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An Effort for Maximizing the Material Removal Rate During the Wire Cutting of Difficult to Machine Inconel X750 Using Electric Discharge Machining Process

Yogesh Shrivastava[1]*, Pawan Kumar Arora[2], Harish Kumar[3]

Abstract

The growing demand for harder materials with exceptional hardness poses a significant challenge for industries as achieving precise machining becomes increasingly tricky. The Inconel family of materials, renowned for their hardness, has been extensively studied. However, with the continuous introduction of new materials, the scope of research remains vast. In this context, Inconel X750, a corrosion and oxidation resistance, nickel-chromium-based alloy with excellent hardness, has gained attention. Despite its significance, there is limited research on processing Inconel X750 using Wire Electrical Discharge Machining (WEDM). To address this gap, the present work focuses on cutting nickel-chromium alloy using brass wires and WEDM. The objective is to examine the influence of various WEDM process parameters, including Pon/off timing and current, on the Material Removal Rate by identifying the ideal set of process parameters to maximize the MRR. From the results, a suitable range of machining parameters has been determined. The obtained capacity to input parameters are Pon (100–110 µS), Poff (55–63 µS), and current (10–12 A). The findings of this study will contribute to enhancing the machining efficiency of difficult-to-machine materials, offering valuable insights to industries seeking to overcome challenges associated with precise machining in the pursuit of more rigid materials.

Keywords: WEDM; Inconel X750; Modeling; Optimization; Machining

INTRODUCTION

Inconel X750, a high-performance superalloy, has gained prominence due to its exceptional properties and versatility. Chosen for its remarkable attributes, this alloy finds applications across various industries and offers promising prospects. Inconel X750's popularity is attributed to its outstanding properties, including High-Temperature Resistance: Inconel X750 excels in high-temperature environments, making it ideal for gas turbines and rocket engines. Corrosion Resistance: It resists corrosion in harsh conditions, benefiting aerospace, chemical, and marine industries. Mechanical Strength: With high tensile strength, it's used in load-bearing components like springs and fasteners. Creep Resistance: It withstands deformation under long-term, high-temperature loads and is valuable in nuclear reactors and heat exchangers. Machining of materials that are hard to cut is always a vital component that has been studied by numerous researchers throughout the years [1–8]. Several researchers have reported that the MMR of the difficult-to-cut material is always lower. To increase the MRR, a lot of work has been done. Scott et al. [9] have developed a multi-objective optimization problem and its solution for selecting the optimal WEDM machine parameter values. MRR and surface quality served as the

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model's performance indicators. A factorial design approach has been employed to project outcomes due to several machining parameters. Rajurkar and Wang. [10] used a thermal model to analyze the phenomenon of wire rupture. An intensive experimental examination has been conducted to ascertain how the study's machining parameters affect the outputs of machining performance, namely MRR and surface finish.

Tosun and Co-gun [11] investigated how machining parameters impacted the wire wear ratio based on wire weight loss in WEDM. Tosun et al. created a statistical technique to choose the optimal WEDM machining settings for wire craters with the lowest practical size. Kumar Mohanty et al. [12] investigated nine different balanced experiments that make up the studied EDM performance for multi-response optimization using the VIKOR technique following Taguchi-based design of experiments. The assumptions MRR, TWR, SR, and RO were the machining performance metrics. The ANOVA findings show that the framework is workable and that the current has the most influence (74.82%) on the preferred solution value. Multi-criteria decision-making (MCDM) problems have a better application potential with the VIKOR technique. Mishra and Routara. [13] Examined Grey relation grade (GRG), an objective function, was created by combining machining performances. The most important element determining assessment value was found using an ANOVA. Pulse time (Ton) and peak current (Ip), with respective discounts of 46% and 34%, are the two most important variables, followed by flushing pressure (FP). Toff, Ton, and Ip each have a 31%, 31%, and 45% impact on the tool wear rate. The EDM process parameters were optimized using the suggested GRA-based Taguchi technique, and the results were satisfactorily confirmed. Anand et al. [14] conducted magnetically-assisted EDM studies and contrasted the results to the GRA-based Taguchi method and conventional EDM with copper as the tool element. The optimal setting raised MRR by 41.42% and decreased SR by 2.17%, according to the results. The default setting was 15 amps—tone 150 µs, voltage 85 volts, servo voltage 30%. EDM significantly improves MRR and SR. Prasanna et al. [15] employed an AA7075-Si-C alloy work substance, a copper tool, and kerosene oil as the dielectric medium to perform the EDM process. The MRR is used to measure EDM performance. The possibility of assigning a priority weight to a specific response was investigated using PCA. The machining results demonstrate how directly dependent MRR is on the present values. The confirmatory test shows the effective machining response to accomplish the intended outcome. Khullar et al. [16] used the RSM approach with the NSGA-II. Experiments were created utilizing the RSM technique with a core composite design, and an ANOVA test was run on the input parameter. According to the prime parameters, MRR and SR are 1.167 mm3/min and 1.280 m, respectively. The findings indicate that the Pon measurements of 31.1% and Poff values of 30.49% had the most considerable impact on MRR. Cogun et al. [17] conducted many trials to examine tool electrode wear in EDM die sinking under various machining settings. Haron et al. [18] discovered a potential relationship between the machinability parameters (material removal rate and electrode wear) and the EDM parameter (discharge current). Yilmaz et al. [19] employed fuzzy sets (triangular-shaped) and expert guidelines for each machining level to use fuzzy logic to correlate the EDM parameters. Aditya Kumar et al. [20] Taguchi technique The influence of wire EDM settings on material removal rate and surface roughness was investigated. Built a mathematical model for hybrid genetic algorithm simultaneous optimization and suggested a process parameter. Arshad Noor Siddiquee et al. [21] research centered on reducing surface roughness by adjusting deep drilling settings of a CNC lathe machine using a solid carbide cutting tool on AISI 321 austenitic stainless steel.. Using the Taguchi L18 orthogonal array as the experiment design, this method substantially enhanced the surface finish for the deep drilling operation. Srinivasa Rao et al. [22] investigated a hybrid method for submerged arc welding; a combination of Grey, fuzzy, and Taguchi techniques was used, and a TiO_2-Al2O_3-CaO flux system was used for the investigation. The experimental data from three separate characteristics were integrated this way, and the performance index increased by 15.72 at 34 volts and 11% at 32, respectively. S. Assarzadeh et al. [23] Using a statistical method in planned machining, they simulated and optimized process parameters in EDM of tungsten carbide-cobalt composites utilizing cylindrical copper tool electrodes. The experiments were designed and analyzed using the response surface method. They discovered that the rate and amount of discharge energy influenced all responses, albeit in a contentious way. Chen et al. [24] used the Taguchi design method to fine-tune the EDM process settings for cutting the aluminum alloy A6061-T6. The analysis of means and analysis of variance techniques are used to assess the relative effects of each parameter on the SR to examine the experimentation data and establish the best machining settings.

Nikalje et al. [25] worked to assess how process variables impacted the optimization of MDN 300 steel in EDM, and the Taguchi technique was applied. The results showed that while the optimal values of components of TWR and SR were similar, they were not identical to those for MRR and RWR. SEM was used to analyze the structural characteristics of the machined surface and determine how parameters affected the results. Dhanabalan et al. [26], utilizing brass electrodes, investigated the effects of various parameters on the MRR, TWR, and SR for two different grades of titanium. He also discussed the multi-objective optimization for the orthogonal array-based EDM approach utilizing Grey relational analysis. Fionava et al. [27] investigate the impact of the material's propensity for corrosion on the structure change in Inconel 601 caused by heat treatment. It has been discovered that the sensitizing time at a temperature of 700°C determines the corrosion behavior in a sulphuric acid environment. Mohanty et al. [28] examine the differences in machining performance between copper, brass, and graphite electrodes when working with Inconel 718 superalloy. Surface roughness, MRR, radial overcut, and TWR have been selected as the output parameters for this study. It was discovered that using a graphite tool can increase MRR, but the high discharge energy harms radial overcut and surface roughness. Additionally, brass tool electrodes can be utilized for superior surface integrity, but they offer less MRR. When compared to tools made of copper and brass, graphite offers less TWR. Dhar et al. [29] determine how the air gap voltage, current, and Pon time affect the EWR, MRR, and radial overcut in the EDM of the Al-4Cu-6Si alloy-10wt% SiCp composite. EWR, MRR, and radial overcut were discovered to rise dramatically as the current rose, whereas MRR and ROC increased as pulse duration increased. Gap voltage was likewise shown to have minimal impact. Agarwal et al. [30] conducted empirical WEDM process parameter modeling on Inconel 718 using RSM. Peak current, Poff time, wire tension, spark gap voltage, wire feed rate, and Pon time are the parameters that are used as input variables. The surface roughness and cutting rate of the input parameters are determined. Unune et al. [31] outlined how random elements in electric discharge machining (EDM) performance cause inconsistent material removal in each discharge. V. R. Srinivasn et al. [32] Analysis of Inconel 600's surface integrity properties. In that work, trials were carried out utilizing Taguchi's L9 orthogonal array, and the best machining parameters for minimizing surface roughness were discovered. Hewidy et al. [33] generated an empirical relationship using the WEDM process parameters of Inconel 601 to assess the material removal rate and surface quality. Bikash Choudhuri et al. [34] discovered that the model predicted by ANN was superior to RSM in a comparative modeling and multi-objective optimization study on H21 tool steel utilizing an intelligent hybrid approach. To optimize the process parameters of the WEDM process, the model developed by ANN was eventually combined into a swarm of particle optimization (PSO) technique. Bijaya bijeta nayak [35] analyzed deep cryo-treated Inconel 718 and WEDM machining parameters. The parametric optimization was carried out utilizing the BAT technique employing an Artificial Neural Network (ANN) model that was created. Bobbili et al. [36] Pon, Poff, and SV are the most important variables in obtaining MRR and SR, according to an analysis of the WEDM parameters caused by high-strength armor steel. Kupan et al. [37] examined the EDM properties in Inconel 718 deep hole drilling. Peak current, Pon time, electrode rotation, and duty factor are the input parameters, while MRR, SR, TWR, and through hole are the performance parameters. They emphasized that larger MRR and lower SR were found with lower tool electrode settings. Sandhu et al. [38] observed that (-)ve-polarity graphite electrodes produce higher MRR. Agarwal et al. [30] created empirical models using the RSM approach to predict the cutting rate and surface hardness when milling Inconel 718. Anil Kumar et al. [39] have used a one-variable-at-a-time strategy to examine the effects of input factors on the machining characteristics of Inconel 718 aluminum AEDM with copper electrodes. It has been noted that particle size and concentration have an impact on the effectiveness of machining. Manohar et al. [40] investigated The effect of changing electrode bottom profiles on Inconel 718 EDM machining. According to experimental results, in terms of MRR, surface roughness, and RCL thickness, convex profile electrodes outperform concave and flat profile electrodes produced. Flat-design electrodes are preferred over convex and concave electrodes in EWR. MuthuKumar et al. [41] investigated response surface approaches for ROC prediction in Incoloy 800 copper electrode electrical discharge machining. By taking into account ROC response, they concluded that ANOVA, according to the data, current and voltage are significant characteristics; however, pulse-on and pulse-off time are not. Hewidy et al. [33] simulated the machining parameters for Inconel 601 wire electrical discharge mining, which were calculated using RSM. Investigations were done into how input parameters affected the metal removal rate, wear ratio, and surface roughness. These variables included peak current, duty factor, wire tension, and water pressure. They found that as peak current value and water pressure increased, the volumetric metal removal rate rose. According to this tendency, which was true before the advent of arcing, the wear ratio increases with an increase in peak current and reduces with an increase in duty factor and wire tension. Peak current increases cause the MRR to decrease after a certain threshold.

After conducting a vast literature review on the use of Inconel X750 in wire electrical discharge machining (WEDM), several key findings emerged:

Inconel X750 is a challenging material to machine due to its high hardness, strength, and temperature resistance.

WEDM is a suitable machining process for Inconel X750 because it does not generate heat-affected zones or residual stresses in the material, which can compromise its properties.

EDM wire selection is critical for machining Inconel X750. Copper or brass wires are commonly used due to their excellent electrical conductivity and thermal stability. However, the piece should consider wire diameter, material composition, and tensile strength to minimize wire breakage during machining.

The input variables like pulse duration and peak current significantly impact Inconel X750 machining efficiency in WEDM.

Deionized water as a dielectric fluid has been observed to improve the material removal rate in Inconel X750 WEDM.

More work needs to be reported related to using statistical methods for optimizing the process parameters of WEDM during the cutting of Inconel X750.

These key findings provide insights into the challenges, parameters, and strategies associated with WEDM of Inconel X750, highlighting the importance of process optimization for successful machining of this challenging material.

The objectives of the work are to process the problematic cut material, i.e., Inconel X750, using wire EDM and to optimize the process parameters for maximum material removal rate. During the optimization of the process parameters, the feasibility of the obtained solutions has also been checked to eliminate constraints during the optimization of quality characteristics.

METHODOLOGY

In order to understand the methodology, a flow chart has been drawn as shown in Figure 1

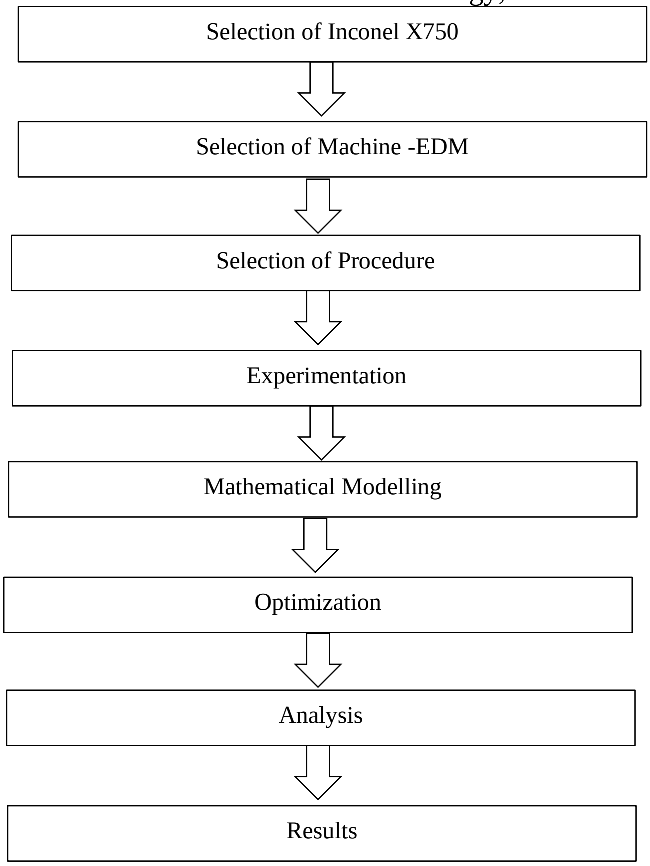

Figure 1. Flow chart.

EXPERIMENTATION

Material

Inconel X-750 is a precipitative-hardening nickel-chromium alloy. It stands out for having great high-temperature strength, decent corrosion resistance, and the capacity to sustain thermal fatigue.

The alloy is strengthened by heating the alloy to a high temperature to dissolve the alloying elements and then chilling the alloy to allow the components to form a fine, coherent precipitate inside the matrix. Gamma prime (') and gamma double prime (") phases combine to produce the alloy's microstructure, giving it great strength and resistance to deformation at high temperatures. Inconel X-750 is also well recognized for its resistance to creep, a material's propensity to distort over time, and at high temperatures under steady stress. This feature is essential for aerospace and power generation applications, where components are subjected to increased pressure and temperatures for prolonged periods.

Inconel X-750 offers outstanding mechanical qualities and good corrosion resistance in various conditions, including saltwater and seawater, acidic and alkaline solutions, and both. This qualifies it for usage in chemical processing and marine conditions. The alloy may be produced and machined using conventional methods, albeit these tasks can be complex due to its high strength and hardness. For the Inconel X-750 to be welded without breaking or losing its mechanical qualities, specialized methods must be used. Inconel X-750 is a high-performance alloy with outstanding high-temperature strength, corrosion resistance, thermal fatigue resistance, and creep resistance. It is commonly employed in applications requiring dependable performance at high temperatures and in corrosive environments, such as aerospace, power generation, and chemical processing.

The nickel-chromium alloy Inconel X-750 has excellent oxidation and corrosion resistance at high temperatures. It is best suited for high-temperature applications, including gas turbines, nuclear reactors, and aircraft engines because it maintains high strength and creep resistance. Table 1 shows the material's chemical composition, Inconel X 750. Table 2 shows the mechanical characteristics of the material Inconel X 750.

Process Parameters for WEDM

In the present work, pulse on time, pulse off time, and peak current have been chosen as input parameters. The selection of input parameters is based on the literature review. Other parameters have been kept constant during the processes. Moreover, the output parameter considered is Material Removal Rate (MRR) (mm^3/min). Table 3 shows the selected input parameters and their respective levels.

Moreover, in order to develop DoE, BBD has been used the develop DoE has been discussed below.

Box–Behnken Designs (BBD)

To optimize process parameters and study the relationship between multiple factors and their effects on the machining outcomes. The BBD design helps achieve two primary goals: response surface modeling and optimization. The experimental runs are performed, and the corresponding responses, i.e., material removal rate, have been measured. The collected data is then used to generate a mathematical model. The BBD-based DoE has been shown in Table 4.

Table 1. Chemical Proportion of Inconel X 750

Elements	Composition Percentage
Nickel (Ni)	74.4%
Chromium (Cr)	16.42%
Aluminum (Al)	0.55%
Manganese (Mn)	0.46%
Carbon (C)	0.049%
Silicon (Si)	0.28%
Iron (Fe)	8.02%
Sulfur (S)	0.008%
Titanium (Ti)	2.35%
Copper (Cu)	0.29%
Cobalt (Co)	0.26%
Niobium (Nb)	0.78%

Table 2. Mechanical Properties of Material Inconel X 750

Properties	Values
Tensile strength	1260–1415 MPa (183–205 ksi)
Melting point	1393–1427°C (2530–2600°F)
Density	8.28 g/cm^3
Yield strength	1035–1210 MPa (150–175 ksi)
Elongation	25–30%
Hardness	HRC 30–40

Table 3. Process Parameters

S.N.	Factor	Level 1	Level 2	Level 3
1	Pulse on time (P_{on})	100 (μS)	105 (μS)	110 (μS)
2	Pulse off time (P_{off})	55 (μS)	59 (μS)	63 (μS)

3	Current, I	10 (A)	11 (A)	12 (A)

Table 4. Box-Behnken Design based DoE

Exp. No.	P_{on} Time, PO (μS)	P_{off} Time, PF (μS)	Current, I (A)
1	105	59	11
2	105	63	12
3	110	55	11
4	100	59	10
5	110	59	10
6	105	55	10
7	105	63	10
8	105	59	11
9	105	59	11
10	100	63	11
11	110	63	11
12	110	59	12
13	100	55	11
14	105	55	12
15	100	59	12
16	105	59	11
17	105	59	11

Using the DoE as listed in Table 4, experiments have been performed. The picture of the actual EDM machine and workpiece has been shown in Figures 2 and 3, respectively. While performing the machining, following factors have been taken into consideration as mentioned in Table 5.

Figure 2. Wire EDM Machine.

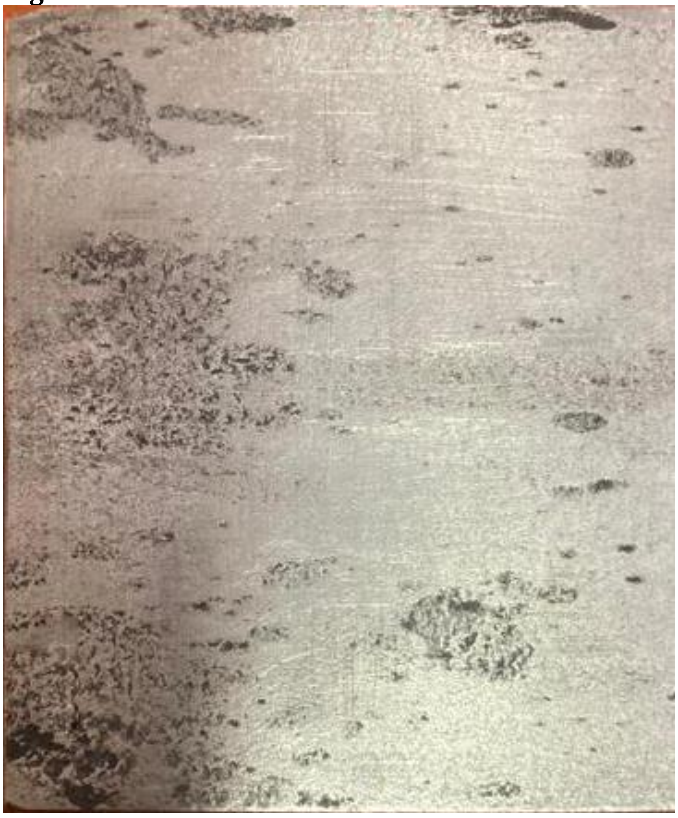

Figure 3. Workpiece before cut

Table 5. Constant Parameter

S.N.	Parameters	Value/Range
1.	EDM Machine	
2.	Electrode	Brass (diameter 0.25 mm)
3.	Pulse on time (P_{on})	105–110 (μS)
4.	Pulse off time (P_{off})	55–63 (μS)
5.	Current (A)	10–12
6.	Voltage (V)	50
7.	Stand of distance	0.5 mm
8.	Dielectric	Distilled water

The above-shown parameters were constant during the machining operations.

Electrical Discharge Machining (EDM): EDM is a precision machining process widely used in manufacturing to create intricate shapes and features in hard materials that are difficult to machine with traditional techniques. EDM uses electrical discharges to remove material, making it an essential process in aerospace, automotive, and toolmaking industries. To achieve optimal results, EDM relies on carefully controlled parameters and settings. In this article, the authors have delved into the critical parameters of EDM machining and explored the effects of varying these parameters on the machining process.

EDM Machine: The wire EDM setup available at the National Institute of Technology, Delhi, India, has been used for experimental work.

Electrode: For the present work, Brass electrodes with a diameter of 0.25 mm have been used. It is

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the most commonly used electrode specification.

Pulse on time (Pon): This parameter determines the duration of the electrical discharge. The range of values for Pon is 105–110 microseconds (μS). Longer pulse times allow for deeper material removal but may affect surface finish.

Pulse-off time (Poff): Poff is the interval between discharge pulses. It ranges from 55–63 microseconds (μS). A shorter Poff time can lead to faster machining but may also increase electrode wear.

Current (A): The electrical current used during EDM machining typically falls within the range of 10–12 Amperes (A). Higher currents produce more aggressive material removal but can generate additional heat and wear.

Voltage (V): A constant voltage of 50 volts (V) is often applied during EDM machining. This voltage helps maintain stable and controlled discharges.

Standoff distance: A standoff distance of 0.5 mm is maintained between the electrode and the workpiece. This distance ensures the stability and consistency of the machining process.

Dielectric: Distilled water is commonly used as the dielectric fluid in EDM machining. Dielectric fluids play a critical role in flushing away debris and managing heat during the process.

Output Parameter

Material removal rate (MRR) has been taken as a response parameter. It refers to the volume of material removed from a workpiece in a given period during a machining operation. It is an essential parameter in manufacturing and machining processes as it helps determine the efficiency and productivity of the procedure.

MRR is typically expressed in cubic units per unit of time, such as cubic millimeters per minute (mm^3/min) or cubic inches per hour (in^3/hr). The formula for calculating MRR is

$$\text{MRR}\ (\text{mm}^3/\text{min}) = \frac{\text{Initial Weight}\ (\text{mm}^3) - \text{Final Weight}(\text{mm}^3)}{\text{Time Taken (min)}}$$

To measure the material removal rate, first, we estimate the initial weight of the workpiece, then we make a single cut and again measure the final weight of the workpiece. This process is repeated seventeen times to calculate all the MRR of seventeen experiments. Table 6, mentioned below, shows the calculated value of MRR using the following process parameters: Pon time, Poff time, and current.

Figure 4 shows the image of Inconel X750 having 17 cuts for 17 sets of experiments as listed in Table 6.

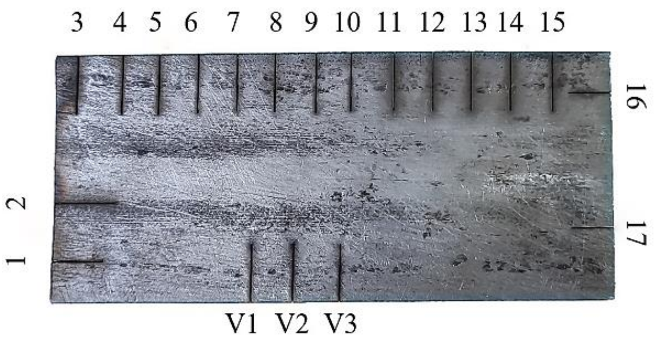

Figure 4. Workpiece after cuts.

Table 6. Calculated values of MRR

Exp. No.	P_{on} Time, PO (Micro sec)	P_{off} Time, PF (Micro sec)	Current, I (Ampere)	MRR (mm^3/min)
1	105	59	11	21.42
2	105	63	12	22.19
3	110	55	11	20.07
4	100	59	10	20.76
5	110	59	10	21.29
6	105	55	10	21.35
7	105	63	10	21.33
8	105	59	11	21.42
9	105	59	11	21.43
10	100	63	11	20.82
11	110	63	11	20.71
12	110	59	12	20.06
13	100	55	11	19.49
14	105	55	12	20.41
15	100	59	12	19.66
16	105	59	11	21.43
17	105	59	11	21.43

Table 7. R-sq values of the generated model

Standard Error (S)	R-sq	R-sq (adj)
0.307803	92.47%	82.78%

RESULTS AND DISCUSSION

For the given set of input conditions, experiments have been performed. The measured output is shown in Table 6. The obtained response values have been used to generate a mathematical model with the help of Response surface methodology (RSM). The summary of R-sq values of the developed model has been shown in Table 7. From the R-sq values, it is clear that the model is significant. Moreover, the analysis of variance has been discussed in the following subheading.

Analysis of Variance

ANOVA analysis has been done to identify the significance of the input parameters. The p-value shows the F-value's statistical significance. The F-value is the ratio of variation within groups to variance between groups. Table 8 Represents the Analysis of Variance. From the table, it can be noted that the input parameter, pulse off, is more significant.

Moreover. The residual plots for the analysis have been shown in Figure 5. Similarly, Figure 6 shows the Pareto Chart.

Mathematical Modeling

The model equation represents the mathematical relationship between the input factors (Peak Current, P_{on} Time and P_{off} Time) and the response variable MRR. It shows how the factors contribute to the predicted response.

$$MRR= -447.7 + 9.15\ PO + 0.80\ PF - 6.96\ A - 0.04062\ PO*PO - 0.00863\ PF*PF + 0.032\ A*A - 0.00862\ PO*PF - 0.0065\ PO*A + 0.1125\ PF*A$$

The equation needs to be optimized to determine the most suitable input parameters for maximum MRR. However, while optimizing the equation, the obtained combination of input parameters is not feasible, or it is difficult to use the exact value of input parameters due to the restriction of the minor count of the machine. Also, it has been found that several times, the obtained combination of input parameters cannot be used due to other machining constraints. Hence, several researchers advised and reported it to bring a feasible range of input parameters for which contour plots have been drawn using the equation. These contour plots have been examined to obtain the content of possible input parameters. Figure 7 to Figure 9.

Table 8. ANOVA Table

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	8.14073	0.90453	9.55	0.004
Linear	3	2.70549	0.90183	9.52	0.007
PO	1	0.24043	0.24043	2.54	0.155
PF	1	1.73848	1.73848	18.35	0.004
A	1	0.72658	0.72658	7.67	0.028
Square	3	4.49842	1.49947	15.83	0.002
PO*PO	1	4.33922	4.33922	45.80	0.000
PF*PF	1	0.08037	0.08037	0.85	0.388
A*A	1	0.00445	0.00445	0.05	0.835
2-Way Interaction	3	0.93682	0.31227	3.30	0.088
PO*PF	1	0.12074	0.12074	1.27	0.296
PO*A	1	0.00478	0.00478	0.05	0.829
PF*A	1	0.81130	0.81130	8.56	0.022
Error	7	0.66320	0.09474		
Lack-of-Fit	3	0.66311	0.22104	9525.07	0.000
Pure Error	4	0.00009	0.00002		
Total	16	8.80393			

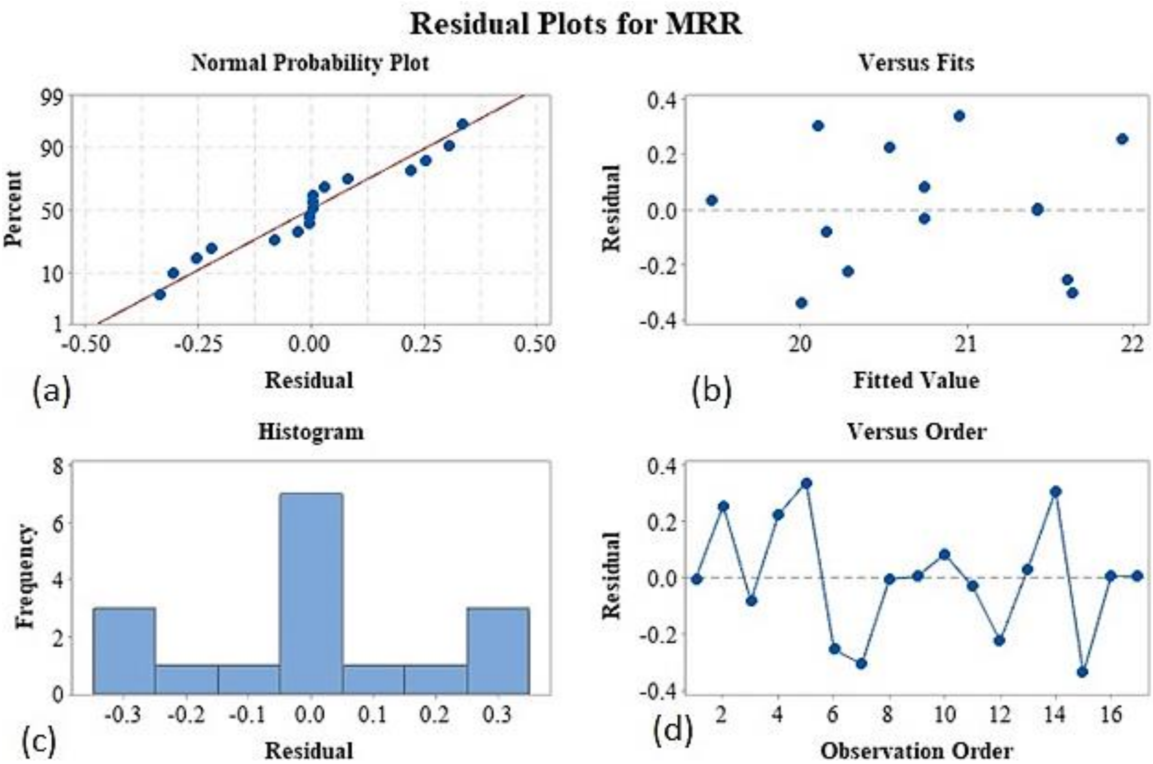

Figure 5 Residual plots of MRR, (a) Normal probability plot (b) Residual versus fitted value plot (c) Histogram (d) Residual versus observed value plot.

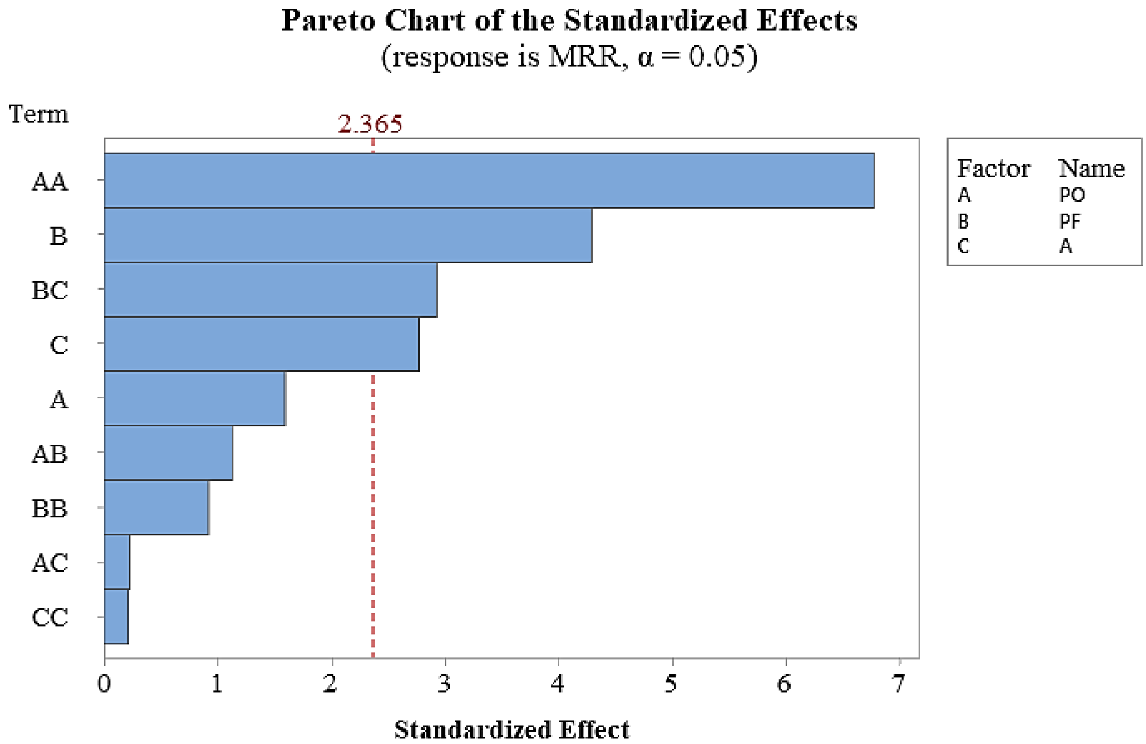

Figure 6. Pareto Chart of the Standardized Effects.

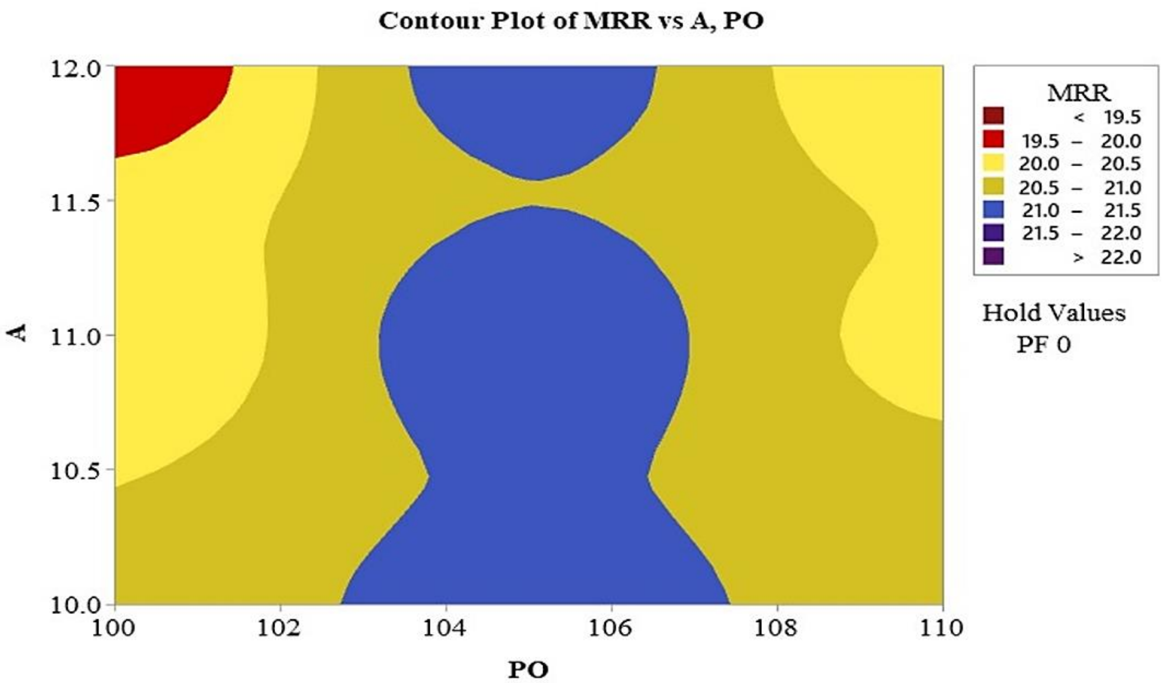

Figure 7. Contour Plot of MRR vs P_{on} time, P_{off} time.

A contour plot is a graphical depiction of a three-dimensional surface on a two-dimensional plane. The contour plot displays the relationship between the Material Removal Rate (MRR) and input parameters, taking two at a time. In the scheme shown in Figure 7, the red color indicates the minimum value of MRR, and the violet color indicates the maximum value of MRR. The yellow region offers a moderate MRR value. From the plot, a range of PO and PF has been selected for full MRR, as shown in Table 9.

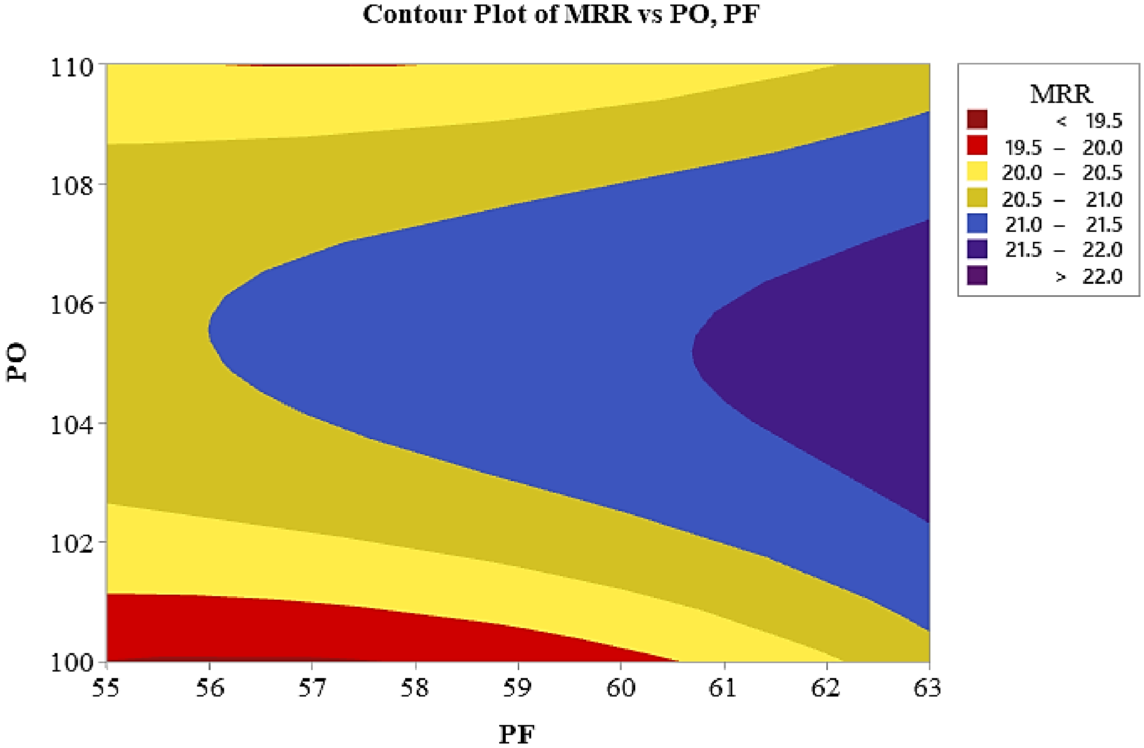

Figure 8. Contour Plot of MRR vs Current, P_{off} time.

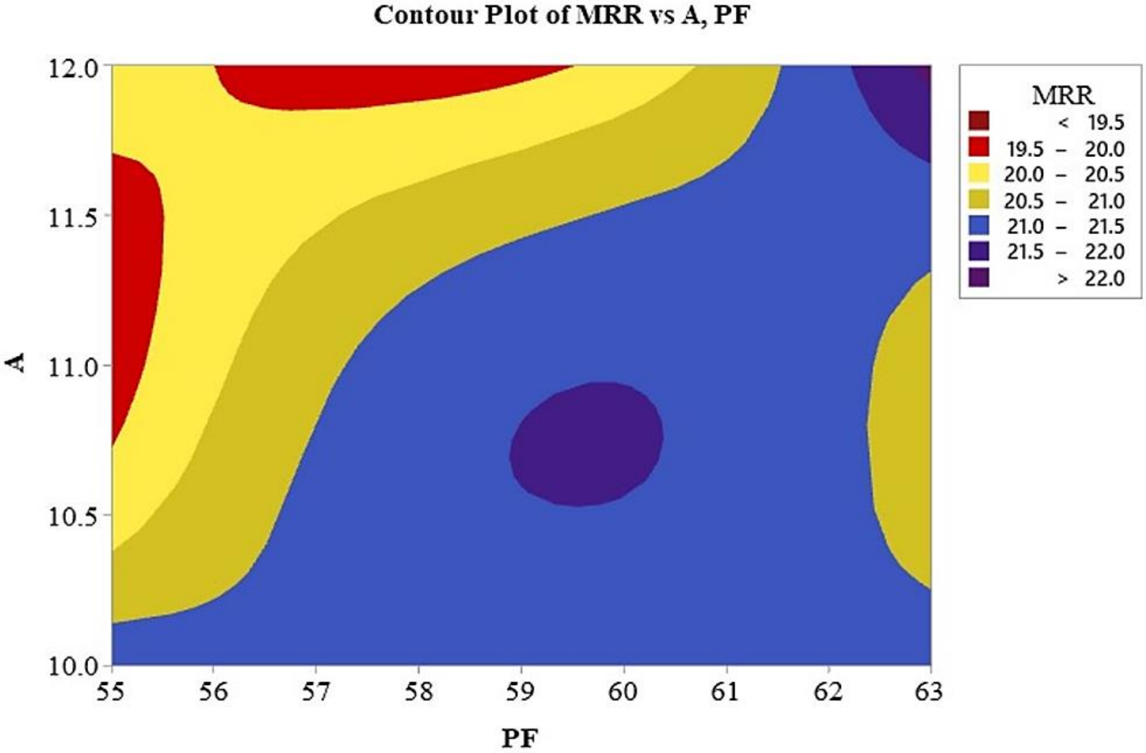

Figure 9. Contour Plot of MRR vs current, P_{off} time.

Table 9. Contour Plot of MRR vs P_{on} time, P_{off} time

Parameter	Range
P_{on} time (PO)	103–107
P_{off} time (PF)	60–63

Table 10. Contour Plot of MRR vs Current, P_{off} time

Parameter	Range
P_{off} time (PO)	103–107
Current (A)	10–11.4

Table 11. Contour Plot of MRR vs current, P_{off} time

Parameter	Range
P_{off} time (PF)	57–62
Current (A)	10–11.3

Table 12. Intersection of plots

Parameter	Range
PO	103–107
PF	60–62
A	10–11.3

Table 13. Validation of experiment

Parameter	Validation experiment 1	Validation experiment 2	Validation experiment 3
PO	103	104	104
PF	60	61	62
A	10	11	11
MRR	21.9	22.1	22.2

In the contour plot shown in Figure 8, the red color indicates the minimum value of MRR, and the violet color indicates the maximum value of MRR. The yellow region offers a moderate MRR value. From the plot, a range of PO and A has been selected for total MRR, as shown in Table 10.

In the plot shown in Figure 9, the red color indicates the minimum value of MRR, and the violet color indicates the maximum value of MRR. The yellow region offers a moderate MRR value. A range of A and PF has been selected from the plot about total MRR, as shown in Table 11. The plots in Figures 7–9 show the contour plot of input parameters vs. MRR. For each scheme, a suitable range of input parameters about maximum MRR has been identified, as shown in Tables 9–11. An intersection range has been determined from these tables, as shown in Table 12. The PO, PF, and A content listed in Table 12 resembles the most suitable range of input parameters about maximum MRR. Moreover, to verify the obtained field, validation experiments have been performed. Table 13 shows the list of validation experiments conducted to verify the range. The figure of a workpiece having validation experiments can be seen in Figure 4 marked, with V1, V2, and V3. From the validation experiment, it has been found that the value of MRR is maximum or greater than 21 mm^3/min for each validation experiment. Hence, the obtained range is significant.

CONCLUSION

The present work is focused on maximizing the material removal rate during the wire cutting of difficult-to-machine Inconel X750 using an electric discharge machining process. The proposed methodology seems beneficial for identifying a suitable cutting range of input parameters, especially for difficult-to-cut materials. It has been observed that the optimization of machining parameters results in a single combination of input parameters. However, the obtained single range is often not feasible for the system to feed because of that the researchers use to round off the accepted range of input parameters, drastically changing the results. In the proposed methodology, content has been identified for each input parameter. Any combination selected from the field will result in optimized output. The range of input parameters facilitated the users to work more precisely. The following are the conclusive key points.

- Inconel X750 is a difficult-to-machine material, and more work needs to be reported for machining such material.
- Wire EDM is the most suitable solution for machining the Inconel X-750.
- A mathematical model has been generated using the response values at complex input sets. The model's R-sq values demonstrate that it is substantial and well-fitted.
- From the ANOVA analysis, it has been found that the pulse-off time is a more significant parameter.
- Further, contour plots have been drawn using the mathematical model to identify the range of suitable machining zones. From the contour plots, relevant content has been placed.
- It has been concluded that for the given machining conditions if the input parameters are selected for the obtained range, the MRR will be maximum.
- The obtained range to input parameters are Pon (100–110 μS), Poff (55–63 μS), and current (10–12 A).
- Moreover, validation experiments have been performed to validate the obtained range of input parameters. The validation experiments show that the accepted content is significant.

The same methodology can be implemented to optimize surface roughness and other output parameters shortly.

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