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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

The electric discharge machine is a novel machining technique. When the tool and the work item do not communicate. Components composed of difficult-to-machine hard 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. Another analysis of variance is to identify the factors causing the different answers mentioned above. EDAX was also used to investigate the material composition of the workpiece. Machined workpiece surfaces were evaluated using scanning electron microscopy to assess surface accuracy and microstructural characteristics (SEM). The following conclusions may be drawn from this work. The MRR parameter that is most affected is pulse off time. As pulse-off time lengthens, MRR increases. According to the response graph, the greatest MRR value that can be attained under the ideal parameters of Ip = 8A, T-ON = 50µs, and T-OFF= 100µs is 0.0115 g/min. The magnitudes of MRR range from 0.0091 to 0.044 g/min. Impact of T ON and T OFF: Higher EWR is 0.0022 g/min is seen in runs with T ON = 70 µs and T OFF = 100 µs.

Keywords: Inconel 625; Novel Al-Ni nano electrode; MRR; RSM; Parameter optimization.

NOMENCLATURE			
EDM	Electrical Discharge Machining	SEM	Scanning Electron Microscope
MRR	Material Removal Rate	µm	Micrometer
EWR	Electrode Wear Rate	µs	Microseconds
SR	Surface Roughness	Ton	Pulse ON
Al-Ni	Aluminum-Nickel	Toff	Pulse OFF
RSM	Response Surface Methodology	A	Ampere

1. INTRODUCTION

Electric discharge machining is completed by the anode and cathode reacting due to extreme heat throughout the zone. This needs melting and evaporating dazzling zone materials. Sinking the tool in EDM oil improves work bit efficiency. The assisting terminal electrode corrodes quickly while being formed of the same material. Workpieces typically act as anodes. Thus, the work piece is generally anode. Maintain a flash slit between the tool and the slop's sidewalls. Flash spreads when the tool and working surface are close and vary with each spark. This supports material removal, and the study showed that electrical conductivity, which is overlooked in tool adaptation, is crucial in EDM operations. Phan *et al*. (2021) through experimental analysis, the study determined that specific technical parameters, were optimal for EDM using an AlCrNi-coated electrode on Ti-6Al-4V titanium alloy. Notably, the research emphasized that the coated tool's electrical conductivity elevated the importance of current as a pivotal factor in the EDM process. This conclusion was corroborated by the experimental results, which he already reported (Raj *et al.* 2024). with an emphasis on machining harder materials and important variables including electrode wear, surface roughness, and material removal rate, this study examined the effects of different dielectric fluids and nanocomposite electrodes on EDM performance. Karbasian *et al.* (2023) investigated how surface roughness modifies load-displacement curves and hardness values and it affects the precision of mechanical property data obtained from indentation testing. Prior research verifies that when surface roughness increases, the P-h curve level and hardness drop as well; however, the impact becomes less pronounced at deeper indentation depths. Sharma *et al.* (2021) reported their investigations that a 0.25 mm wire electrode was used 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) evaluate the effects of several parameters on the rate of output responses in machining operations, in Taguchi's Methodology was used. Comprehensive SEM microstructural analyses of the machined material were conducted to supplement the study. Payal *et al*. (2023) to optimize the input parameters for EDM operations on Inconel 625 super alloy, Taguchi's L9 orthogonal array (OA) 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 (TWR) electrodes.

Dhanabalan *et al.* (2014) enhanced the efficiency of EDM, Dhanabalan and colleagues 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), ANOVA was used in the study 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) shown by the confirmation experiment, the research uses 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) 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. RLT's minimum value at process parameters is 3.72 µm. Toff = 12 µs, Ue = 30 V, Ton = 50 µs, and Ie = 1 A. Senthilkumar *et al.* (2015) focuses on Inconel 625, a tough material with remarkable high-temperature strength and corrosion resistance, to optimize material removal rate in EDM. The authors increase the productivity and efficiency of Inconel 625 machining by systematically changing the EDM process parameters using Response Surface Methodology.

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 is intended to increase the machining process' efficiency and accuracy, with the end objective of achieving an increased material removal rate and surface polish used a multi-objective optimization approach, this study aims to maximize the output performance of the Inconel 625 EDM. To increase machining efficiency, it seeks to identify the ideal balance between surface quality and material removal rate. This is accomplished by modifying process parameters and using an Al-Ni composite electrode. Justin *et al*. (2024b) used Al-Ni nano electrodes and RSM and ANOVA for optimization, this research 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, this work explores 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) Surface quality is greatly improved by coating EDM tool electrodes, which also reduces surface roughness and increases electrode wear resistance. Studies reveal that voltage and current have a significant impact on surface roughness, and that when machining titanium alloys, coated electrodes perform better than uncoated ones. Garg *et al*. (2017) explored WEDM parameters for Inconel 625, emphasizing pulse on/off times' significance in machining optimization. Through response surface methodology, it identifies 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) to optimize MRR and SR, this work examines the EDM parameters for Inconel 825, emphasizing the importance of spark current (Is), pulse on time and duty cycle (DC). It provides better surface morphology and enhanced surface characteristics by using a hybrid RSM-DF and MOGA technique, which is confirmed by advanced surface characterizations and confirmation tests.

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 material removal rate (MRR) and electrode wear rate (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.

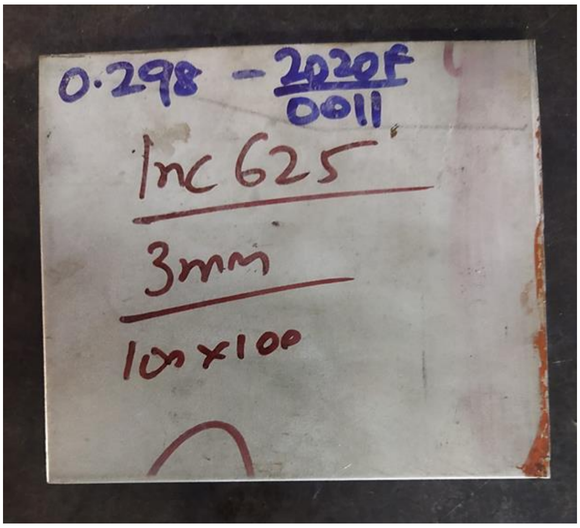

Fig. 1: Work piece material

2. MATERIALS AND METHODOLOGY

2.1 Work Piece Material

Since Inconel 625 is robust and corrosion-resistant, the research employs it as the workpiece. Al-Ni Nanocomposite electrodes are 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 100x100 cm Inconel 625 square was cut into nine sections shown into 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

There are many procedures involved in preparing the Al-Ni Nano electrode (90:10 ratio) for powder metallurgy, which has dimensions of 30 mm in length and 15 mm in diameter, for EDM tool preparation. To achieve homogeneity, high-purity 40 nm-sized powders of nickel and aluminium are first extensively combined using a ball milling technique after being weighed by the appropriate ratio shown in Fig. 3 (a and b). Green compacts are then created by compacting the combined powder using a hydraulic press at high pressure. To encourage densification and particle bonding, these green compacts are further heated to increased temperatures of 600 °C in a controlled environment furnace. This temperature is usually higher than the melting point of the eutectic mixture. The compacted material is turned or ground after sintering to give it the final dimensions of 30 mm in length and 15 mm in diameter.

2.3 Experimentation Setup

The samples were machined on an electronics EMS 5030 EDM shown in fig 4. The machine looks like the illustration below. EDM is a group of "non-traditional" or "unconventional" machining techniques. The liquid dielectric in between the conductors should be interrupted and replaced often to describe EDM. The specifications of the EDM used in this experiment. The Electronics EMS 5030 utilized a machining machine, which uses EDM Oil as the dielectric fluid, which is one of the requirements of the EDM setup. The instrument used is a composite Nano electrode made of Al and Ni. The machine has a maximum load capacity of 700 kg and is 1700 x 1040 x 535 mm (height x width x depth).

2.4 EDM Oil

IPOL SEO 450 is produced utilising high-quality, minimally aromatic, carefully chosen hydrocarbon primary stocks. It is designed with the perfect viscosity for efficient EDM operation with less electrode wear. They almost have no colour, and their minimal aromatic concentration helps to prevent odour and fume formation. When high levels of precision and accuracy are required during electric-discharge machining, IPOL SEO 450 is advised for usage.

Fig. 4: Machining the work piece on EDM

2.5 Input and Output Parameters

Variations of these input parameters, using various mixtures of AMPS, TON, and TOFF, are included in the supplied data. Understanding how modifications to these parameters impact the EDM machining procedure requires the knowledge of these data. This information may be used by researchers to evaluate and improve the EDM procedure for certain purposes, such as raising material removal rates.

2.6 Calculation for MRR

To calculate the weight difference of a work piece before and after EDM machining are given in equation 1,

$$\text{MRR} = \{\text{Initial Weight of specimen Wi} - \text{Final Weight of the specimen Wf}\} \quad \dots (1)$$

Where, Wi -Weight of the work piece before machining, Wf -Weight of the work piece after machining.

2.7 Calculation for 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. The following formula in equation 2 is used to determine the electrode wear rate.

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

2.8 RSM Optimization Technique

The optimization approach known as Response Surface Methodology (RSM) is essential for improving the accuracy and efficiency of Electrical Discharge Machining (EDM). EDM 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

Findings and comments from our thorough examination of electrical discharge machining utilizing various input parameters, including AMPS, TON and TOFF, in this part. The experimental data gathered offers an insightful understanding into the complex dynamics of the EDM process. We want to clarify how these factors affect material removal rates and tool wear through careful investigation. We identify trends, optimizations, and future improvements in EDM machining by contrasting our results with previously published literature. This section's discussion will begin with an experiment examination using RSM analysis on die-sinking EDM of the superalloy Inconel 625.

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

In Fig. 5 shows the Inconel 625 after EDM machining with Al-Ni Electrodes. The EDM machining of Inconel 625 with Al-Ni Nanocomposite electrodes is 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 µs), 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 (µs)	TOFF (µs)	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 ($p < 0.0001$) are shown in the analysis of variance in table 3, suggesting that the suggested model sufficiently fits the data. Pulse ON and Pulse OFF, two of the components, show significant effects with high F-values (916.16 and 10.26, respectively). The model is also highly influenced by interaction effects, such as AB, AC, and BC ($p < 0.05$), highlighting the need to including these interactions in the prediction model. Nevertheless, the response variable is not significantly affected by the squared term for Pulse OFF C2 ($p = 0.7327$), indicating that it makes little contribution to the model.

The standard deviation of 0.0010 indicates low variability in Table 4, while the high R^2 value of 0.9958 suggests a strong correlation between the observed and predicted values, validating the model's accuracy. The Fig. 6 shows the normal plot response surface methodology graph. This is a graphical depiction of the RSM analysis that usually displays the primary impacts and interactions of the input parameters (e.g., current, TON, and TOFF) on the response variable (in this instance, MRR).

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

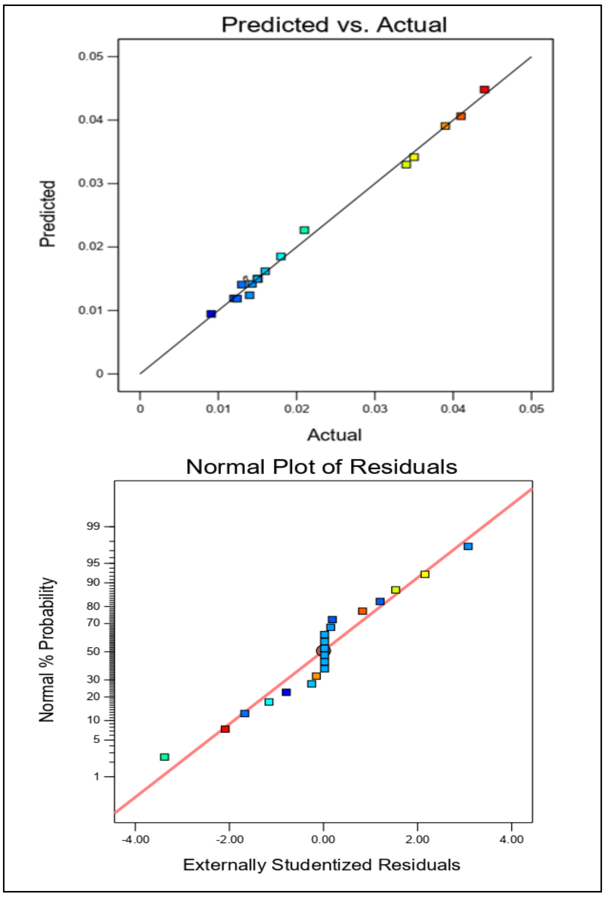

Fig. 6: Diagnostic plot for MRR

The 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.

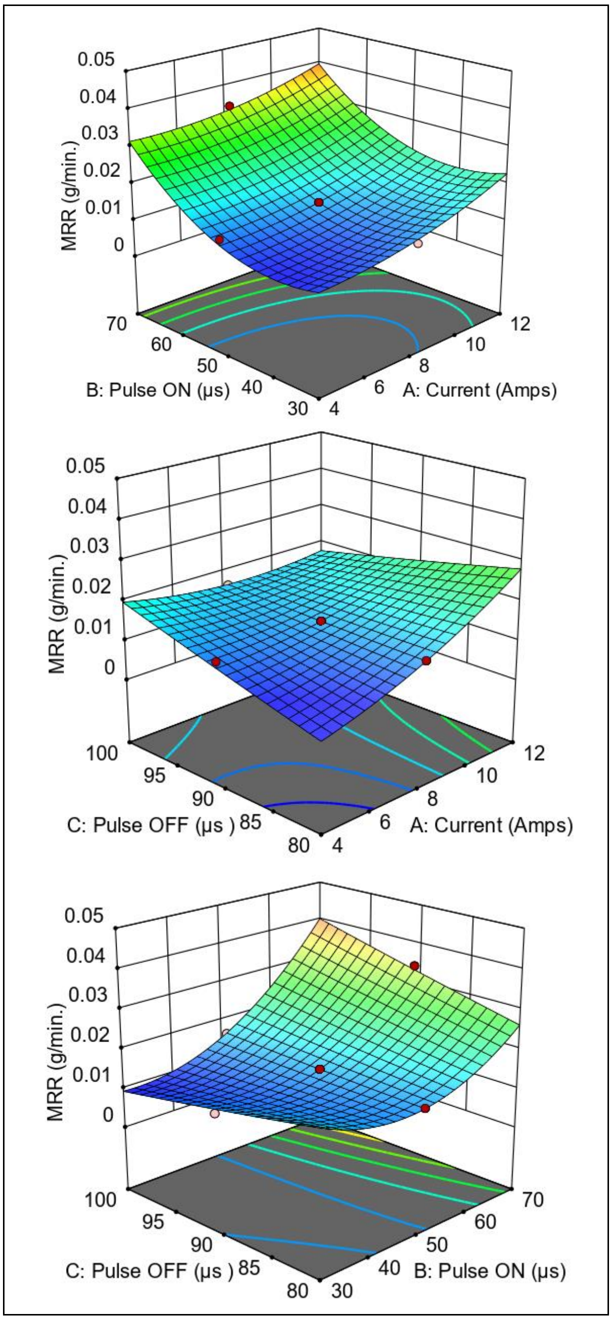

Fig. 7: MRR 3D RSM graph vs Current, TON and TOFF

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. Observations: 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 interplay 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. MRR 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.

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

Table 6, 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. 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 distribution of errors is shown by the fact that the residuals in Fig.8's normal probability plot lie in a straight line. Every observed value is also compared to the model-derived anticipated value shown in Fig. 8. The response ranges from 0.0141 g/min to 0.0021 g/m, as can be seen, with a maximum to lowest ratio, and the regression model reasonably matches the real 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 mm^3/min. Impact of Ton and Toff: Higher EWR 0.0022 g/min. with TON = 70 µs and TOFF = 100 µs, suggesting possible sensitivity to pulse length.

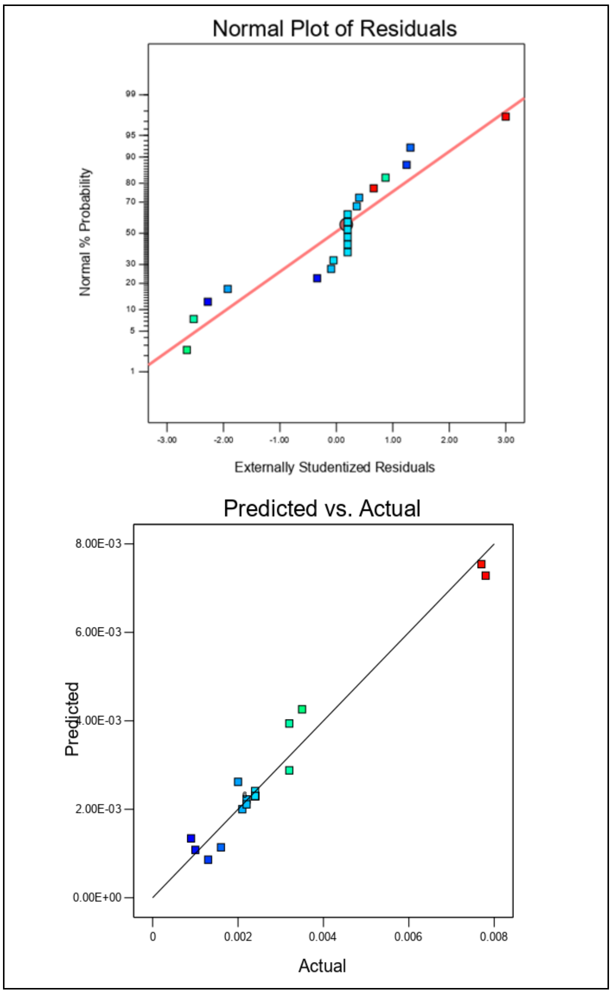

Fig. 8: Diagnostic plot for EWR

From Fig. 10, the Current of 8A appears to be effective show consistent MRR values around 0.015 g/min, indicating a stable performance. A Ton of 50 µs and a Toff of 90 µs also seem to contribute to higher MRR. While EWR varies across the runs, it generally correlates with MRR trends, suggesting that optimizing MRR can indirectly lower EWR. Ton of 30 µs and a Toff of 80 µs, exhibit the lowest EWR among runs with similar MRR values, suggesting that these parameters might contribute to lower wear rates.

From the table 7, the predicted mean and median for MRR are both 0.044, closely aligning with the observed value of 0.044, demonstrating a high degree of accuracy in prediction. Similarly, for EWR, the predicted mean and median are 0.00206356, slightly higher than the observed value of 0.001, with a standard deviation of 0.000508945, indicating some variability in the prediction.

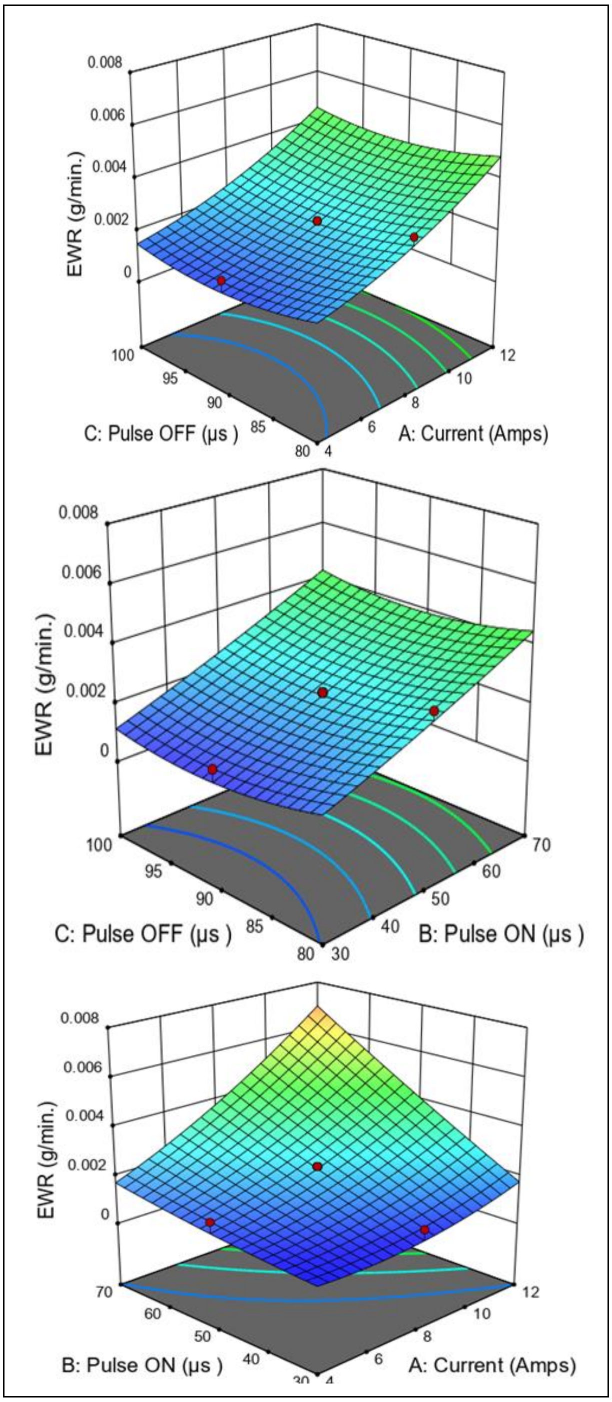

Fig. 9: EWR 3D RSM graph vs Current, TON and TOFF

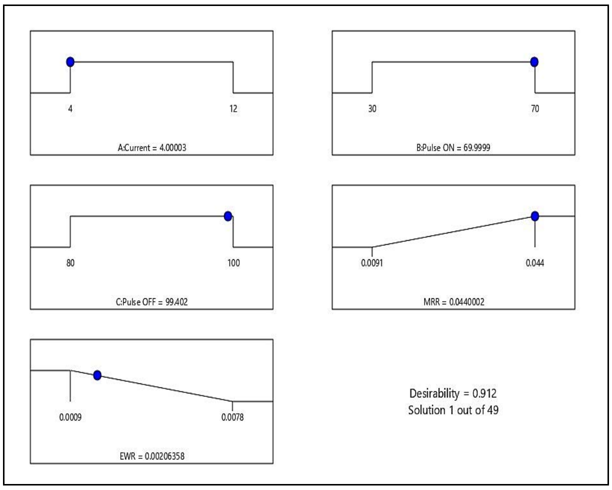

Fig. 10: Ram plot showing MRR and EWR optimal condition

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

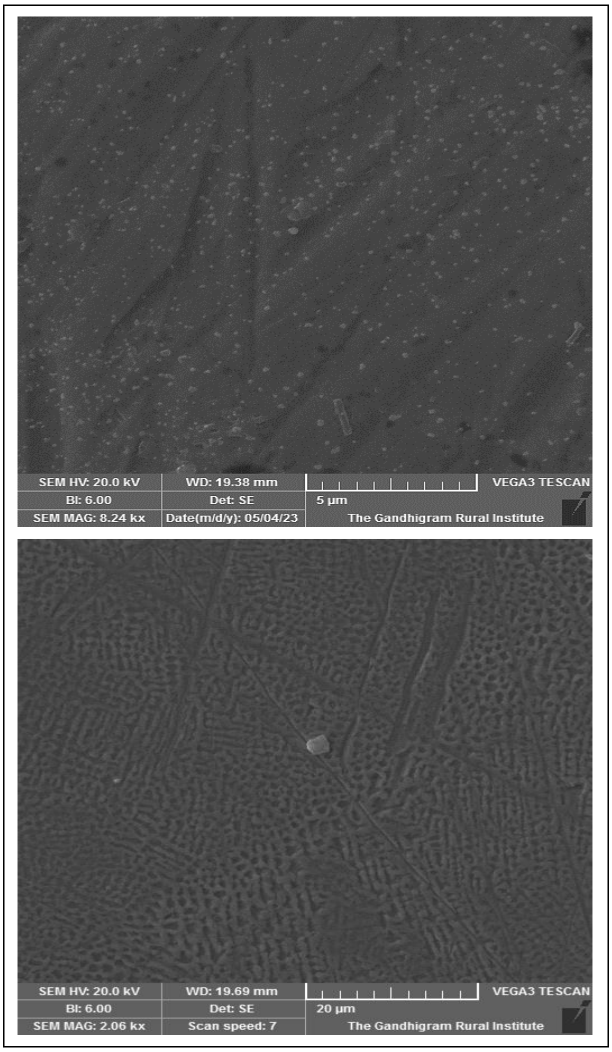

Fig.11: Work piece before machining with EDM

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

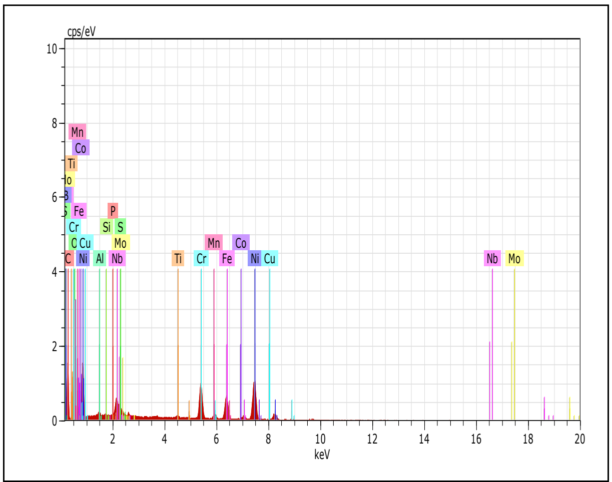

Fig. 12: Work piece before machining with EDM

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

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 surface's chemical composition. SEM analysis of Workpiece 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. From the Fig 13, when hard materials like Inconel come into contact with gas bubbles, tiny holes are created. The materials of the work piece in the machining zone are quickly heated by the electrical discharge machining. After a pulse-off time and a 90-millisecond spark discharge, the machined surface is cooled using an EDM oil flush. Deeper craters are created within the work piece by longer sparking times and higher duty cycles, which remove more material and leave the surface less polished.

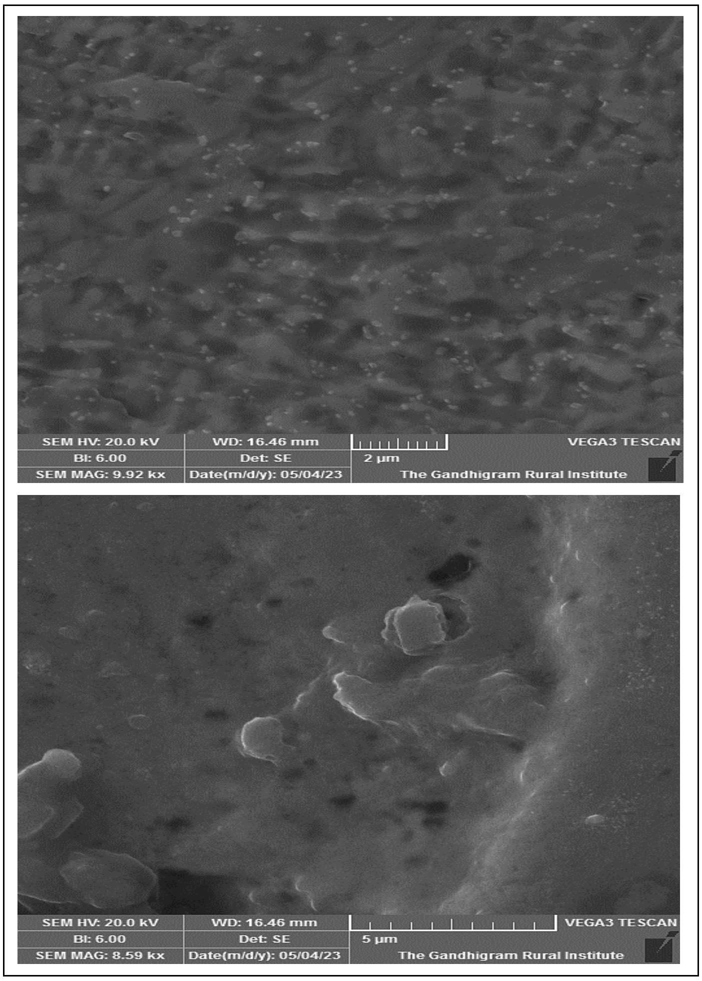

Fig. 13: Work piece after machining with EDM

5. CONCLUSION

Numerous experimental investigations have been carried out to examine the impact of various machining settings on various performance indicators, including MRR and EWR. From this work, the following conclusions may be made.

- The optimal conditions, featuring a moderate current of 8A, a short Ton of 50 µs, and a medium Toff of 90 µs, consistently produce superior Material Removal Rate (MRR) values across multiple runs. The maximum attainable MRR value under these optimal conditions, with Ip = 8A, Ton = 50 µs, and Toff = 100 µs as per the response graph, is 0.044 g/min. Variations in pulse duration exert a more pronounced influence on the MRR metric compared to changes in current intensity.

- Lower MRR values tend to occur under extreme conditions, such as low current (4A) combined with short Ton (30 µs) and Toff (80 µs). Extreme deviations from the optimal condition, such as high Toff (100 µs) at low current (4A), result in unexpectedly low MRR values.

- The potential EWR values span from 0.0009 to 0.0078, indicating varying wear properties. Potential is shown by the optimal operating conditions of runs with lower EWR values with EWR = 0.0009 g/min.

- Lower EWR values tend to coincide with higher MRR outcomes, suggesting an inverse relationship between material removal rate and electrode wear rate. Extreme deviations from optimal conditions, such as high Toff (100 µs) at low current (4A), result in unexpectedly high electrode wear rates.

- To optimize MRR further while minimizing electrode wear, adjustments in pulse duration, especially Ton and Toff, should be prioritized over variations in current intensity.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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