Research Article

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Influence of Novel Al-Ni Electrodes on Roughness and Machining Time in Inconel 625 EDM Machining: A Comprehensive RSM Performance Analysis

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ABSTRACT

In the context of Inconel 625 machining, this study explores the effects of novel Al-Ni nano electrodes on surface roughness and machining time. Thorough performance study was undertaken to clarify the complex connections between the machining settings, electrode composition, and final surface quality. Important insights were obtained via methodical experimentation and data analysis, which helps optimize the machining procedures for improved productivity and surface quality when milling Inconel 625. This research presents an experimental investigation of the effects of the Electric Discharge Machining (EDM) input parameters, namely current, pulse-on time, and pulse-off time, on the surface roughness and machining time output parameters. Inconel 625 was the material of choice for the work piece. Electric discharge machining oil was used as the dielectric fluid and aluminium nanocomposite as the tool electrode. Response surface methodology (RSM) approach was employed in the experimentation. ANOVA was used to optimize the parameters and obtain the lowest possible surface roughness (SR) and machining time. The findings show that pulse-off time is the most significant motivating factor for SR. The current is the main determining factor for machining time. The Central Composite Design approach was used for optimization.

Keywords: Electric discharge machine; Al-Ni nanocomposite electrode; RSM; Surface roughness; Machining time.

1. INTRODUCTION

In this work, we examine how surface roughness and machining time during Inconel 625 machining are affected by Novel Al-Ni electrodes. We seek to decipher the complex interactions between electrode composition, machining settings, and surface quality by using a thorough performance analysis. In the context of Inconel 625 machining, we get important insights that help optimize machining operations for increased efficiency and surface polish through methodical testing and data analysis. One non-traditional machining method is the electric discharge machine (EDM). It finds several uses in the die-making, punching, and mold-making industries. It is also used in the production of surgical components as well as whole automotive parts. Haron *et al.* (2001) investigated the influence of machining parameters of steel, where the work piece and tool electrode are both submerged in a dielectric fluid, such as kerosene or EDM oil. The spark gap is the distance between the electrode and work piece, which varies according on the operating circumstances.

Abbas *et al.* (2007) analyzed the feasibility of machining tungsten carbide ceramics by EDM using a graphite electrode and the Taguchi technique reveals that the Electrode Wear Ratio (EWR) and Surface Roughness (SR) are mostly affected by the current. The most important element affecting Material Removal Rate (MRR) is the pulse duration. Amin *et al.* (2009) found that the graphite electrode provides the highest MRR for tungsten carbide machining when compared to copper and copper tungsten electrode. Haron *et al.* (2008) used XW42 tool steel to investigate MRR using copper and graphite electrodes with varying diameters. Graphite electrode is suitable for finishing, whereas copper is suitable for roughing. Khanra *et al.* (2007) analyzed the wear resistance of copper, copper alloys, and graphite. In order to achieve the optimal blend of electrical, thermal, and wear resistance, a novel composite called ZrB2-Cu was designed. Compared to the copper tool, this composite showed higher MRR with lower Tool Wear TWR.

Kristian *et al.* (2004) reported that the EDM could be the sole technique available for creating deep slots in materials with poor machinability. Compressed air was used as a dielectric and copper electrode was used as a tool in the investigation of SS 316L in an earlier work (Lee and Li, 2001). Another study emphasizes how important it is to comprehend how EDM settings affect Inconel 625 machining in order to maximize productivity and surface quality (Dikshit *et al*. 2019). The study provides insights into the complex interaction between peak current, pulse on time, pulse off time, and machining outcomes by utilizing empirical modelling and statistical analysis. The focus on composite desirability in parameter optimization illustrates a methodical strategy for reaching the intended machining outcomes. The created model's dependability was validated by the strong agreement between anticipated and experimental findings, indicating its usefulness in real-world machining operations. A thorough 5-factor-4-level experimental methodology examined the machinability of four Inconel super alloy grades using electro-discharge machining (Datta *et al*. 2019). By combining a satisfaction function approach with the Taguchi technique, the ideal parameter settings are found. Significant carbon migration and residual carbides after dielectric pyrolysis are shown by surface integrity analysis. The range of material removal rates and surface roughness values across different Inconel grades is 1.8249 mm^3/min to 36.3132 mm^3/min and 4.9667 µm to 14 µm, respectively. These variations highlight the intricacy of EDM procedures and the necessity of exact parameter optimization specific to each material. In order to improve MRR Jeykrishnan *et al.* (2018) explored the use of the Taguchi approach to optimize EDM parameters such as current, pulse on time, and pulse off time. Research on Inconel 625 alloy using copper electrodes demonstrated the effectiveness of EDM in cutting difficult materials and provided information on parameter relationships for increased performance and efficiency.

Sharma *et al.* (2022) conducted a research to maximize the MRR, SR, and TWR of electrical discharge machining for Inconel 625. For improved machining efficiency, the ideal amounts of current, pulse on time, pulse off time, and gap voltage were found using RSM and adaptive network-based fuzzy inference system (ANFIS). The timing of on and off of pulses was found important in determining MRR and SR. Also, ANFIS showed excellent accuracy in response optimization. Subramanian and Nancharaiah (2020) conducted research on using the Taguchi Method, where they examined the effects of wire EDM settings on MRR and SR in Inconel 625. Pulse off time, pulse on time, and servo voltage were optimized for maximizing MRR and minimizing SR using Taguchi orthogonal array L9 and ANOVA analysis. Goyal *et al*. 2018 demonstrated the usefulness of the Taguchi approach and provided information to improve the accuracy of wire EDM procedures and productivity for Inconel 625 alloys. They employed diffused wire tool electrodes (plain and cryo-treated) to optimize SR on Inconel 625 by wire electrical discharge machining. In order to evaluate the effects of machining factors such as current, wire feed, tension, and pulse on/off timings, Taguchi's L18 orthogonal array was utilized. This study focused on producing rectangular slits for a range of industrial uses, emphasizing the value of Design of Experiment (DoE) optimization methods for improving machining productivity and surface smoothness. Talla *et al*. (2017) examined how graphite powder in powder-mixed EDM (PMEDM) affects Inconel 625's surface integrity. They found improvements in hardness, decreased tensile residual stress, and white layer thickness in addition to decreased surface roughness and crack density. Jayakumar (2021) optimized the EDM parameters for Inconel 625 in order to minimize SR and maximize MRR. The study examined the effects of current, voltage, pulse on time, and electrode bottom profile on machinability responses using Taguchi's L9 orthogonal array.

Parthiban *et al*. (2024) employed response surface methodology and particle swarm optimization (PSO) to examine the effects of input parameters on MRR, tool TWR, overcut (OC), and taper ratio (TR) in micro-EDM of Hastelloy C276. The study clarified the link between input and output features using RSM-based Box-Behnken design. The PSO approach provided better optimization than conventional RSM techniques, indicating possibilities for better micro-EDM processes in aerospace applications. Chaurasia *et al*. 2024) carried out a study to understand the robustness of Laser Directed Energy Deposition in repairing Inconel 625. Microstructural examination revealed different grain structures. The study proved the efficacy of laser-directed erosion restoration in restoring and augmenting the mechanical integrity of Inconel 625 components.

Le and Hoang, (2024) investigated the use of tungsten carbide powder in dielectric liquid during EDM of SKD61 steel along with its effects on SR, Wire EDM, TWR, and MRR. The best process variables were found using Box-Behnken design and mathematical modelling. An ANOVA test verified the suitability of the model. Current had a major impact on SR, MRR, and TWR, as revealed by multi-attribute optimization using TOPSIS, DA, and NSGA II-EAMR. This highlighted the effectiveness of DA in minimizing TWR and maximizing MRR, while TOPSIS was found to be superior in lowering SR and enhancing surface quality. Yadav *et al.* (2024) employed an intelligent hybrid strategy that uses ANOVA, RSM, Artificial Neural Network (ANN), and Non-dominated Sorting Genetic Algorithm (NSGA-II) to optimize tool nose radius and cutting parameters in order to improve the machinability of Incoloy 925. The study suggested that the hybrid model helps companies choose the best machining parameters for Ni-based alloy machining, supporting environmentally friendly production practices. Sivaiah *et al*. (2024) investigated the environmentally friendly Minimum Quantity Lubrication (MQL) technique for end milling Inconel 825. The study showed that the MQL technique could significantly reduce cutting temperature and surface roughness when compared to dry conditions, and also improve machinability in difficult-to-cut materials. Taguchi techniques were used by EDM to optimize 25 combinations of process variables for Si_3N_4–TiN. The optimal parameters were found by using GRA and TOPSIS to identify important factors such as pulse current and pulse-on time. These factors included 12 A current, 7 µs pulse-on time, 4 µs pulse-off time, 12 kg/cm^2 dielectric pressure, and 36 V spark gap voltage (Srinivasan *et al.* 2022). Narashima *et al.* (2022) researched hybrid fiber-metal laminate for vehicle bumpers with the goal of improving impact resistance. It achieved a deformation range of 0.017378 m to 0.03114 m and a maximum stress prediction of 2.424 × 102 MPa by mixing basalt fiber with aluminum and glass fiber, mimicking the qualities of the parent material and promising superior performance through simulation comparison in everyday use.

With the above background, an experimental research on the effects of current, pulse on time, and pulse off time on the output parameters of surface roughness and machining time is presented in this work. Inconel 625 was selected as the work piece material, while EDM oil was used as the dielectric fluid and an aluminium composite as the tool electrode. In order to minimize surface roughness and machining time, the experimental design makes use of the response surface methodology in conjunction with ANOVA for parameter optimization.

2. MATERIALS AND METHODOLOGY

2.1 Material Selection

This study aims to investigate the potential efficacy of aluminium nanocomposite electrodes as EDM tool materials on Inconel 625 work pieces. An Al-Ni nanocomposite electrode with a range of process parameters (input current, pulse on time, and pulse off time) was originally used in EDM. The Inconel 625 work piece was sliced into a spherical shape with a depth of 2 mm. Standard Inconel 625 specimens were tested for comparative analysis. The SR and MT of the composite aluminium nanotool were determined at various process settings.

2.1.1 Selection of Work Piece

Inconel 625 grade alloy material was purchased from a material store in 100 ×100 mm in size, with a 10 mm thickness and cut into 9 discrete squares. These work pieces were machined using an electrical discharge machining technique. Inconel 625 is mostly used die and mold making industry. Nonconventional machining methods are employed to fill dies with complicated shapes. Inconel 625 castings provide excellent defense against seawater corrosion and chloride stress corrosion cracking. In Inconel 625 castings, molybdenum can be found in relatively high quantities, offering outstanding high temperature strength up to around 1800 °F (982 °C), along with strong fatigue and high creep strength. Niobium is added to a solid solution alloy comprising nickel, chromium, and molybdenum called Inconel 625. This alters the atomic structure of the alloy when combined with molybdenum, giving it an unusually high hardness in the overheated form without a purposeful strengthening heat treatment. Figure 1 shows the prepared specimen for machining with EDM.

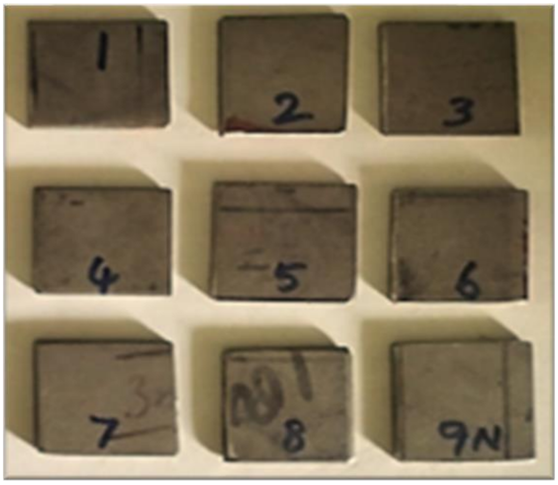

Fig. 1: The work piece of Inconel 625 for machining EDM

Table 1. Composition of Inconel 625

Element	Content (%)
Ni	58%
Cr	23%
Mo	9%
Fe	5%
Nb + Ta	3.44%
Co	1%
Mn	0.5%
Si	0.5%
Al	0.4%
Ti	0.4%
C	0.1%
P	0.015%
S	0.015%

(a) Chemical Composition of Inconel 625

The composition of Inconel 625 is outlined in Table 1. This alloy is rich in chromium and high in nickel, with a composition of 58% Ni, 23% Cr, 9% Mo, and 5% Fe. Its robust qualities and uses across a range of sectors are further enhanced by the modest percentages of elements such as Nb + Ta (3.44%), Co (1%), Mn (0.5%), Si (0.5%), Al (0.4%), and Ti (0.4%), as well as trace amounts of C, P, and S (0.1%, 0.015%, and 0.015%, respectively).

(b) Mechanical Properties

The mechanical properties of Inconel 625 are displayed in Table 2.

Table 2. Mechanical properties of Inconel 625

Properties	Metric
Tensile strength	130 Mpa
Yield strength	65 Mpa
Elongation	30 %
Hardness	195 Mpa

2.1.2 Selection of Electrode

Aluminum with nickel-based reinforcement was chosen as the electrode material in this experiment. The tool electrode for electrical discharge machining (Fig. 2) was developed using powder metallurgy.

Fig. 2: Nano electrode Al-Ni

Aluminium is a low-density material that can be quickly cast, machined, and molded and has great corrosion resistance and high thermal conductivity. Nickel is a silvery-white, ductile, flexible, and strong metal. Nickel alloys are known for their strength, ductility, and corrosion and heat resistance. Aluminum and its alloys are vital to aerospace industry. Nickel is also used as a reinforcement (10 wt% of nickel is alloyed with aluminum). Table 3 shows the composition of nano electrodes with weight percentage. An important development in the production of electrodes for a range of industrial uses is the use of powder metallurgy to fabricate Al-Ni electrodes, which are 90% aluminium and 10% nickel. Precise control over composition and microstructure is made possible by powder metallurgy processes, which make it easier to produce electrodes with customized qualities to satisfy particular needs. These electrodes are appropriate for a variety of electrochemical processes because the combination of aluminium and nickel provides a special mix of mechanical strength, corrosion resistance, and electrical conductivity. Combining powders of aluminium and nickel, compaction under regulated pressure, and sintering at high temperatures are the steps in the process that lead to the correct density and metallurgical bonding. Excellent thermal stability, oxidation resistance, and improved performance in challenging working settings are displayed by the resultant electrodes.

Table 3. Weight % of aluminium composite electrode

Aluminium Wt. %	Nickel Wt. %
90	10
Aluminium (gram)	Nickel (gram)
13	2

2.2 Research Methodology

Various steps in the methodology are shown in Fig. 3.

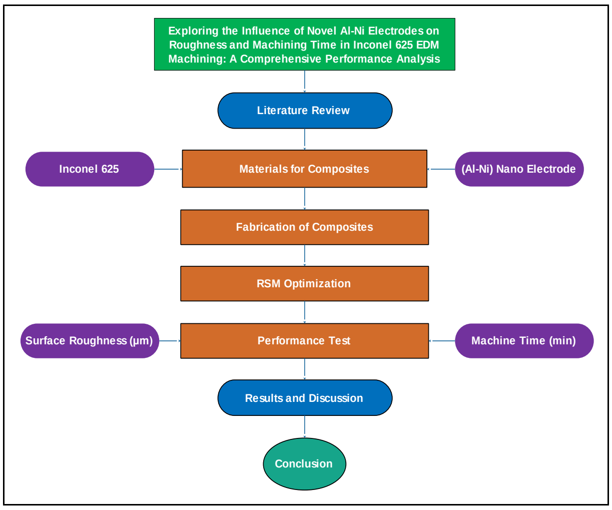

Fig. 3: The flow methodology of experiment analysis

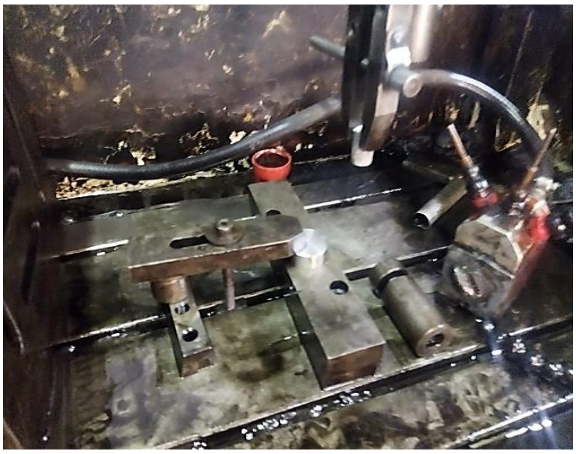

Fig. 4: EDM Machine experimental setup

2.3 EDM Machining of Work Piece

The experiment was carried out on an EDM gadget. Electrical discharge machining is illustrated in

Fig. 4. It is a non-traditional method of machining, which removes material from a part by electrically discharging the work piece repeatedly and in the presence of a dielectric fluid.

2.3.1 Gap Setting

A gap of 0.25 mm between tool electrode and work piece was maintained before machining operation.

2.3.2 Selection of Process Parameters

Machining parameters: The fixed and variable machining parameters are as follows:

Sparking Voltage (V) : 80 V

Servo Control : Electro Mechanical

Polarity : Normal (Electrode-Positive)

Dielectric Fluid : EDM Oil

Electric discharge machining oil is made with high-quality lubricant base oil to provide unrivalled performance. It is a clear, colorless, fragrant and non-toxic dielectric fluid. Its high flash point and low viscosity contribute to a safe and comfortable work environment. In this research, based on literature review, a specialized spark erosion oil was chosen (IPOL SEO 450).

Table 4. Surface roughness and machining time

Std.	Current (A)	Pulse ON (µs)	Pulse OFF (µs)	Surface Roughness (µm)	Machining Time (minutes)
1	8	50	90	4.207	23.17
2	12	70	80	6.423	17.58
3	12	50	90	5.834	22.15
4	8	50	90	4.207	23.17
5	8	50	90	4.207	23.17
6	8	70	90	5.171	18.29
7	8	50	90	4.207	23.17
8	4	30	80	3.308	43.11
9	8	50	90	4.207	23.17
10	12	30	80	4.526	30.43
11	4	70	80	6.55	24.16
12	12	70	100	6.423	17.58
13	4	50	90	6.714	31.37
14	8	50	90	4.207	23.17
15	4	70	100	6.558	24.16
16	8	50	100	4.111	22.01
17	4	30	100	6.714	43.11
18	8	50	80	4.209	24.07
19	12	30	100	4.526	30.43
20	8	30	90	4.779	34.41

2.3.3 Variable Machining Parameters

Discharge Current : 4, 8 and 12 A
Electrode Material : Al-Ni

Similarly, the input and output parameters are given below.

Output Parameters

a) Surface Roughness (SR)
b) Machining Time (Mt)

2.4 Evaluation of Parameters

a) Surface Roughness (SR)

A surface profilometer was used to measure the surface profile along a specified length of the machined surface.

b) Machining Time (Mt)

The time to be taken for machining a work piece in a desired or required shape was estimated using stop clock.

c) Response Surface Methodology

In the current investigation, the RSM was used to design the experiments. The central composite design approach predicts the number of tests carried out in order to acquire only the necessary trials and avoid making the same mistake twice.

Fig. 5: Work piece after machining by EDM

3. RESULTS AND DISCUSSIONS

The collected data were analyzed to determine how electrode composition affects surface roughness and machining time, Mt (Table 4). Our research clarifies the subtleties of the Al-Ni electrodes' performance and provides important information for enhancing the Inconel 625 EDM process. This discussion may contribute to the investigation of cutting-edge materials and precise machining methods. Figure 5 shows the work piece machined by EDM.

There were variances in the standard input factor time during the experimental runs of the RSM. The data analysis shows complex correlations between the machining performance and the input parameters. These results give a comprehensive knowledge of the relationship between machining parameters and results, which is helpful in optimizing the EDM process for Inconel 625 employing new Al-Ni nano electrodes.

An extensive statistical analysis of an experimental investigation on EDM machining is shown in Table 5. The response variable is strongly impacted by at least one factor, since the model demonstrates overall significance ($p = 0.0034$). With a low p-value (0.0029) and a considerable F-value (15.30), Pulse On Time (B) stands out as a highly significant factor that appears to have a major impact on the machining process. Notable are the quadratic impacts of Pulse On (B^2) and Pulse Off (C^2), which highlight their significant influence. The absence of a fit test results in a well-fitted model ($p = 0.6913$), confirming the model's accuracy in describing the correlation between the response variable and the components in EDM machining.

Table 5. ANOVA table for surface roughness

Source	Sum of Squares	df	Mean Square	F value	P value
Model	20.51	9	2.28	6.59	0.0034
A-Current	0.4461	1	0.4461	1.29	0.2825
B-Pulse on	5.29	1	5.29	15.30	0.0029
C-Pulse off	1.10	1	1.10	3.18	0.1048
AB	0.0627	1	0.0627	0.1813	0.6793
AC	1.46	1	1.46	4.21	0.0672
BC	1.44	1	1.44	4.18	0.0683
A^2	6.78	1	6.78	19.61	0.0013
B^2	0.2021	1	0.2021	0.5847	0.4621
C^2	0.8136	1	0.8136	2.35	0.1560
Residual	3.46	10	0.3457		
Lack of Fit	3.46	5	0.6913		
Pure Error	0.0000	5	0.0000		
Cor Total	23.97	19			

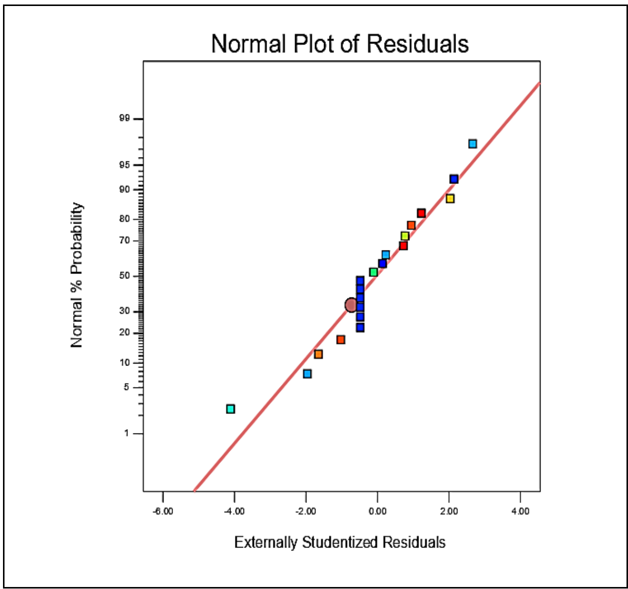

Fig. 6: Normal distribution of surface roughness value

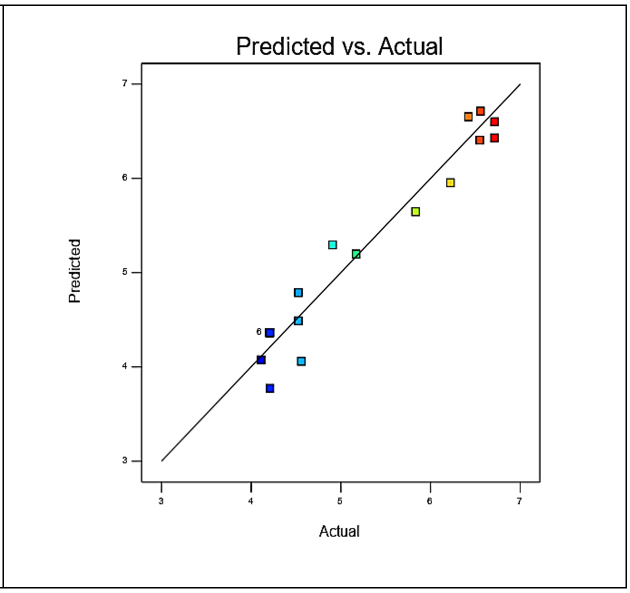

Fig. 7: Surface roughness predicted vs Actual plot

Figures 6 and 7 show the normal distribution of surface roughness value and the comparative plot of predicted vs. actual SR values. The Predicted vs. Experimental plot is a graphical representation that compares the anticipated values from a statistical model with the actual experimental values.

The link between surface roughness and the independent variables (Current, Pulse On, and Pulse Off) in EDM machining may be shown visually via a 3D surface graph. The best combinations of input parameters for obtaining the required surface roughness may be found by looking for patterns in the 3D surface plot. Lower altitudes or colder hues are signs of ideal parameter settings that provide a better surface quality. Investigating the interplay between input parameters throws light on the complex interactions that lead to surface roughness changes. The 3D graph in Fig. 8 offers a thorough knowledge of the EDM process and helps identify the ideal machining settings by graphically capturing the multidimensional influence of input parameters on surface roughness.

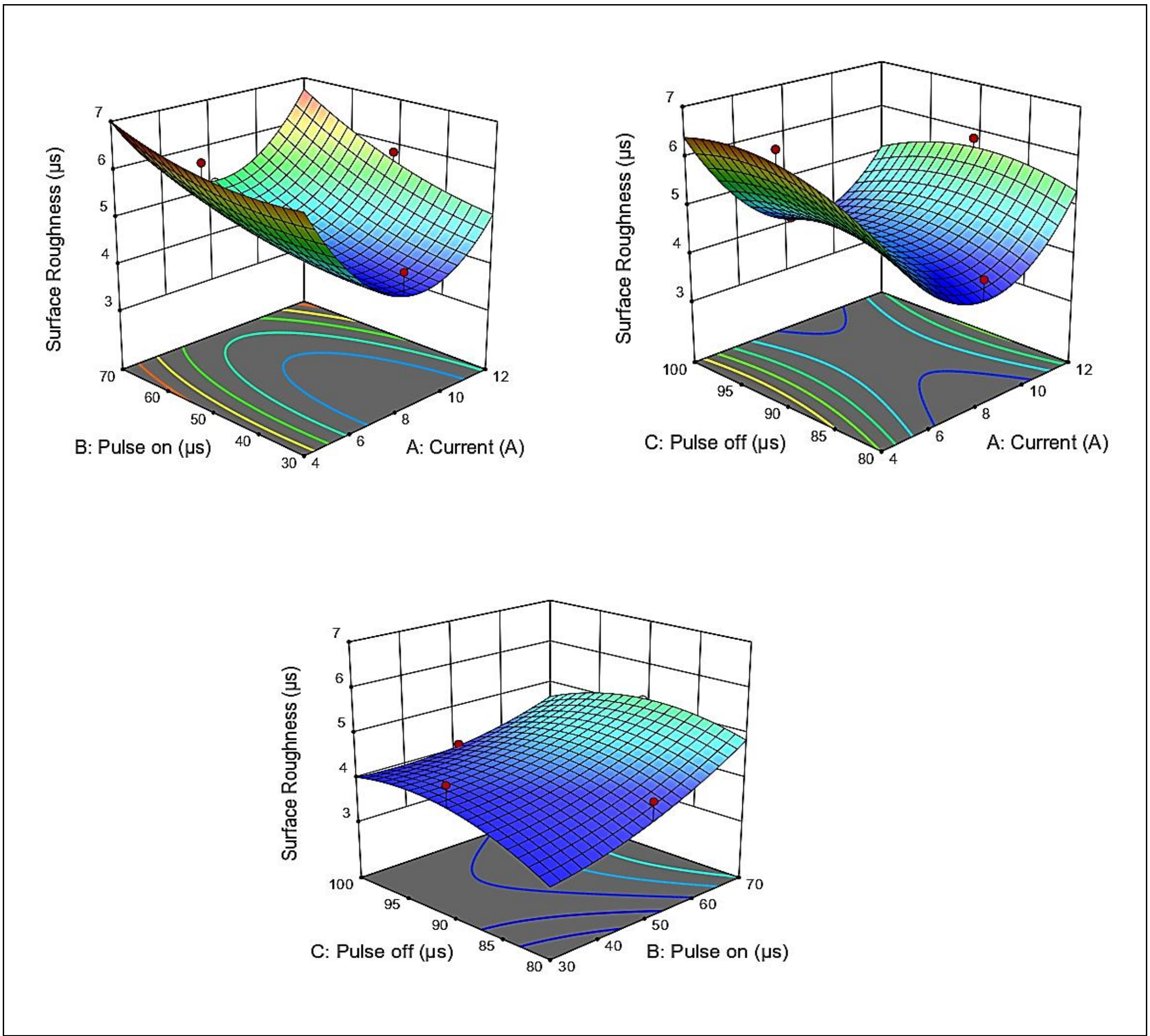

Fig. 8: 3D Surface roughness vs Pulse ON, Pulse OFF & Current

Table 6. ANOVA table for machining time

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	1012.46	9	112.50	508.63	< 0.0001
A-Current	227.91	1	227.91	1030.47	< 0.0001
B-Pulse on	635.53	1	635.53	2873.46	< 0.0001
C-Pulse off	0.4244	1	0.4244	1.9200	0.1961
AB	18.61	1	18.6100	84.1200	< 0.0001
AC	0.0000	1	0.0000	0.0000	1.0000
BC	0.0000	1	0.0000	0.0000	1.0000
A²	28.69	1	28.6900	129.720	< 0.0001
B²	21.87	1	21.8700	98.8800	< 0.0001
C²	0.6603	1	0.6603	2.9900	0.1147
Residual	2.21	10	0.2212		
Lack of Fit	2.21	5	0.4423		
Pure Error	0.0000	5	0.0000		

The response variable is strongly influenced by at least one factor (Table 6). From the values, it turns out that the model is very significant ($p < 0.0001$). Two of the individual components, current (A) and pulse on (B), show significant effects, supported by large F-values and very low p-values ($p < 0.0001$). The combined influence of current and pulse on the response variable is shown by the extremely significant interaction term AB ($p < 0.0001$). The absence of a fit test indicates a well-fitted model ($p = 0.4423$), meaning that the selected model well captures the relationship between the response variable and the variables. Strong statistical support is shown by the study for the importance of current, pulse on, and their combination in affecting the results.

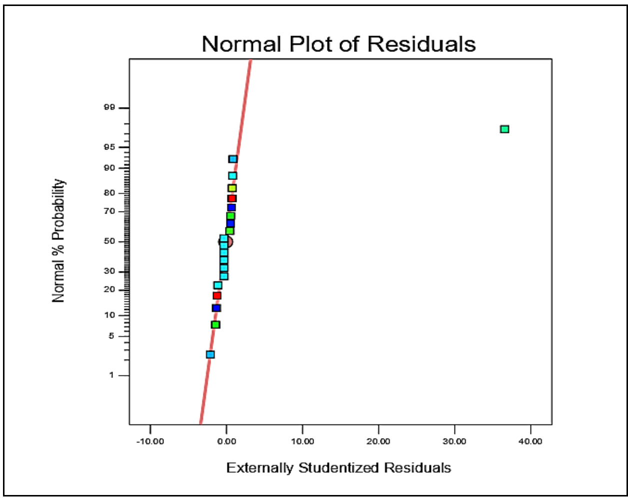

Fig. 9: Normal distribution of machining time

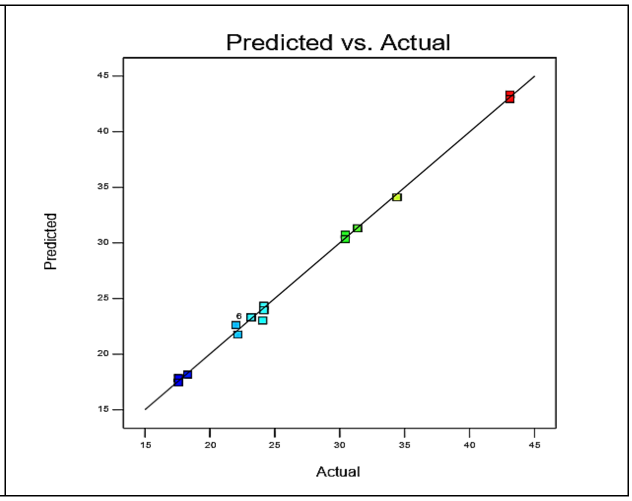

Fig. 10: Machining time predicted vs Actual plot

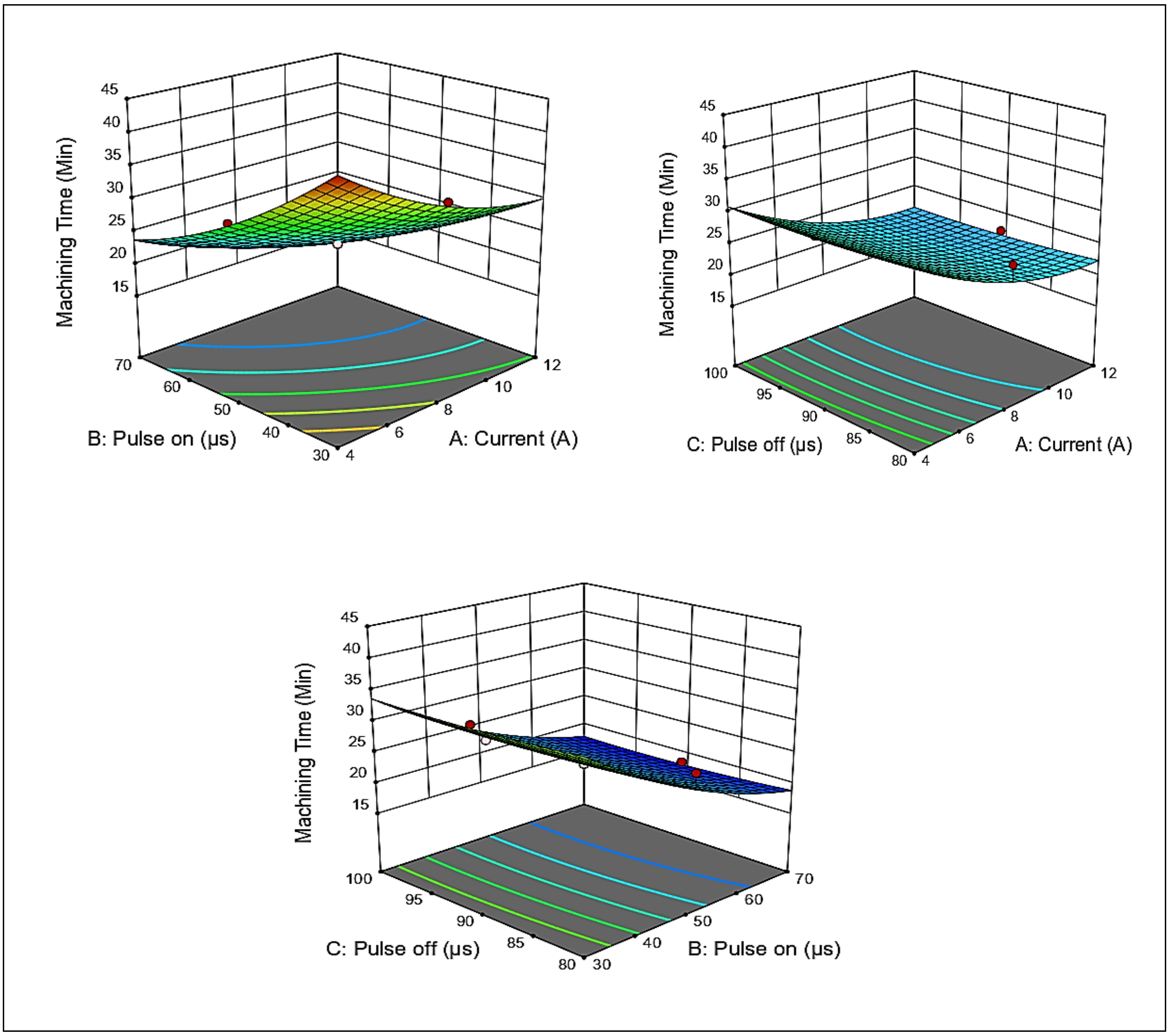

Fig. 11: 3D Surface plot graph of machining time vs. Pulse ON, Pulse OFF & Current

Figures 9 and 10 show the standardized impacts of standard current, pulse ON time, and pulse OFF time on the machining time in Inconel 625 EDM. The relative importance of each parameter and any trends or patterns affecting machining time can be determined by visually analyzing the normal plot. The RSM model's projected values and the actual experimental machining times are compared in the projected vs. experimental plot for machining time. The RSM model's prediction abilities are visually validated when data points match with the diagonal line, which indicates the model's accuracy in forecasting machining times based on standard current, pulse ON time, and pulse OFF time. Figure 11 shows the intricate interactions of pulse on, pulse off and current on machining time. A region's ideal or suboptimal machining conditions are shown by contour lines or color changes. This study used RSM to produce an intricate 3D surface map that provides a thorough grasp of how input parameters and machining time interact in EDM. The determination of ideal machining settings for increased EDM process efficiency is made easier by the visual depiction.

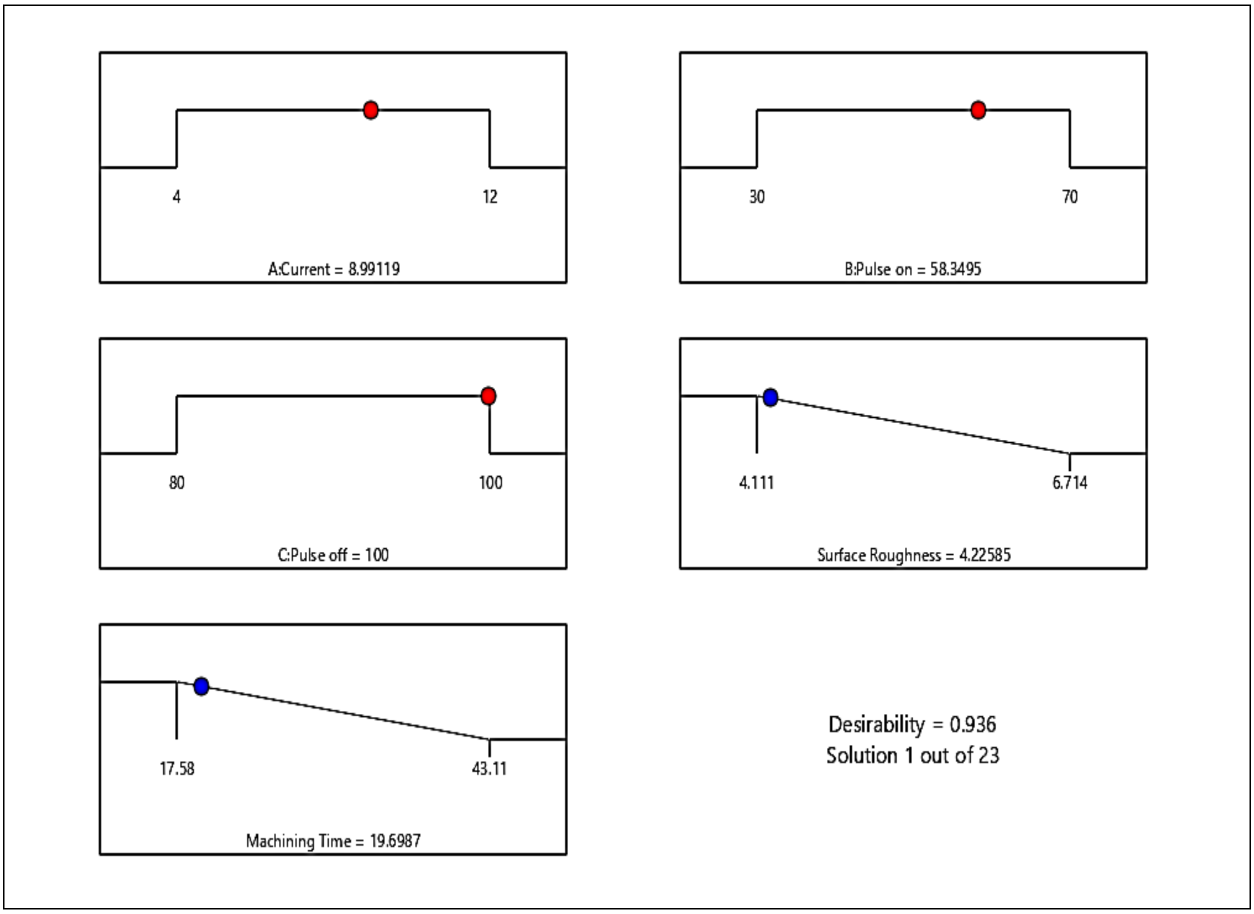

Fig. 12: RAM plot curve surface roughness and Machining time vs. Pulse ON, Pulse OFF & Current

Table 7. Confirmation test table

Response	Predicted Mean	Predicted Median	Observed	Std. Deviation	n	S.E Prediction
Surface Roughness	3.77244	3.77244	4.209	0.333066	1	0.406683
Machining Time	24.5027	24.5027	27.07	1.14165	1	1.39398

The link between surface roughness / machining time, current, and pulse on/off timings is depicted in the Ram plot (Fig. 12). It helps to optimize EDM settings for better surface finish and efficiency by showing trends where longer pulse durations and higher currents may correspond with increasing surface roughness, while shorter machining times are linked to higher currents and particular pulse lengths. For surface roughness and machining time the confirmation test table (Table 7) helps to evaluate the predictive model's accuracy and dependability in forecasting surface roughness and machining time in the current context by comparing anticipated and observed values.

4. CONCLUSION

This experimental investigation examined the effects of an aluminum nanocomposite tool electrode on surface roughness and machining time in the context of machining Inconel 625.

- Based on systematic testing and analysis, pulse on time was shown to be the key influencing factor for surface roughness, followed by pulse off time and current.
- The ideal values for decreasing surface roughness during Inconel 625 machining were: current (4 A), pulse on time (30 µs), and pulse off time (80 µs).
- The research focused on current as the most important parameter in terms of machining time reduction, highlighting its relevance in reducing the amount of time needed to mill Inconel 625.
- The parameters to minimize the amount of time needed to machine Inconel 625 were: current (12 A), pulse on time (70 µs), and pulse off time (90 µs).
- These results highlight the importance of careful parameter selection in achieving desired results, especially in Inconel 625 machining.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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