-750 using Taguchi-GRA approach. While investigation considered process parameter as spark gap voltage, pulse on time, pulse off time, wire feed rate, peak current and wire tension on their responses was cutting speed and SR [6]. Sreenivasa Rao et al. studied the surface integrity issues of Inconel-690 with wire-cut EDM while RSM-CCD technique. They observed that the hardness of machined surface is less compared to the hardness of base metal due to movement of Zn and Cu from wire electrode to machining surface [7]. Anshuman kumar et al.investigated multi objective optimization of wire EDM process parameters on Inconel 718.Wire tension, wire speed, discharge current and pulse on time was selected as process parameters for the performance responses like MRR and SR.Taguchi L27 orthogonal array was used for designing, planning and conducting the experiments. Multi response optimization of EDM parameters was adopted simulated annealing algorithm to achieve better MRR and Ra [8]. Satish kumar et al. studied the parametric optimization of powder mixed EDM for nickel-based Inconel-800 super alloy using RSM. The experiments were designed using Box-Behnken method along with desirability approach for multi response parameter optimization.They observed that peak current, pulse-on-time significantly affect the MRR [9]. Rahul et al.studied the surafe integrity and metallurgical characteristics of Inconel 825 in EDM using cryogenically treated copper electrode. They investigated the surface cracks and white layer thickness onto the EDMed Inconel 825 work surface [10].

From the above literature most of the authors have reported on machining of nickel-based alloys using with different tools like copper, copper-chromium and graphite. But very few were emphasized to machining of Inconel X-750 using W-Cu electrode. So that in this paper was discussed about optimizing the machining characteristics of EDM for machining of Inconel X-750 using W-Cu electrode.

4. EXPERIMENTAL PROCEDURE

4.1 Workpiece and tool material

In the present study, Inconel X-750 was used as a work piece material for conducting the experiments in die-sink EDM machine. W-Cu electrode of 16mm diameter was selected as a tool material. Figure1 shows the workpiece material which is a Inconel X-750 after machining. The percentage of elements present in the Inconel X-750 was shown in the Table 1.

Table 1: Chemical composition of Inconel X-750

Element	Ni	Cr	Fe	Nb	Ti	Al	Mn	Si	S	Cu	C	Co
%	70.00	14.11	8.22	1.29	2.45	0.84	1.00	0.50	0.01	0.50	0.08	1.00

Figure 1: Machined samples of Inconel X-750

4.2 Machine tool

The experiments are done using SPARKONIX S35 EDM die-sinking machine with CNC controller was shown in Figure 2 (a). Each experiment was conducted with a depth of cut of 0.5 mm and the machining time is noted for every experiment. The work piece was submerged in the tank having the dielectric fluid as shown in Figure 2(b). Electrode which is a W-Cu was arranged to the tool holding device. For improving the cutting speed, the dielectric fluid with grade of SAE 40 oil was used.

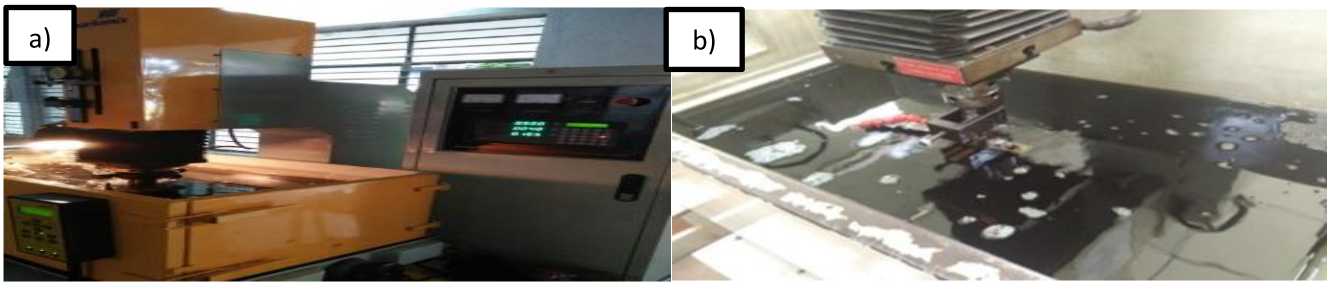


Figure 2: (a) Sparkonix S35 EDM machine, (b) Work piece immersed in Dielectric fluid

4.3 Selection of machining parameters and levels

The number of trial experiments was conducted for selecting the best process parameters of an EDM machine. Out of all process parameters, some of best parameters were selected and their levels were mentioned in the Table 2. The selection of process parameters using RSM L27 design of experiments is to avoid the greater number of experiments which leads to save more experimentation cost. Based on literature and preliminary experimentation four process parameters were selected in this study. They were discharge current, voltage, pulse on time and Pulse off time with three levels of approach were shown in Table 2.

Table 2: Process parameters and levels

Symbol	Parameters	Units	Levels		
			-1	0	+1
A	Voltage	V	15	25	35
B	Discharge Current	Amps	8	12	16
C	Pulse- on- time	µs	20	60	100
D	Pulse- off- time	µs	20	30	40

4.4 Evaluation of EDM performance characteristics

MRR, SR and TWR considered as the performance characteristics in this study. These performance responses were used to assess the performance of the EDM by varying the levels of input process parameters.

Material removal rate (MRR) is shown in equation 1

$$MRR(mm^3 / \min) = \frac{WML(g)*1000}{\rho_w(g / cm^3)*T_m(\min)} \quad (1)$$

Where,
WML (weight mass loss) = (Wb– Wa)
Wb = Mass of workpiece material before machining (g)
Wa = Mass of workpiece material after machining (g)
Tm = machining time (min)
ρw = density of work piece material (g/cm3)

Tool wear rate (TWR) is shown in equation 2

$$TWR(mm^3 / \min) = \frac{TML(g)*1000}{\rho_w(g / cm^3)*T_m(\min)} \quad (2)$$

TML= (T-Ta)
TML= Tool mass loss
Tb = mass of tool material before machining (g)
Ta = mass of tool material after machining (g)
Tm = machining time (min)
ρt = density of tool material (g/cm3)
Surface Roughness (Ra)

The surface roughness of the machined component is measured with a Metrix plus micro surf 10 instrument was shown in Figure 3.

Figure 3: Surface roughness tester

4.5 Design of Experiments

4.5.1 Response surface methodology (RSM) for single parametric optimization

Mathematical Modelling is a method of creating relationship between process variables and desired responses to analyse the optimum conditions. RSM is one of the most effective statistical and mathematical techniques applied for modelling and analysis of process parameters for different problems. In this paper, RSM Box-Behnken, four parameters and three levels was used for the design of experiments. It is an effective tool for designing and optimizing the process by combing several machining parameters and evaluates their compound interactions for the effect of output responses. Residual plots for accuracy, contour plots and response curves are analysed using RSM.

The two significant response surface designs i.e. central composite design (CCD) and Box-Behnken design (BBD) which are used to study the output performances. Box-Behnken is a method of statistical design which does not contain fractional factorial design to obtain optimum responses. The BBD has a smaller number of trials than CCD with the same number of factors and is used in the present investigation to conduct EDM experiments. Twenty-seven sets of experiments were conducted according to the BBD response surface method. The RSM lay out with 27 experiments was shown in the Table 3. The Box Behnken lay out with uncoded factors and experimental results was shown in Table 4.

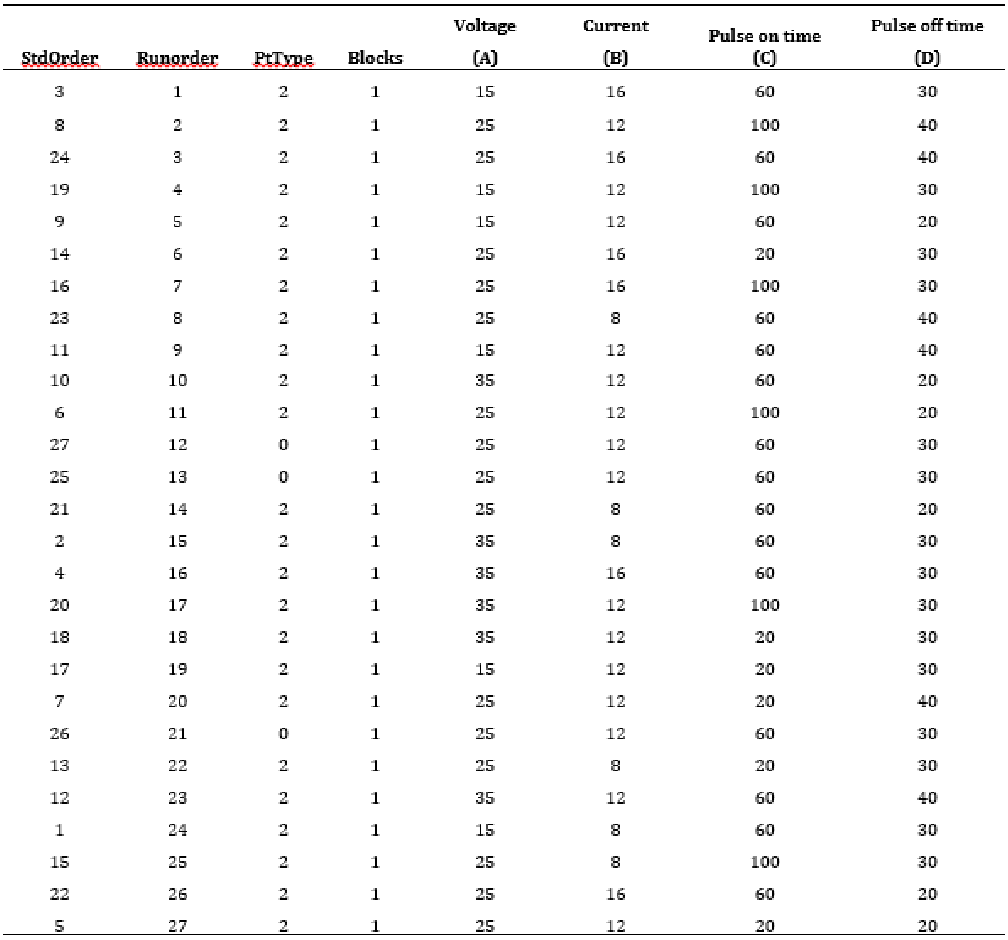
5. RESULTS AND DISCUSSION

Experiments are planned and conducted according to RSM-BBD layout. The experimental result for MRR, TWR and SR was shown in the table 4 and has been analyzed using three dimensional graphs and ANOVA analysis.

5.1 Effect of process parameters on MRR

The effect of different machining parameters like current, pulse-on-time, pulse-off-time on MRR is shown in the Figure 4(a) and 4(b). The experimental results were analyzed using Minitab software. The ANOVA results show that the quadratic model is statistically significant for analysis of MRR. The significance of the model terms and lack of fit is tested using ANOVA analysis. The value of Prob>F is less than 0.05 indicates that the model terms are significant for MRR but if exceeds 0.1 terms are insignificant. The F test is conducted to see the significance of process parameter on the output responses like MRR and SR. In this study A, B, C, A2, B2, C2, BC, BD are significant model terms as shown in the ANOVA Table 5.

Table 3: RSM Box-Behnken Design layout



StdOrder	Runorder	PtType	Blocks	Voltage (A)	Current (B)	Pulse on time (C)	Pulse off time (D)
3	1	2	1	15	16	60	30
8	2	2	1	25	12	100	40
24	3	2	1	25	16	60	40
19	4	2	1	15	12	100	30
9	5	2	1	15	12	60	20
14	6	2	1	25	16	20	30
16	7	2	1	25	16	100	30
23	8	2	1	25	8	60	40
11	9	2	1	15	12	60	40
10	10	2	1	35	12	60	20
6	11	2	1	25	12	100	20
27	12	0	1	25	12	60	30
25	13	0	1	25	12	60	30
21	14	2	1	25	8	60	20
2	15	2	1	35	8	60	30
4	16	2	1	35	16	60	30
20	17	2	1	35	12	100	30
18	18	2	1	35	12	20	30
17	19	2	1	15	12	20	30
7	20	2	1	25	12	20	40
26	21	0	1	25	12	60	30
13	22	2	1	25	8	20	30
12	23	2	1	35	12	60	40
1	24	2	1	15	8	60	30
15	25	2	1	25	8	100	30
22	26	2	1	25	16	60	20
5	27	2	1	25	12	20	20

Table 4: RSM-Box Behenken method with uncoded factors and experimental results

Storder	Run order	Pt Type	Blocks	Voltage (A)	Current (B)	Pulse on time (C)	Pulse off time (D)	MRR	SR	TWR
3	1	2	1	15	16	60	30	40.453	4.98	**1.387**
8	2	2	1	25	12	100	40	24.990	5.12	**0.865**
24	3	2	1	25	16	60	40	41.424	4.66	**1.449**
19	4	2	1	15	12	100	30	25.378	5.75	**0.926**
9	5	2	1	15	12	60	20	28.259	5.02	**1.005**
14	6	2	1	25	16	20	30	24.555	4.38	**0.967**
16	7	2	1	25	16	100	30	33.696	5.12	**1.266**
23	8	2	1	25	8	60	40	11.621	3.65	**0.558**
11	9	2	1	15	12	60	40	33.705	4.62	**1.133**
10	10	2	1	35	12	60	20	19.805	4.65	**0.573**
6	11	2	1	25	12	100	20	21.321	5.76	**0.682**
27	12	0	1	25	12	60	30	28.664	4.89	**0.884**
25	13	0	1	25	12	60	30	28.498	4.78	**0.868**
21	14	2	1	25	8	60	20	12.934	5.13	**0.650**
2	15	2	1	35	8	60	30	7.611	4.32	**0.229**
4	16	2	1	35	16	60	30	30.499	4.65	**1.065**
20	17	2	1	35	12	100	30	15.416	5.63	**0.625**
18	18	2	1	35	12	20	30	14.614	3.86	**0.460**
17	19	2	1	15	12	20	30	18.928	4.37	**0.565**
7	20	2	1	25	12	20	40	22.705	3.59	**0.740**
26	21	0	1	25	12	60	30	29.587	4.87	**1.034**
13	22	2	1	25	8	20	30	14.475	3.54	**0.222**
12	23	2	1	35	12	60	40	26.893	4.23	**0.632**
1	24	2	1	15	8	60	30	14.438	4.86	**0.448**
15	25	2	1	25	8	100	30	5.685	5.82	**0.366**
22	26	2	1	25	16	60	20	32.257	4.35	**1.390**
5	27	2	1	25	12	20	20	16.944	3.98	**0.728**

A three-dimensional surface plot of MRR is shown in the figure. The effect of current and pulse off time is shown in the Figure 4(a). It is clear from the Figure 4(a) that MRR increases with increase in current due to amount of energy and heat produced to the workpiece results in melting and vaporization. The three-dimensional plots show that as the current increases from 8 amps to 16 amps the MRR increases gradually. Higher the current, increases the spark intensity and rise in sparking area temperature leads to melting of work piece material resulting in increase of material removal rate. Regression Equation for MRR is shon in equation 3.

$$MRR = -19.1 + 0.765 A + 3.83 B + 0.2158 C - 0.538 D - 0.02303 A*A - 0.1935 B*B - 0.004353 C*C + 0.02802 B*C + 0.0655 B*D \quad (3)$$

To predict each response with different combination of parameters RSM-single response optimization is used. The normal probability plot for MRR shows that all the points on the normal plot come close to form a straight line. This indicates that the data is fairly normal and there is no deviation in the normality. Every experiment is compared with the predicted data. Optimized contour plot of MRR,3D surface plot for the overall desirability of MRR is shown in the Figure C. The optimum conditions for each process parameter are shown in the Figure 4C.

The model F value of 73.25 indicates that the model is significant. The multiple regression coefficient (R2) is calculated to identify whether fitted model expresses the observed value. The R2 of 97.49% is in reasonable agreement with the Adj R2 of 96.16%.

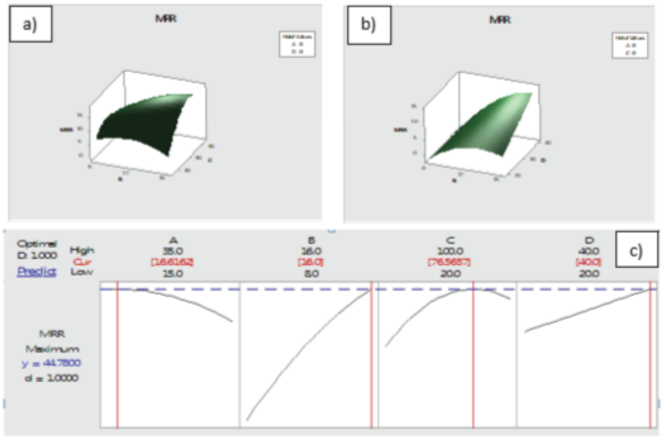


Figure 4: (a) current vs pulse off time, (b) current vs pulse on time, (c) optimum plots of MRR

Table 5: Analysis of Variance for MRR

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	9	2225.07	97.49%	2225.07	247.230	73.25	0.000
Linear	4	1813.92	79.47%	80.79	20.198	5.98	0.003
A	1	178.82	7.83%	13.78	13.780	4.08	0.059
B	1	1544.05	67.65%	26.45	26.446	7.84	0.012
C	1	16.96	0.74%	19.44	19.441	5.76	0.028
D	1	74.09	3.25%	12.38	12.382	3.67	0.072
Square	3	303.31	13.29%	303.31	101.104	29.95	0.000
A*A	1	0.56	0.02%	31.81	31.812	9.43	0.007
B*B	1	11.76	0.52%	57.53	57.529	17.04	0.001
C*C	1	290.99	12.75%	290.99	290.992	86.21	0.000
2-Way Interaction	2	107.84	4.72%	107.84	53.919	15.97	0.000
B*C	1	80.38	3.52%	80.38	80.380	23.81	0.000
B*D	1	27.46	1.20%	80.38	27.458	8.14	0.011
Error	17	57.38	2.51%	27.46	3.375		
Lack-of-Fit	15	56.69	2.48%	57.38	3.779	10.98	0.087
Pure Error	2	0.69	0.03%	56.69	0.344		
Total	26	2282.45	100.00%	0.69			
S	1.83718					R-sq	97.49%
Press	220.410					R-sq(adj)	96.16%

5.2 Effect of process parameters on Surface roughness

As shown in the figures below indicates the three-dimensional response plots on the input parameter of SR. The Figure 5 (a) shows the effect of current and pulse off time on SR. The Figures shows that with increase in current SR increases. The increase of current leads to increase of spark energy results in broad and greater pits in the machining zone. Figure 5(b) displays the three-dimensional plot of current vs pulse on time. At highest value of pulse- on -time more explosion energy passes through the material surface results in melting and evaporation of material surface. So better surface roughness is obtained at the lowest pulse on time only. From Figure 5(c) the effect of pulse on time and pulse off time on SR is shown .SR is high at the highest value of pulse off time as molten material is flushed away and the machined gap is cleaned at pulse off time. Figure 5 (d) shows the effect of voltage on pulse on time. It shows that the surface roughness increases at low voltage and decreases at high voltage. So better surface roughness is formed at the minimum values of current (8 amps), pulse on time (30 µs) and maximum values of pulse off time (40µs) and voltage (36v).

Regression equation for SR is shown in equation 4

The second order regression equation for the performance characteristics of SR in terms of input parameters is expressed as follows:

$$SR=3.221-0.03346\,A+0.0830\,B+0.04722\,C+0.0053\,D-0.01072\,B*B-0.002590\,D*D+0.000244\,A*C-0.002406\,B*C+0.011188\,B*D-0.000156\,C*D \qquad (4)$$

The model F value of 243.65 indicates that the model is significant. From the ANOVA table A, C, B^2, D^2, AB, BC, BD are significant model terms as shown in Table 6. It is identified that the discharge Current has a high impact on surface roughness. The multiple regression coefficient (R^2) is calculated to identify whether fitted model expresses the observed value. The R^2 of 99.35% is in reasonable agreement with the Adj R^2 of 98.94%. At low value of pulse on time better surface roughness is identified.

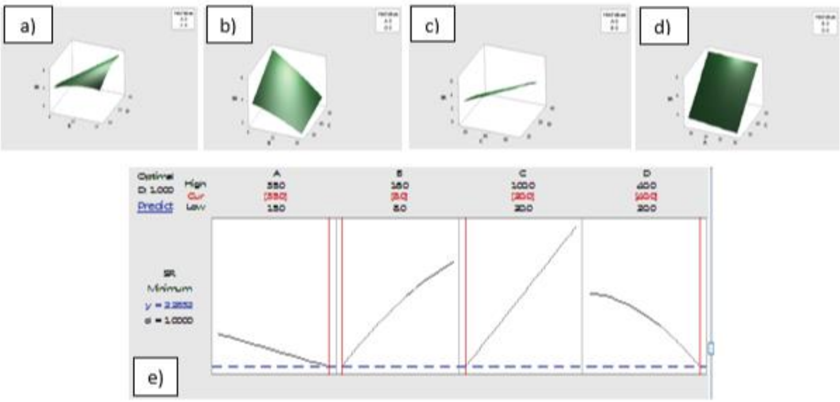


Figure 5: a) Current vs Pulse off time, b) Current vs Pulse on time, c) Ton vs Toff, d) voltage vs Pulse on time, e) Optimum plots of SR

Table 6: Analysis of Variance for SR

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	10	10.7031	99.35%	10.7031	1.07031	243.65	0.000
Linear	4	8.7309	81.04%	1.3827	0.34567	78.69	0.000
A	1	0.4256	3.95%	0.1733	0.17334	39.46	0.000
B	1	0.0560	0.52%	0.0129	0.01294	2.95	0.105
C	1	7.4892	69.52%	0.5805	0.58045	132.14	0.000
D	1	0.7600	7.05%	0.0003	0.00033	0.08	0.786
Square	2	0.5246	4.87%	0.5246	0.26232	59.72	0.000
B*B	1	0.0955	0.89%	0.1881	0.18815	42.83	0.000
D*D	1	0.4292	3.98%	0.4292	0.42918	97.70	0.000
2-Way Interaction	4	1.4476	13.44%	1.4476	0.36189	82.38	0.000
A*C	1	0.0380	0.35%	0.0380	0.03803	8.66	0.010
B*C	1	0.5929	5.50%	0.5929	0.59290	134.97	0.000
B*D	1	0.8010	7.44%	0.8010	0.80103	182.35	0.000
C*D	1	0.0156	0.15%	0.0156	0.01563	3.56	0.078
Error	16	0.0703	0.65%	0.0703	0.00439		
Lack-of-Fit	14	0.0634	0.59%	0.0634	0.00453	1.32	0.513
Pure Error	2	0.0069	0.06%	0.0069	0.00343		
Total	26	10.7734	100.00%				
S	0.203569					R-sq	98.11%
Press	0.0662782					R-sq(adj)	99.35%
						R-sq(pred)	98.94%

5.3 Effect of process parameters on TWR

The ANOVA table 7 of TWR is shown below. The model F value of 70.86 indicates that the model is significant. From the ANOVA table it was shown that A, B, C, A^2, C^2 are significant model terms was shown in table 7. The multiple regression coefficient (R^2) is calculated to identify whether fitted model expresses the observed value. The R^2 of 94.40% is in reasonable agreement with the Adj R^2 of 90.6

Regression Equation for TWR is equation (5)

In terms of actual factors, final second order regression equation for the performance characteristic of TWR for the process parameters can be expressed by the following equation 5.

$$TWR = -1.352 + 0.0507\ A + 0.10521\ B + 0.01812\ C - 0.001328\ A*A - 0.000133\ C*C \quad (5)$$

It was shown from the following Figure 6(a) indicates that with increase in current and pulse on time TWR increases. More discharge energy occurs when the high current passed through the electrode results in the increase of TWR. Due to the fact that Tungsten-Copper electrode has high thermal conductivity than any other tool material, so it generates more heat during machining time. Figure 6(b) and 6(c) shows the effect of voltage and current on TWR. The figure depicts that for each level of voltage with increase in current there is increase of TWR. At highest values of voltage TWR is low.

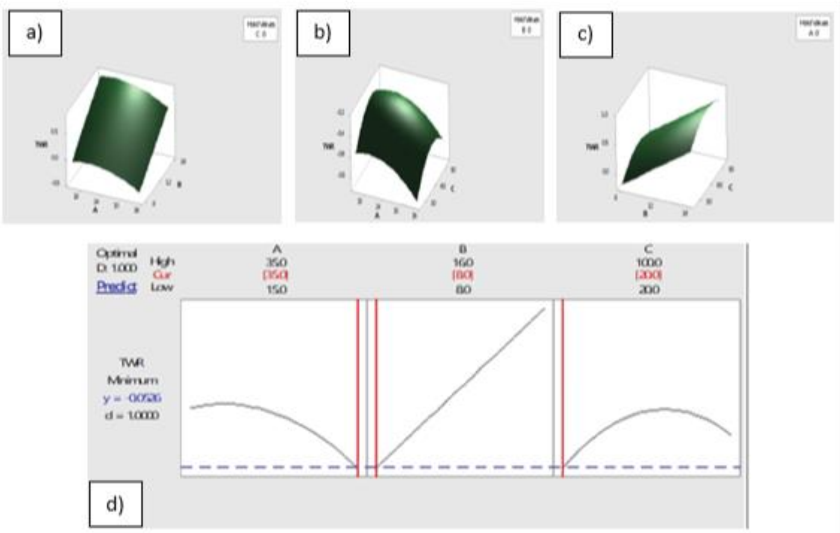


Figure 6: a) voltage vs current, b) voltage vs ton, c) current vs ton, d) optimum plots of TWR

Table 7: Analysis of Variance for TWR

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	5	2.85490	94.40%	2.85490	0.57098	70.86	0.000
Linear	3	2.51157	83.05%	2.49804	0.83268	103.34	0.000
A	1	0.29494	9.75%	0.06452	0.06452	8.01	0.010
B	1	2.12511	70.27%	2.12511	2.12511	263.73	0.000
C	1	0.09152	3.03%	0.35263	0.35263	43.76	0.000
Square	2	0.34333	11.35%	0.34333	0.17167	21.30	0.000
A*A	1	0.05440	1.80%	0.11291	0.11291	14.01	0.001
C*C	1	0.28893	9.55%	0.28893	0.28893	35.86	0.000
Error	21	0.16921	5.60%	0.16921	0.00806		
Lack-of-Fit	19	0.15240	5.04%	0.15240	0.00802	0.95	0.630
Pure Error	2	0.01681	0.56%	0.01681	0.00841		
Total	26	3.02411	100.00%				
S	0.0897653					R-sq	94.40%
Press	0.282728					R-sq(adj)	93.07%
						R-sq(pred)	90.65%

5.4 Surface characteristics

It was observed from top surface of the figure that globules of debris, large and small melted drops, pocket marks, overlapped craters are produced as shown in the figure. During discharge of spark in the machining gap the particles are eroded, and crater is formed. As huge amount of heat is generated in spark gap the eroded particles are melted and flushes away in the dielectric fluid. However due to insufficient flushing pressure all the particles are not removed from the machined area. At pulse off time as there is no spark occurs, the molten material resolidifies forming the debris on the work piece surface. Figure 7 show the EDM-machined surfaces with the Highest (MRR (a)=41.425mm3/min and Ra(b)=3.54µm). In EDM process particles are eroded and attached to the material surface and the molten material at the machining gap gets expelled randomly.

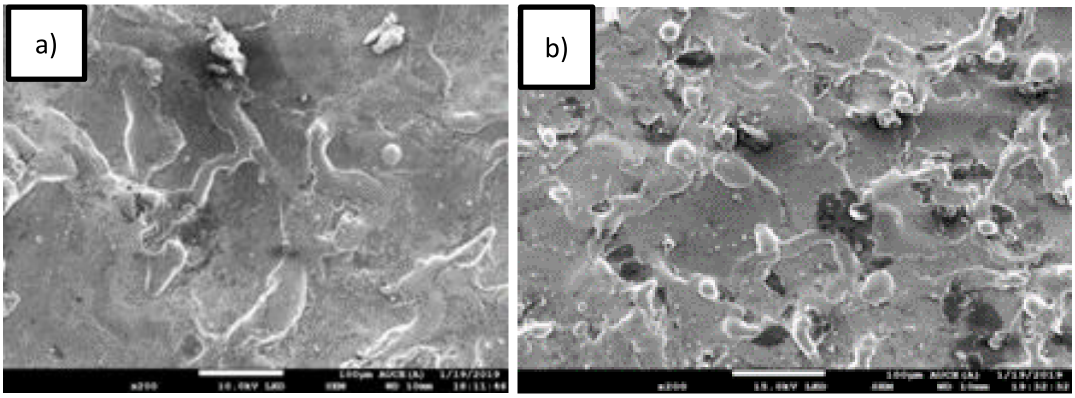
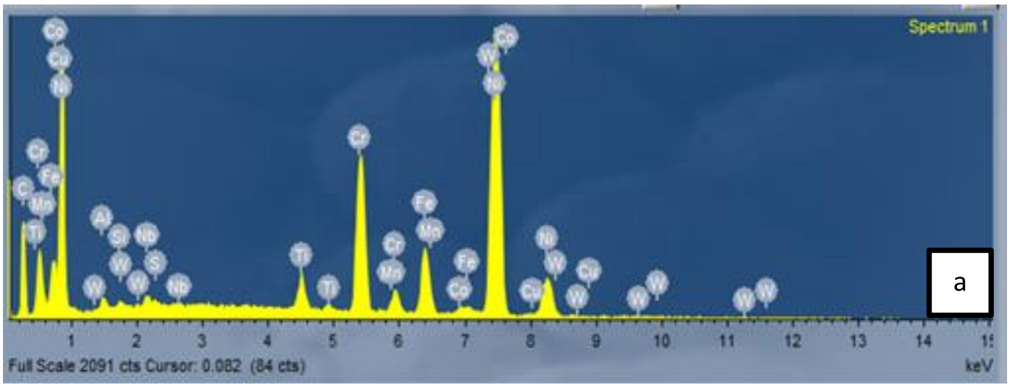


Figure 7: a) SEM micrographs of Maximum MRR, b) SEM micrographs of minimum SR

5.5 EDX analysis

According to the energy levels the elements presents in the recast layer are identified with their peaks as shown in the Figure 8. Based on the figure the energy level values found the tungsten is clearly observed and found compared to the base material. The metal particles during spark erosion moves from electrode to workpiece and gets deposited on the machined surface. The percentage of energy levels of different elements at different locations are shown and tabulated. It was identified that the percentage of carbon is more than that of the elements detected in minimum surface roughness. The element tungsten is detected in the Table 8 with maximum MRR as the migration of particles in the machining zone moves and deposited on the work piece surface which is affected with the machining parameters such as discharge current, pulse on time and pulse off time. EDX analysis of minimum SR is shown in table 9.



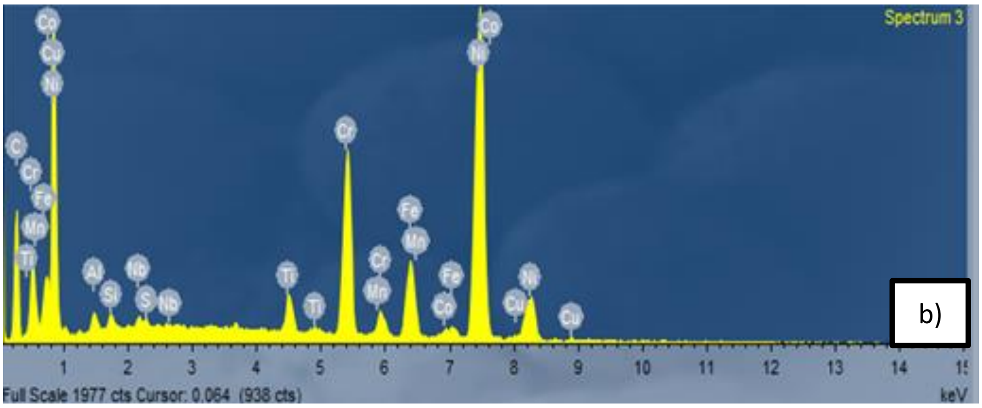


Figure 8: a) EDX analysis at maximum MRR, b) EDX analysis at minimum SR

Table 8: EDX analysis of maximum MRR

Element	Weight%	Atomic%
C K	60.41	65.78
Al K	1.07	0.52
Si K	0.41	0.19
S K	0.07	0.03
Ti K	3.75	1.02
Cr K	24.58	6.18
Mn K	0.23	0.05
Fe K	13.40	3.14
Co K	1.75	0.39
Ni K	100.52	22.39
Cu K	0.09	0.02
Nb L	1.89	0.27
W M	0.42	0.03
Total	208.58	

Table 9: EDX analysis of minimum SR

Element	Weight%	Atomic%
C K	67.60	68.66
Al K	1.25	0.57
Si K	0.92	0.40
S K	0.19	0.07
Ti K	3.75	0.95
Cr K	23.95	5.62
Mn K	0.17	0.04
Fe K	13.19	2.88
Co K	1.26	0.26
Ni K	97.25	20.21
Cu K	0.60	0.12
Nb L	1.69	0.22
Total	211.83	

5.6 Multi objective optimization on the basis of ratio analysis (MOORA)

Multi attribute optimization or multi response optimization is the process of optimizing two or more objectives with different constraints. To solve various types of complex decision-making problems in the manufacturing industry MOORA is found to be the most appropriate method in terms of accuracy and quick computational time. The MOORA method was applied to find out the best optimum parameters for machining. The methodology of the present research is done in the following steps

Step1: Formation of a decision matrix consisting of all alternatives in combination with their corresponding outcomes.

$$X = \begin{pmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{pmatrix} \qquad (6)$$

where, x_{ij} = Performance measure of the *i*th alternative on *j*th attribute. *m* = number of alternatives and *n* = number of attributes.

Step 2: Development of a ratio system for each alternative. This can be done by normalizing the data sets of the decision matrix. The normalization can be performed using the following formula

$$x_{ij}^{*} = \frac{x_{ij}}{\sqrt{\sum_{i=j}^{m} x_{ij}^{2}}} \qquad (7)$$

where, x_{ij}^{*} = Normalized value of the *i*th alternative on *j*th and lies between 0 to 1.

Step 3: Evaluation of overall assessment value

After calculating the normalized performance measures in the third step these are added together for larger is better or beneficial criterion and subtracted for lower is better or non-beneficial criterion. The following equation 9 shows the overall assessment of performance measures.

$$y_i = \sum_{j=1}^{g} x_{ij}^{*} - \sum_{j=g+1}^{n} x_{ij}^{*} \qquad (8)$$

Calculation of overall assessment value using equation as given below

$$y_i = \sum_{j=1}^{g} w_j x_{ij}^{*} - \sum_{j=g+1}^{n} w_j x_{ij}^{*} \qquad (9)$$

where, w_j known as the weight of j^{-th} criterion.

Step 4: Assign ranking to overall assessment

Finally, in descending order we sorted the Overall Assessment value. The alternative having the highest assessment rank is the best alternative. Evaluation of overall assessment value and rank of MOORA is shown in table 12.

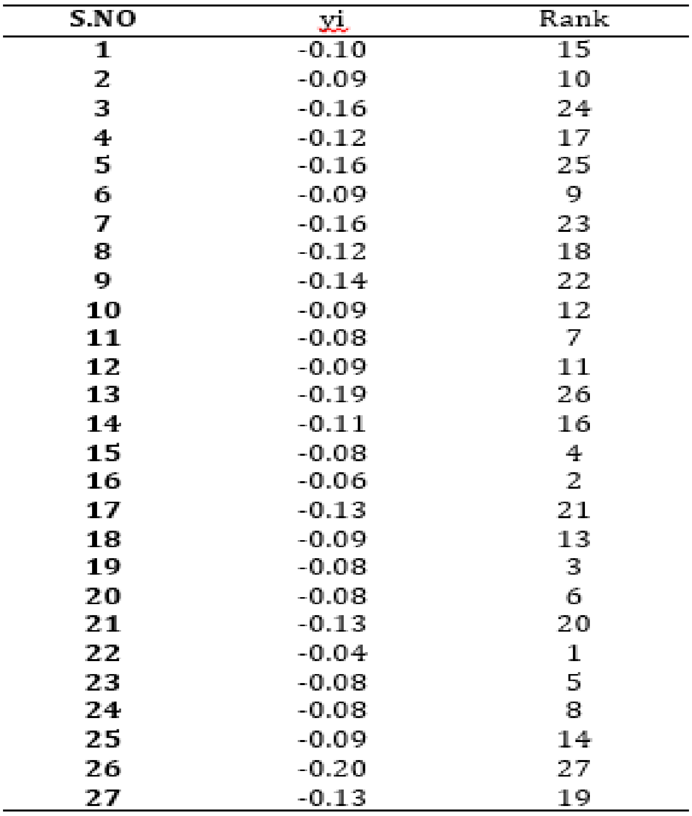
Table 10: Sum of squares of standard decision matrix

S.NO	MRR^2	SR^2	TWR^2
1	1636.45	24.80	0.73
2	624.50	26.21	0.25
3	1715.95	21.72	2.68
4	644.04	33.06	0.47
5	798.57	25.20	1.82
6	602.95	19.18	0.34
7	1135.42	26.21	1.93
8	135.05	13.32	0.69
9	1136.03	21.34	1.54
10	392.24	21.62	0.27
11	454.59	33.18	0.05
12	821.62	23.91	0.38
13	812.14	22.85	3.11
14	167.29	26.32	0.23
15	57.93	18.66	0.05
16	930.19	21.62	0.11
17	237.65	31.70	0.44
18	213.57	14.90	0.34
19	358.27	19.10	0.15
20	515.52	12.89	0.41
21	875.39	23.72	1.04
22	209.53	12.53	0.01
23	723.23	17.89	0.36
24	208.46	23.62	0.10
25	32.32	33.87	0.01
26	1040.51	18.92	3.94
27	287.10	15.84	0.91

Table 11: Normalization of performance measures

S.NO	MRR	SR	TWR
1	0.31	0.20	0.19
2	0.19	0.21	0.11
3	0.32	0.19	0.37
4	0.20	0.23	0.16
5	0.22	0.20	0.31
6	0.19	0.18	0.13
7	0.26	0.21	0.32
8	0.09	0.15	0.19
9	0.26	0.19	0.28
10	0.15	0.19	0.12
11	0.17	0.23	0.05
12	0.22	0.20	0.14
13	0.22	0.19	0.40
14	0.10	0.21	0.11
15	0.06	0.18	0.05
16	0.24	0.19	0.07
17	0.12	0.23	0.15
18	0.11	0.16	0.13
19	0.15	0.18	0.09
20	0.18	0.15	0.15
21	0.23	0.20	0.23
22	0.11	0.14	0.02
23	0.21	0.17	0.14
24	0.11	0.20	0.07
25	0.04	0.24	0.02
26	0.25	0.18	0.45
27	0.13	0.16	0.22

Table 12: Evaluation of overall assessment value of MOORA



S.NO	yi	Rank
1	-0.10	15
2	-0.09	10
3	-0.16	24
4	-0.12	17
5	-0.16	25
6	-0.09	9
7	-0.16	23
8	-0.12	18
9	-0.14	22
10	-0.09	12
11	-0.08	7
12	-0.09	11
13	-0.19	26
14	-0.11	16
15	-0.08	4
16	-0.06	2
17	-0.13	21
18	-0.09	13
19	-0.08	3
20	-0.08	6
21	-0.13	20
22	-0.04	1
23	-0.08	5
24	-0.08	8
25	-0.09	14
26	-0.20	27
27	-0.13	19

6.CONCLUSIONS

In this paper the essential machining parameters for performance measures like MRR, SR and TWR was identified and analysed with the EDM process. RSM Box-Behnken design of experiments is used to obtain optimum parameter combination for higher rate of MRR and lower level of surface roughness. Multi objective optimization using MOORA is used to determine optimal set of process parameters. The results obtained from the present study is extremely useful for selecting the optimum machining conditions for Inconel X-750 alloy, the following conclusions are drawn.

- The current is most important process parameter affecting the MRR and TWR. However, it has also effect on SR. Pulse on time has most significant effect on SR, the effect of current and pulse on time on SR and TWR is also more significant than their individual effect.
- The optimum process parameters (Voltage 35v, Current 16 amps Pulse on time 100µs, Pulse off time 40 µs) yielding maximum MRR value at 44.780 mm3/min and corresponding values of R^2 and R^2 (pred.) 0.9749.
- The MOORA with highest rank determines the optimum combination of input parameters, out of all experiments the alternative having the highest assessment value is the best combination of process parameter.
- In MOORA the highest value of yi represents the best alternative whereas the lowest value of yi represents the worst.
- The optimum values identified using MOORA are MRR=14.4, SR=3.54, TWR=0.084
- SEM analysis shows the surface characteristics of the machined specimen having globules of debris, large and small melted drops, pocket marks, overlapped craters
- EDX analysis reveals the increase of carbon content for the machining performance having highest MRR than that of lowest SR experimental values

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