



Optimization of Material Removal Rate and Wear Rate in EDM Machining of Inconel 625 Using a Novel Nano Al-Ni Composite Electrode: A Response Surface Methodology Approach

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ABSTRACT

Electrical discharge machining is a non-traditional machining process in which there is no direct contact between the tool and the workpiece. It is commonly used for machining components made of hard and difficult-to-machine materials. In the current experimental inquiry, the process factors that influence the machining concert process and its effectiveness are explored. The response table for each set of machining limitations is used in conjunction with the response surface methodology in the research to determine the appropriate levels of machining factors. The work's machining input parameters are optimized for maximum material removal rate (MRR) and reduce the electrode wear rate (EWR) when electro-discharge machining Inconel 625 using the tool Nano Al-Ni composite electrode. Analysis of variance (ANOVA) was performed to identify the factors responsible for the variations in the results mentioned above. Energy-dispersive X-ray spectroscopy was also used to determine the elemental composition of the workpiece. Machined workpiece surfaces were evaluated using scanning electron microscopy to assess surface accuracy and microstructural characteristics. The following conclusions were drawn from this work. The most influential parameter affecting MRR was pulse-off time. It was observed that MRR increased with an increase in pulse-off time. According to the response graph, the greatest MRR value that can be attained under the ideal parameters of $I_p = 8A$, $T_{ON} = 50 \mu s$, and $T_{OFF} = 100 \mu s$ is 0.0115 g/min . The magnitudes of MRR range from 0.0091 to 0.044 g/min . Higher EWR of 0.0022 g/min was seen in runs with $T_{ON} = 70 \mu s$ and $T_{OFF} = 100 \mu s$.

Keywords: Inconel 625; Novel Al-Ni nano electrode; Material removal rate; Parameter optimization.

1. INTRODUCTION

Electric discharge machining (EDM) is carried out through controlled electrical discharges between the anode and cathode, generating extreme localized heat in the machining zone. The process involves melting and evaporating the material in the localized discharge zone due to intense heat generation. In EDM, once an abbreviation is introduced, only the abbreviated form is used thereafter, except when it appears at the beginning of a paragraph. Tool sinking in EDM oil improves machining efficiency. The auxiliary electrode wears rapidly even when made of the same material. The workpiece typically acts as the anode and is therefore considered the anode in EDM operations. A small spark gap is maintained between the tool and the sidewalls of

the slot. This gap expands during each discharge when the tool and work surface are in close proximity and varies with every spark. This mechanism supports material removal. The study also indicated that electrical conductivity, often overlooked in tool design, plays a crucial role in EDM performance. through experimental analysis, identified the optimal machining parameters for EDM using an AlCrNi-coated electrode on Ti-6Al-4V titanium alloy. The study highlighted that the electrical conductivity of the coated tool increased the significance of current as a key process parameter in EDM. This finding was further supported by experimental results reported by Raj *et al.* (2024). Focusing on machining harder materials, the study also examined the effects of different dielectric fluids and nanocomposite electrodes on EDM performance. Key responses such as electrode

wear, surface roughness, and material removal rate were analyzed. Karbasian *et al.* (2023) investigated how surface roughness modifies load-displacement curves and hardness values and affects the precision of mechanical property data obtained from indentation testing. Prior research has shown that an increase in surface roughness leads to a decrease in the P-h curve level and hardness. However, this effect becomes less significant at greater indentation depths. Sharma *et al.* (2021) used a 0.25 mm wire electrode to machine 13 mm diameter AISI D2 die steel. The research used a Taguchi L9 orthogonal array for systematic exploration to examine the effects of important process parameters on EDM responses. Jeykrishnan *et al.* (2016) studied and optimized the input factor to reduce machining time while preserving high MRR and reducing EWR. Goyal *et al.* (2017) evaluated the effects of several parameters on the rate of output responses in machining operations. Comprehensive SEM microstructural analyses of the machined material were conducted to supplement the study. Payal *et al.* (2023) optimized the input parameters for EDM operations on Inconel 625 super alloy. Taguchi's L9 orthogonal array and analysis of variance were used in the study. The material removal rates of copper-tungsten electrodes were higher than those of tungsten inert gas electrodes.

Dhanabalan *et al.* (2014) performed studies on a variety of alloy compositions, particularly Inconel 625 by lowering roughness, and integrating silicon carbide powder into the dielectric fluid during EDM greatly improved surface quality, particularly at higher electrode rotating speeds. Previous studies show that electrode revolution is an important feature that, when regulated, improves surface properties. Kundu *et al.* (2023) used ANOVA to examine the effects and interactions of the machining parameters. Regression analysis was used to confirm a trustworthy model that fit the results of the experiments effectively. The experimental results were found to be the best parameters for maximizing MRR.

Kumar (2022) studied and used Taguchi's L9 orthogonal array efficiently to speed up testing and choose the best machining variable settings. The research targeted at minimizing tool wear, maximizing removal rate. Mathew *et al.* (2023) used RSM and the firefly algorithm to optimize machining settings for turning AISI 1045 medium carbon steel to minimize flank wear and surface roughness while maximizing MRR. Phan *et al.* (2021) reported that compared to conventional machining, EDM processing modifies the surface layer structure, requiring particular finishing techniques to address the recast layer. Research shows that although voltage does not affect on the recast layer thickness, discharge current, pulse on time, and pulse off time do. The minimum value of RLT obtained under the process parameters was 3.72 μm . $T_{\text{off}} = 12 \mu\text{s}$, $U_e = 30 \text{ V}$, $T_{\text{on}} = 50 \mu\text{s}$, and $I_e = 1 \text{ A}$. Senthilkumar *et al.* (2015) focused on Inconel 625, a tough material with remarkable high-

temperature strength and corrosion resistance, to optimize material removal rate in EDM. The authors increased the productivity and efficiency of Inconel 625 machining by systematically changing the EDM process parameters using RSM.

Payal *et al.* (2023) used an Al-Ni powder metallurgical electrode and a Taguchi method to optimize the EDM settings for Inconel 625. By methodically changing process variables and electrode composition, it was intended to increase the machining process efficiency and accuracy, with the end objective of achieving an increased material removal rate and Using a multi-objective optimization approach, this study aimed to maximize the performance of EDM on Inconel 625. It focused on achieving an optimal balance between surface quality and MRR to improve machining efficiency. This was accomplished by optimizing process parameters and employing an Al-Ni composite electrode. Justin *et al.* (2024b) used Al-Ni nano electrodes and RSM and ANOVA for optimization. Their work examined the effects of EDM parameters on surface roughness and machining time during Inconel 625 machining.

Sharma *et al.* (2022) used RSM and ANFIS techniques to optimize MRR, SR, and TWR, as well as identify pulse on/off periods as critical determinants and obtain high predicted accuracy. Their work explored the ideal EDM parameters for Inconel 625. The findings provide insightful information for the EDM sector, enabling effective Inconel alloy machining. Phan *et al.* (2021) reported that coating EDM tool electrodes significantly improved surface quality by reducing surface roughness and enhancing electrode wear resistance. The study also found that voltage and current had a strong influence on surface roughness. In addition, coated electrodes performed better than uncoated electrodes when machining titanium alloys. Garg *et al.* (2017) explored WEDM parameters for Inconel 625, emphasizing pulse on/off times' significance in machining optimization. Through response surface methodology, they identified optimal settings while highlighting the influence of parameters on cutting speed, gap current, and surface roughness, offering insights into surface topography effects for enhanced machining processes. Sharma *et al.* (2022) optimized MRR and surface roughness in EDM of Inconel 825 by analyzing key process parameters such as spark current, pulse-on time, and duty cycle. The study employed a hybrid RSM-DF and MOGA approach, which resulted in improved surface morphology and enhanced surface characteristics. The findings were validated through advanced surface characterization techniques and confirmation experiments.

From the literature review, it seems that, limited research has been conducted on the performance of composite materials such as Inconel 625 using a novel

Al-Ni nano electrode in EDM. Few studies have explored residual data analysis, particularly concerning Inconel, utilizing the EDM process. However, there remains a gap in examining the optimal process parameters for EDM of Inconel 625 using the Novel Nano Al-Ni electrode. This article presents optimized EDM process settings aimed at enhancing MRR and EWR. Aluminum and nickel Nano powder (Al-Ni) were selected as the electrode material, and the machined electrode surface characteristics were analyzed. Experimental investigations employing the Design of Experiments (DOE) method are conducted to scrutinize the research's focus on geometrical tolerances and optimizing EDM input process parameters for Inconel 625.

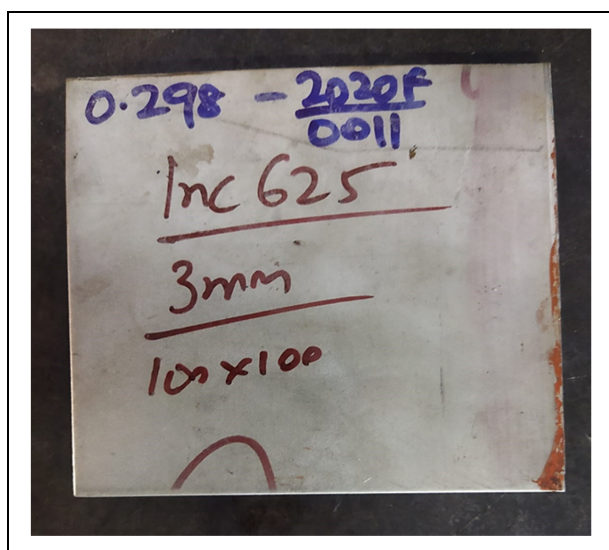


Fig. 1: Work piece material

2. MATERIALS AND METHODOLOGY

2.1 Work Piece Material

Since Inconel 625 is robust and corrosion-resistant, the research employed it as the workpiece. Al-Ni nanocomposite electrodes were used for Inconel 625 compatibility and electrical conductivity. Molybdenum and niobium in the nickel-chromium matrix make Inconel 625 a strong solid solution alloy. Propulsion motors, propeller blades, and underwater gearbox sheathing employ this alloy. A vendor-provided 100 × 100 cm Inconel 625 square was cut into nine sections (Fig. 1).

2.2 Tool Material

Some of the previous journal references decided to use powder metallurgy form to make aluminium composite electrode with nickel reinforcement for the EDM machining electrode in this investigation. In an earlier investigation, 90% of the aluminium had 10% nickel added to it as shown in Fig. 2. Table 1 shows the weight percentage of the electrode.



Fig. 2: Tool electrode (Al 90 % -Ni 10%) of size 15 mm diameter and 30 mm length

Table 1. Weight percentage of tool electrode

Alumni Wt. %	Nickel Wt. %
90	10

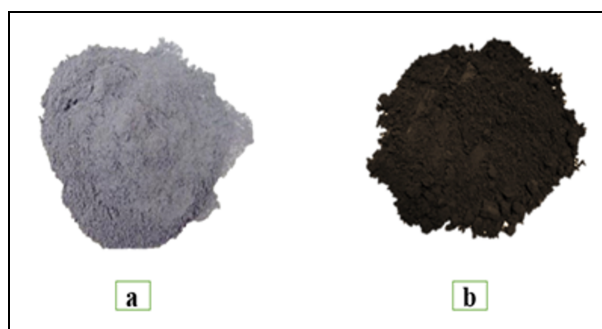


Fig. 3: Nano sized aluminium and nickel powder

The Al-Ni nano electrode (90:10 ratio) was prepared using powder metallurgy for EDM tool fabrication. The electrode was designed with dimensions of 30 mm in length and 15 mm in diameter. High-purity nickel and aluminium powders (particle size ~40 nm) were accurately weighed according to the required composition and thoroughly mixed using ball milling to ensure homogeneity (Fig. 3a and 3b). The blended powder was then compacted using a hydraulic press to form green compacts under high pressure. These compacts were subsequently sintered at 600 °C in a controlled atmosphere furnace to promote densification and particle bonding. The sintering temperature was maintained above the eutectic melting point of the alloy system. Finally, the sintered compacts were machined by turning or grinding to obtain the final electrode dimensions of 30 mm length and 15 mm diameter.

2.3 Experimentation Setup

The samples were machined using an Electronics EMS 5030 EDM machine (Fig. 4). Electrical Discharge Machining (EDM) is a non-traditional machining process in which material is removed through controlled electrical discharges between the tool and workpiece separated by a dielectric fluid. The dielectric medium is periodically flushed and replaced to maintain

stable machining conditions. In this study, EDM oil was used as the dielectric fluid. A composite nano-electrode made of aluminium and nickel (Al–Ni) was employed as the tool electrode. The EDM machine had a maximum load capacity of 700 kg and overall dimensions of 1700 × 1040 × 535 mm (height × width × depth).

2.4 EDM Oil

IPOL SEO 450 is recommended for electrical discharge machining applications where high precision and accuracy are required. The oil was produced using high-quality, low-aromatic, carefully selected hydrocarbon base stocks. It was designed with an optimal viscosity suitable for efficient EDM operation and reduced electrode wear. The fluid is nearly colourless, and its low aromatic content helps minimize odour and fume generation.



Fig. 4: Machining the work piece on EDM

2.5 Input and Output Parameters

Variations in input parameters, using different combinations of AMPS, TON, and TOFF, are included in the dataset. Understanding how these parameters influence the EDM process is essential for analysing machining behaviour. This information can be used by researchers to evaluate and optimise the EDM process for specific objectives, such as improving MRR.

2.6 Calculation of MRR

The material removal rate (MRR) was calculated from the weight difference of the workpiece before and after EDM machining, as given in Equation (1):

$$MRR = W_i - W_f \dots (1),$$

where W_i is the initial weight of the workpiece before machining and W_f is the final weight of the workpiece after machining.

2.7 Calculation of EWR

The rate at which an electrode material is eaten or worn away during a machining or electrical discharge machining (EDM) process is known as the EWR. Equation 2 was used to determine the electrode wear rate.

$$EWR = \{\text{Initial Electrode Mass} - \text{Final Electrode Mass}\} \dots (2)$$

2.8 RSM Optimization Technique

Electrical Discharge Machining is an integral part of contemporary manufacturing processes that uses a succession of electrical discharges to gradually erode conductive materials. To simulate the intricate link between input factors like voltage, current, and electrode material and the output responses like material removal rate, surface quality, and electrode wear, RSM optimization makes use of statistical techniques. Through methodical investigation of this multidimensional parameter space, RSM helps engineers pinpoint ideal machining parameters that optimize efficiency while reducing expenses and flaws.

3. RESULTS AND DISCUSSION

The experimental data gathered offers an insightful understanding into the complex dynamics of the EDM process. The study aimed to clarify how these factors affect material removal rate and tool wear through systematic investigation. Trends, optimizations, and potential improvements in EDM machining were identified by comparing the results with previously published literature.

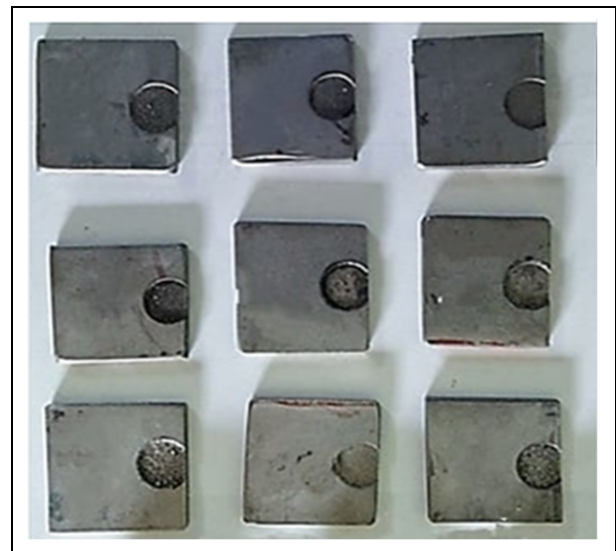


Fig. 5: Inconel 625 after EDM Machining with Al-Ni Electrodes

Fig. 5 shows the Inconel 625 after EDM machining with Al-Ni Electrodes. The EDM machining

of Inconel 625 with Al-Ni Nanocomposite electrodes was investigated in this study. The research focuses on understanding the MRR and EWR in this specific machining process. The results reveal valuable insights into the feasibility and performance of Al-Ni Nano electrodes in EDM machining of Inconel 625, offering potential advancements in aerospace and industrial applications.

A series of EDM experimental runs is presented in Table 2. It shows different combinations of parameters like run number, current (in Amps), pulse duration (T ON and TOFF in μ s), metal removal rate in grams per minute, and electrode wear rate in grams per minute. Different machining conditions were evaluated throughout these trials to determine how they affected the performance of the EDM. Trends in MRR and EWR are shown by data analysis, which correlates variations in current, pulse length, and other factors. For example, longer pulse lengths and higher currents often result in larger MRR, but they also increase electrode wear. To maximize material removal rates while reducing electrode wear, optimizing the EDM process requires a delicate balancing act between both variables.

Table 2. RSM experiments run and outputs

Run	Current (Amps)	TON (μ s)	TOFF (μ s)	MRR (g/min)	EWR (g/min)
1	4	70	80	0.018	0.0022
2	8	50	90	0.015	0.0024
3	12	70	80	0.039	0.0077
4	8	30	90	0.013	0.0013
5	12	70	100	0.041	0.0078
6	8	50	90	0.015	0.0024
7	4	70	100	0.044	0.0022
8	4	50	90	0.014	0.0016
9	8	50	90	0.015	0.0024
10	8	50	90	0.015	0.0024
11	4	30	100	0.012	0.0010
12	12	30	100	0.0124	0.0021
13	12	30	80	0.035	0.0024
14	4	30	80	0.0091	0.0009
15	8	50	80	0.0143	0.0032
16	8	50	90	0.015	0.0024
17	8	50	90	0.015	0.0024
18	12	50	90	0.021	0.0035
19	8	50	100	0.016	0.0020
20	8	70	90	0.034	0.0032

Table 3. Analysis of variance table for metal removal rate

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.0023	9	0.0003	263.33	< 0.0001	significant
A-Current	0.0003	1	0.0003	269.99	< 0.0001	
B-Pulse ON	0.0009	1	0.0009	916.16	< 0.0001	
pulse OFF	1.000E-05	1	1.000E-05	10.26	0.0094	
B	8.611E-06	1	8.611E-06	8.83	0.0140	
AC	0.0003	1	0.0003	314.21	< 0.0001	
BC	0.0003	1	0.0003	291.78	< 0.0001	
A ²	0.0000	1	0.0000	18.48	0.0016	
B ²	0.0002	1	0.0002	206.68	< 0.0001	
C ²	1.202E-07	1	1.202E-07	0.1233	0.7327	
Residual	9.748E-06	10	9.748E-07			
Lack of Fit	9.748E-06	5	1.950E-06			
Pure Error	0.0000	5	0.0000			
Cor Total	0.0023	19				

Significant model effects ($p < 0.0001$) were observed in the analysis of variance in Table 3, indicating that the proposed model adequately fits the data. Pulse ON and Pulse OFF showed significant effects with high F-values (916.16 and 10.26, respectively). The model was also strongly influenced by interaction effects (AB, AC, and BC) ($p < 0.05$), highlighting the importance of including these interactions in the prediction model. However, the squared term for Pulse OFF (C^2) was not significant ($p = 0.7327$), indicating a negligible contribution to the model.

The standard deviation of 0.0010 indicated low variability in Table 4, while the high R^2 value of 0.9958 suggested a strong correlation between the observed and

predicted values, thereby validating the accuracy of the model. Fig. 6 shows the normal plot of the response surface methodology (RSM). This graphical representation illustrated the main effects and interactions of input parameters such as current, TON, and TOFF on the response variable (MRR).

The relative significance of each component and their combined impact on the output response may be shown visually using the normal plot. Plotting the anticipated values of the response variable derived from the statistical model versus the actual observed values from the experimental data is the method used to compare the two sets of data. It acts as a validation

stage to evaluate the model's precision and dependability in forecasting system behaviour. A good fit between the expected and observed values shows how well the model captures the underlying dynamics of the process.

Table 4. Fit statistics

Std. Dev.	0.0010	R ²	0.9958
Mean	0.0206	Adjusted R ²	0.9920
C.V. %	4.78	Predicted R ²	0.9655
		Adeq Precision	50.6358

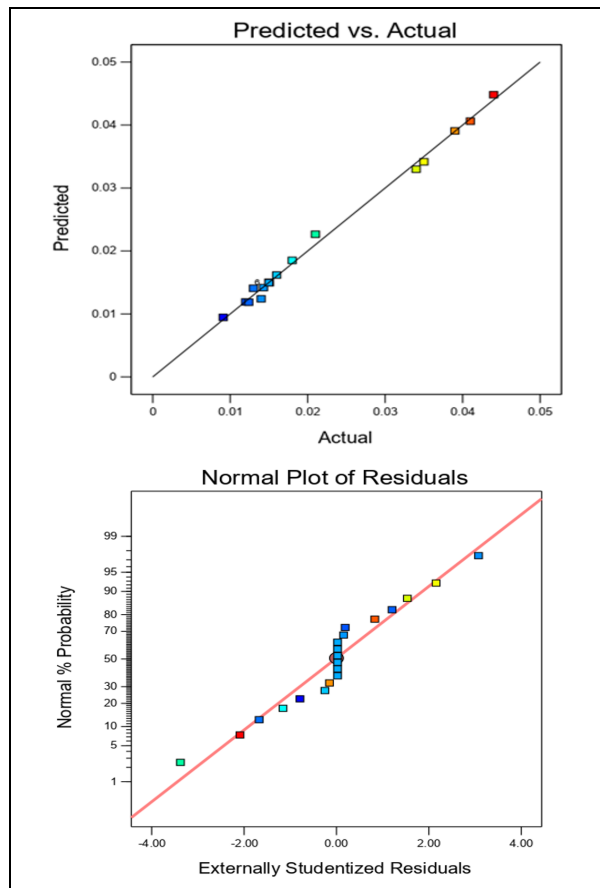


Fig. 6: Diagnostic plot for MRR

The X-axis represents varying values of Pulse ON time, which is one of the crucial input parameters in EDM. It extends from 30 to 70 μs . The Y-axis represents the range of current values, spanning from 4 to 12 amps. The Z-axis represents MRR, indicating the removal rate of material during EDM. The surface plot reveals the complex interplay between Pulse ON time and current in influencing MRR. As Pulse ON time and current values change, MRR varies accordingly. Regions of the plot with steeper inclines or brighter colors indicate where MRR is most responsive to changes in Pulse ON time and current. These regions signify the optimal operating conditions for achieving higher MRR in the EDM process. The surface plot visually illustrates the complex interaction between Pulse ON, OFF time and MRR in EDM. It identifies regions within the plot where changes

in Pulse ON and Pulse OFF times have a significant impact on MRR. These regions may indicate optimal parameter settings for achieving higher MRR, which is improved by lengthening pulse off times, even for brief periods. Notably, due to increased spark power at lower peak currents (4A and 12A), the pulse on time does not affect on MRR, necessitating longer material removal times as shown in Fig 7.

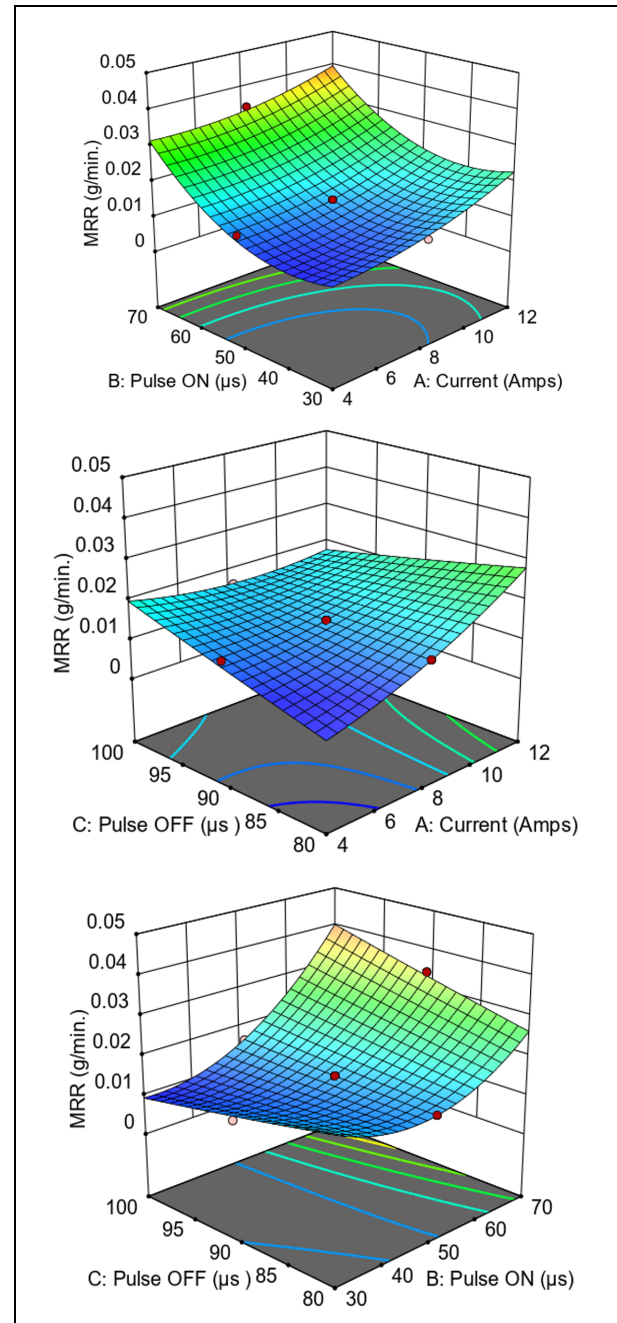


Fig. 7: MRR 3D RSM graph vs Current, TON and TOFF

At least one of the predictors significantly affects the response variable, since the entire model is significant ($p < 0.0001$). The low p-values and high F-values of A-Current ($p < 0.0001$) and B-Pulse ON ($p <$

0.0001) demonstrate their considerable contribution to the model shown in ANOVA Table 5.

Table 5. ANOVA table for EWR

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	0.0001	9	6.747E-06	26.05	< 0.0001
A-Current	0.0000	1	0.0000	93.95	< 0.0001
B-Pulse ON	0.0000	1	0.0000	91.56	< 0.0001
C-Pulse OFF	1.690E-07	1	1.690E-07	0.6524	0.4380
AB	9.031E-06	1	9.031E-06	34.87	0.0002
AC	1.125E-08	1	1.125E-08	0.0434	0.8391
BC	1.125E-08	1	1.125E-08	0.0434	0.8391
A ²	4.400E-07	1	4.400E-07	1.70	0.2217
B ²	2.750E-08	1	2.750E-08	0.1062	0.7513
C ²	5.569E-07	1	5.569E-07	2.15	0.1733
Residual	2.590E-06	10	2.590E-07		
Lack of Fit	2.590E-06	5	5.181E-07		
Pure Error	0.0000	5	0.0000		

Table 6. Fit statistics

Std. Dev.	0.0005	R ²	0.9591
Mean	0.0028	Adjusted R ²	0.9223
C.V. %	18.34	Predicted R ²	0.6864
		Adeq Precision	18.5688

A good connection between the expected and actual values, with a mean of 0.0028, is shown by the coefficient of determination (R^2) of 0.9591 and the standard deviation of 0.0005 (Table 6). On the other hand, the modified R^2 of 0.9223 indicates a rather excellent match, meaning that the model explains 92.23% of the variability in the data. The normal probability plot of residuals in Fig. 8 showed that the residuals were closely aligned along a straight line, indicating a normal distribution of errors. Fig. 8 also compared the observed values with the model-predicted values. The response ranged from 0.0141 g/min to 0.0021 g/min, showing a wide variation between maximum and minimum values. Overall, the regression model showed good agreement with the experimental data.

Fig. 9 shows the 3D surface diagram of prominent EWR values spanning from 0.0009 to 0.0078 g/min, indicating varying wear properties. The potential is shown by the optimal operating conditions of runs with lower EWR = 0.0009 g/min. The greater values of MRR are often linked to greater EWR. The magnitudes of MRR range from 0.0091 to 0.044 mm³/min. The impact of TON and TOFF on electrode wear rate (EWR) was significant. The highest EWR of 0.0022 g/min was observed at TON = 70 μ s and TOFF = 100 μ s, indicating sensitivity of the process to pulse duration parameters.

From Fig. 10, a current of 8 A showed relatively consistent MRR values around 0.015 g/min, indicating stable machining performance. A TON of 50 μ s and a TOFF of 90 μ s also contributed to higher MRR. Although EWR varied across the experimental runs, it generally followed a similar trend to MRR, suggesting

that optimization of MRR can indirectly reduce EWR. A TON of 30 μ s and a TOFF of 80 μ s resulted in the lowest EWR among runs with comparable MRR values, indicating that these parameters may help minimize tool wear.

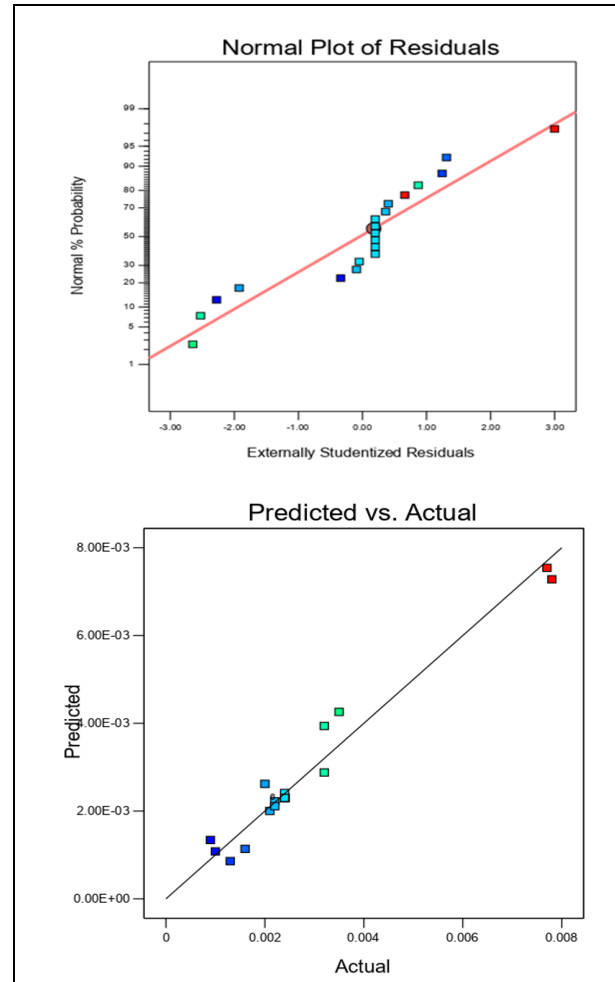


Fig. 8: Diagnostic plot for EWR

From Table 7, the predicted mean and median for MRR were both 0.044, closely matching the observed value of 0.044, indicating high prediction accuracy. Similarly, for EWR, the predicted mean and median were 0.00206356, which was slightly higher than the observed value of 0.001. The standard deviation of 0.000508945 indicated a small degree of variability in the prediction.

Table 7. Confirmation test values

Response	Predicted Median	Observed	Std. Dev
MRR	0.04422810	0.044	0.000987295
EWR	0.00206356	0.001	0.000508945

Cracks and fractures, porosity and voids, inclusions, surface pollutants, grain boundaries and grain structure, and deformation and wear, are a few typical material flaws that may be found with SEM. Fig. 11 shows SEM pictures of the work specimen at various micrometres levels before EDM machining. These

images clearly show that the surface was smoothed before it was machined.

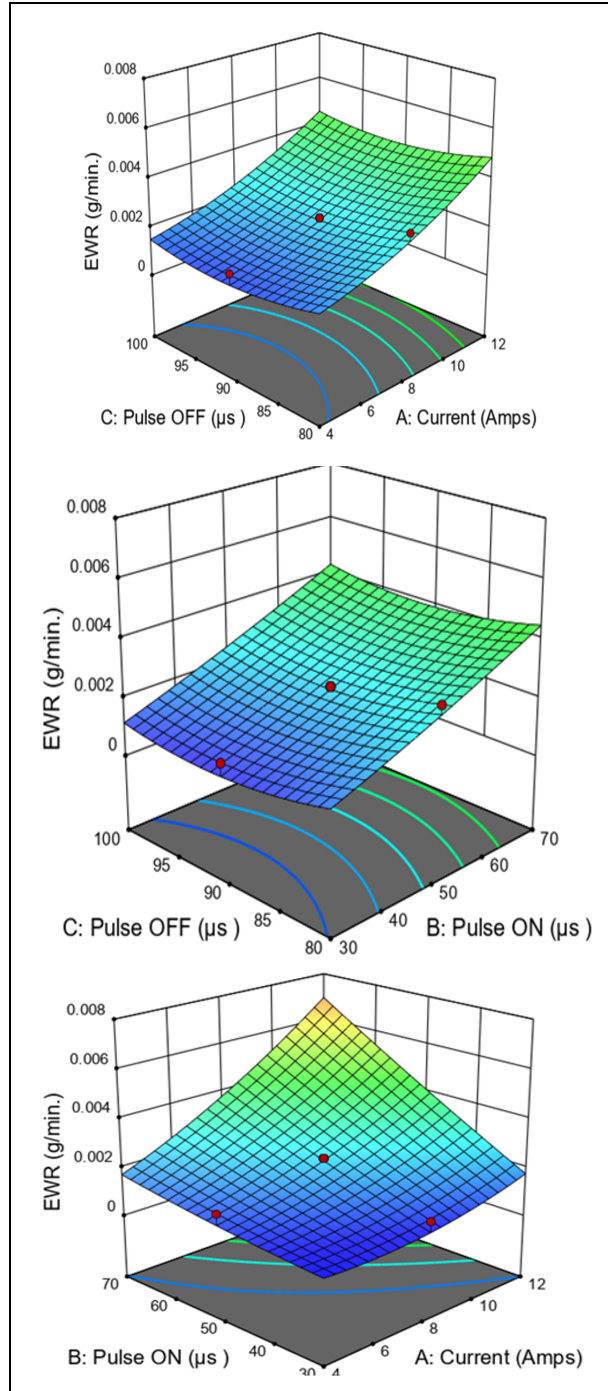


Fig. 9: EWR 3D RSM graph vs Current, TON and TOFF

The exterior of the Inconel workpiece has a significant amount of carbon (58.73%) and chromium (3.71%), as shown in EDAX data Table 8 and Fig. 12. The report validates the chemical composition of the surface.

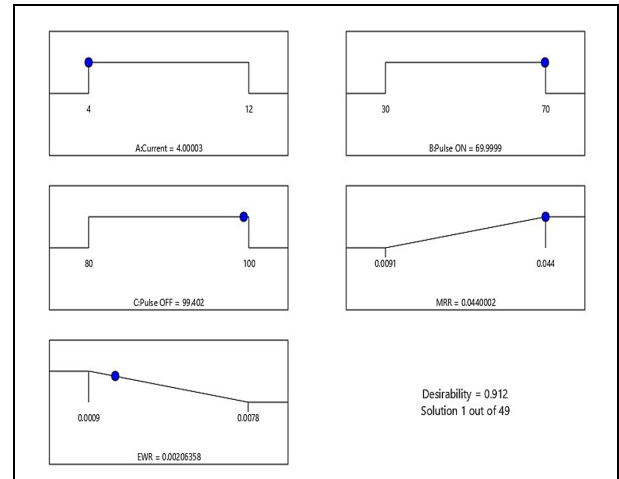


Fig. 10: Ram plot showing MRR and EWR optimal condition

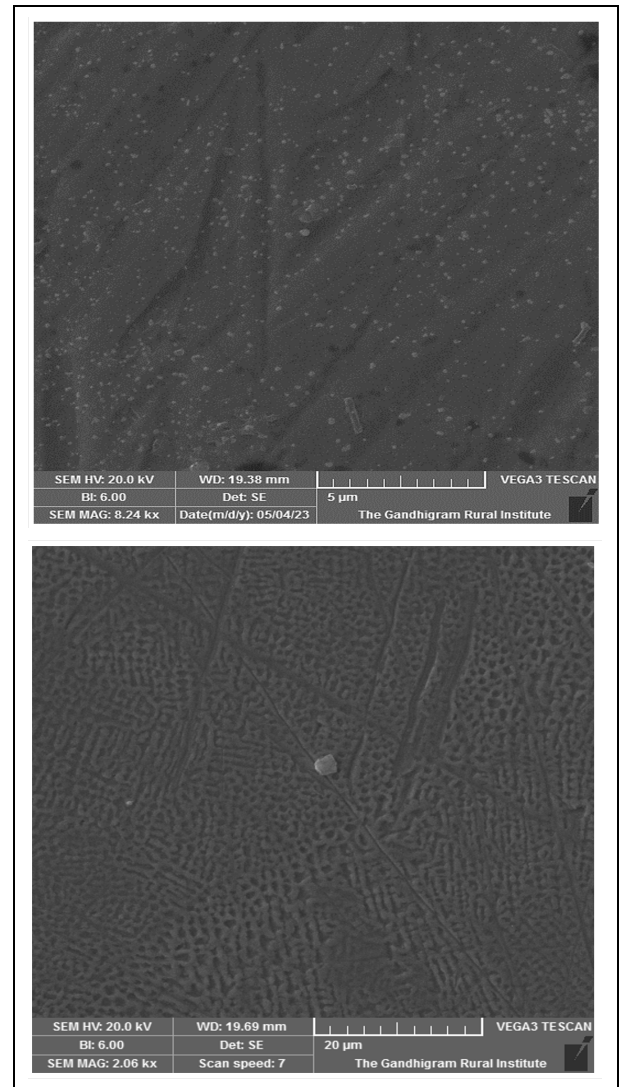


Fig.11: Work piece before machining with EDM

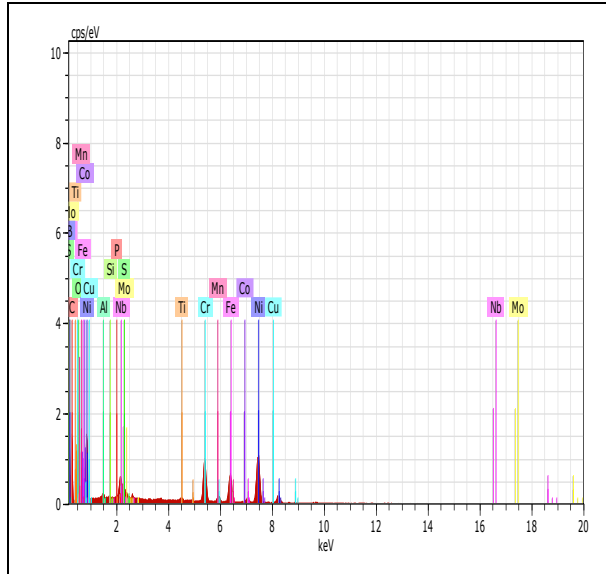


Fig. 12: Work piece before machining with EDM

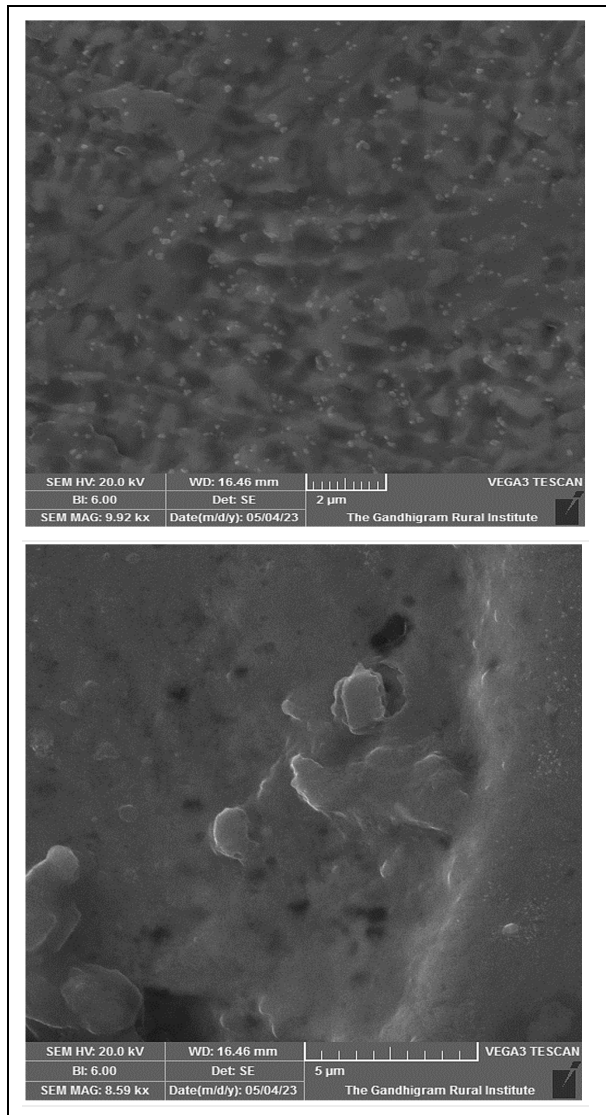


Fig. 13: Work piece after machining with EDM

Materials that are subjected to electrical discharge machining either melt or evaporate due to the high temperatures generated. Droplets develop on the machined surface when the liquid substance solidifies. Fig. 13 shows that during machining of hard materials such as Inconel, interaction with gas bubbles leads to the formation of small voids or micro-holes on the surface. The workpiece material in the machining zone is rapidly heated due to electrical discharges. After the pulse-off time and a 90 ms spark discharge, the machined surface is cooled by flushing with EDM oil. Longer sparking times and higher duty cycles lead to the formation of deeper craters on the workpiece surface, resulting in higher material removal and a rougher, less polished surface finish.

Table 8. EDAX of Inconel before machining

El	AN	Series	unn.	C norm.	C Atom.	C Error
	[wt.%]		[wt.%]	[at.%]	[wt.%]	(1 Sigma)
C	6	K-series	30.29	33.42	58.73	5.32
O	9	K-series	14.18	15.87	21.37	2.77
Ni	29	K-series	23.52	26.01	9.97	0.75
Cr	23	K-series	8.40	9.34	3.71	0.31
Fe	25	K-series	8.67	9.62	3.73	0.33

5. CONCLUSION

The study concludes that optimal conditions involving a moderate current of 8 A, TON of 50 μ s, and TOFF of 90 μ s consistently produced higher MRR values. The maximum MRR of 0.044 g/min was obtained under these conditions, indicating that pulse duration had a stronger influence on MRR than current. Lower MRR values were observed under extreme conditions such as low current (4 A) combined with short TON (30 μ s) and TOFF (80 μ s), as well as at high Toff under low current. The EWR values ranged from 0.0009 to 0.0078 g/min, showing variation with process parameters. Lower EWR was generally associated with higher MRR, indicating an inverse relationship between material removal and tool wear. However, extreme parameter deviations led to increased electrode wear. Optimizing TON and TOFF was found to be more effective than varying current for improving MRR while minimizing electrode wear.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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