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Performance and Wear Analysis of Al-Cu-ZrB2 Nano-Composite Electrodes in EDM Machining of D2 Die Steel

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ABSTRACT

The goal of this research study is to enhance EDM machining performance by reducing electrode wear rate, improving surface roughness, and increasing the material removal rate. To overcome the drawbacks of Pure aluminum electrode Prepared a novel nanocomposite electrode for die-sinker EDM an aluminum base Nanocomposite material reinforced with 2.5% copper and 2.5% zirconium dibromide composite electrodes can lower wear and manufacturing costs. Unlike conventional studies focusing on standard copper or graphite electrodes, our research explores the performance of innovative Al-Cu-ZrB_2 Nano-composite electrodes. It is fabricated through powder metallurgy. The input parameters of the EDM process that affect how well the machining process performs are the discharge current, spark-on time, Pulse off time, workpiece material, tool material and inter-electrode distance. For machining analysis and optimization carried out using Analysis of Variation, the RSM technique of experimentation was selected. The workpiece chosen for EDM machining in this experimental study was D2 Die steel. To get a low wear rate, the following input variables must be used: The lowest wear rate obtained during the EDM machining was 0.0006 g/min, the optimal pulse ON is 50µs, the optimal pulse OFF is 80µs, and the current is 12 amps. The research highlights the attainment of lower surface roughness values (1.710µm) by utilizing specific EDM parameters: Ton set at 30µs, Toff at 100µs, and Current at 12A. Surface imperfections induced by different input factors are identified via the use of optical microscopic pictures.

Keywords: EDM; Novel composite electrode; D2 Die Steel; Parameter optimization; Wear rate; Surface roughness; RSM.

1. INTRODUCTION

Conventional electrode materials used in Electrical Discharge Machining (EDM) include copper and graphite. However, because of these materials' low strength, poor heat conductivity, and quick wear, researchers are now looking at other materials. Because of a special set of qualities, such as superior wear resistance, greater mechanical strength, and better thermal conductivity, Al-Cu-ZrB_2 nanocomposite electrodes have become attractive substitutes. It is well known that adding ZrB_2 nanoparticles to the Al-Cu matrix improves the overall efficiency of EDM machining in order to assess and contrast the performance of Al-Cu-ZrB_2 Nano-composite electrodes with that of traditional copper and graphite electrodes; this research offers a thorough investigation of the electrodes' EDM machining capabilities. The study highlights how the electrode material affects D2 die steel wear behavior during EDM, with a particular emphasis on a thorough examination of wear rates. The study also investigates how minimizing tool wear might enhance surface quality and prolong electrode service life by optimizing electrode composition and manufacturing methods.

Below are a few literature reviews that are relevant to my study project. (Singh *et al.* 2004) In the year 2004, Shankar Singh and colleagues conducted an investigation on En-31 tool steel (IS designation: T105 Cr 1 Mn 60) that had been hardened and tempered to reach a hardness of 55 HRc. The primary objective of the study was to analyze the influence of machining parameters, with a specific focus on pulsed current, on various machining aspects. The research involved employing EDM on the work material using an array of electrodes namely copper, copper tungsten, brass, and aluminum. Pulsed current was deliberately altered, including polarity changes, to observe and comprehend its impact on the machining process and subsequent outcomes. (Kanlayasiri *et al.* 2007) The investigation's results show that parameter settings have a substantial impact on the surface roughness of wire-EDMed DC53 die steel. As these two values rise, the test specimen's surface becomes rougher. Then, a mathematical model that links the factors to surface roughness was created using the multiple regression technique. The developed model has a maximum prediction error of less than 7% and was confirmed using a fresh set of experimental data. (Kunal *et al.* 2023) Using copper as the tool electrode material, an experiment was carried out and meticulously examined to show the effects of various input and output parameters. The Box Benkhen Design, based on the response surface approach, was utilized to enhance the machining variables. The findings of this study are valuable for understanding how the incorporation of B_4C and graphene particles affects the wear resistance properties of Al–Cu alloy-based composites (Sachit *et al.* 2023). The Taguchi method provides a structured approach for analyzing and optimizing the wear performance of these composite materials.

Singh *et al.* (2019) the study examines wear mechanisms in aluminum alloy (AA5083) composites reinforced with 300 mesh-sized boron carbide (B4C) particles. The fabrication employed the stir-casting technique to create composite specimens with varying boron carbide proportions (5%, 10%, 15%, and 20% by weight of the aluminum alloy). The research underscores the significant enhancement in wear resistance displayed by these metal matrix composites when compared to the base alloy, emphasizing their potential. Qiu *et al.* (2017) research investigated Al–Cu particles reinforced with SiC nanoparticles, employing semisolid stirring and ball milling methods. Particle distribution was analyzed using X-ray powder diffraction (XRD) and Scanning Electron Microscope (SEM). The study confirmed substantial reinforcement from the SiC nanoparticles, leading to notable enhancements in the mechanical properties of the composites. Specifically, the tensile strength of the composite significantly improved due to the successful incorporation of SiC particles and the establishment of a strong interfacial bond between SiC and the Al–Cu alloy. (Rengasamy *et al.* 2016) The objective of this work is to investigate the mechanical properties of Al 4032 alloy integrated with in-situ ZrB2 and TiB2 composites. Additionally, the study seeks to optimize EDM process parameters for these composite materials. The research combines experimental analysis and parameter optimization to enhance the understanding of EDM machining characteristics and improve the efficiency and precision of EDM processes on these composite materials.

Kumar *et al.* (2016) investigate the EDM process for Al 2618 alloy integrated with in-situ composites of Si3N4, AlN, and ZrB2, specifically focusing on the behavior of the material at high temperatures. The research involves experimental analysis to understand the effects of EDM under high-temperature conditions and its implications on the machinability of these composite materialsv (Jin *et al.* 2005). The incorporation of ZrB2 in copper coatings is aimed at improving the properties relevant to EDM. The study aims to investigate the fabrication process, structural characteristics, and properties of these coatings, specifically in the context of their performance as EDM electrodes. The assessment likely involves analyzing factors such as wear resistance, thermal conductivity, and other aspects that influence their effectiveness during EDM operations. Khanra *et al.* (2007) evaluate the effectiveness and performance of the ZrB2–Cu composite material, specifically in the context of EDM electrode applications. The research likely encompasses an experimental investigation, analyzing parameters such as material removal rate, electrode wear, surface finish, and other relevant aspects to understand how this composite material enhances EDM processes. (Somani *et al.* 2023) This research includes the characterization of SiC-reinforced Cu-matrix composites, understanding their material properties, analyzing their behavior during EDM processes, and assessing the improvements they bring to the EDM machining performance. Parameters such as material removal rate, electrode wear, and surface finish are likely to be evaluated to determine the effectiveness of these composites in EDM.

Senthamarai *et al.* (2023) study is to understand the wire EDM characteristics of aluminum matrix composites. The use of the TOPSIS method indicates a structured approach for analyzing EDM properties and optimizing the machining process. The research likely delves into experimental analyses to assess parameters such as material removal rate, surface finish, and related characteristics, thus aiding in improving EDM efficiency for these composite materials. (Kumar *et al.* 2023) The incorporation of ZrB2 and fly ash into the Aluminum 7075-based composite likely aims to enhance properties such as wear resistance, friction coefficient, and mechanical strength. The research likely involves experimental analysis and testing, including tribological tests and mechanical tests, to assess how the presence of these components influences the composite's behavior under specific conditions. (Kim *et al.* 2019) The study involved fabricating Al–Cu composites via spark plasma sintering and investigating the impact of varying weight percentages of added copper on the physical and thermal properties. The research findings clearly indicate that the inclusion of copper leads to notable enhancements in the performance of the composites. (Mei *et al.* 2020) The research focused on enhancing the distribution of graphene oxide–Al powder on aluminum by incorporating copper ions using a straightforward electrostatic adsorption method. The study investigated the resulting improvements in the composite's mechanical properties. The addition of copper ions was found to significantly enhance the performance of the composite.

This study examined the Al-Cu-ZrB2 composite that was created via powder metallurgy and its Electrical Discharge Machining (EDM) performance. This kind of manufacturing has several benefits and makes it easier to precisely create complex forms. Aluminum was selected as the main matrix for the composite, and it was strengthened with copper particles and zirconium dibromide (ZrB2). High carbon high chromium steel was used as the workpiece material, and several process parameters were used throughout the EDM process. The composite tool's efficiency was increased, and assessments of Electrode Wear Rate (EWR) and Surface Roughness were carried out. For every sample, a comparative analysis of the machining performance was performed with various input parameters.

2. EXPERIMENTAL METHODS AND METHODOLOGY

2.1 Material Selection and Methods

In this study, an Al-Cu-ZrB_2 nanocomposite is utilized as the electrode to machine D2 die steel workpieces. The focus is to investigate the machining efficiency of this composite material by varying the pulse on time during the EDM process. The Al-Cu-ZrB_2 nanocomposite electrode material was prepared using a powder metallurgy route. The composition and microstructure of the composite were analyzed prior to machining. The EDM process was conducted using a suitable EDM machine equipped with appropriate control parameters. A round cut with a depth of 2 mm was performed on the D2 die steel workpiece.

Various pulse on times were employed to study their effect on the machining performance. The EWR calculated based on the weight loss per minute (g/min) of the composite aluminum tool at different pulse on times. The results illustrate the efficiency of the Al-Cu-ZrB2 nanocomposite electrode in terms of Electrode wear rate and surface roughness during the EDM process. The machined surfaces were examined using an optical microscope to analyze the surface quality, presence of cracks, and other characteristics. Microstructural changes induced by the EDM process were evaluated to correlate with the machining parameters.

2.1.1 Selection of Workpiece

The cylinder's diameter is 30 mm, and its thickness is 10 mm. This work item will be subjected to electrical discharge machining. The work component is described in Figure 1. This experimental study will determine the D2 die steel workpiece material removal rate.

Table 1. Shows the composition of electrode materials

Aluminium Wt.%	Copper Wt.%	ZrB_2 Wt.%
95	2.5	2.5
13.5	0.5	0.5

Fig. 1: D2 die steel workpiece

Fig. 2: EDM electrode

2.1.2 Selection of Electrode

In this research study, Aluminum copper zirconium dibromide Nano powder is used to making the electrode material. Figure 2 shows the EDM tool fabricated by the Powder metallurgy technique for electrical discharge machining. Various reviews of the literature were used to choose the electrode for the research task. Composite with an aluminium base, a low-density material with excellent corrosion resistance, high thermal conductivity, and quick casting, machining, and molding capabilities is aluminium. Additionally, it is non-magnetic and non-sparking. Along with this, aluminium is reinforced with 2.5% copper. Copper is a highly electrically conductive material. 2.5% zirconium dibromide was added to aluminium once more to improve wear characteristics. It resists heat and rusts well. The finely dispersed metal has the ability to ignite spontaneously in air at high temperatures. It cannot dissolve in acids or alkalis.

2.2 EDM Machining Clearance

Before beginning any machining, the space between the tool electrode and the workpiece must be maintained. Typically, this clearance is 0.25 mm.

2.2.1 Selection of Process Parameters

The following machining specifications list the fixed and variable machining factors.

Fixed factors:

Sparking Voltage (V)	80V
Servo mechanism	Electrical and Mechanical
Polarity	Positive
Electrolyte	EDM Oil

2.3 EDM Input Factors

Input Current = 4 amps, 8 amps and 12 amps

EDM Tool = Al-Cu-ZrB_2

2.3.1 Output Parameters

a. Electrode Wear Rate

b. Surface Roughness

2.4 Machining of Workpiece

Fig. 3: EDM Machine experimental setup

Now, the experiment is being conducted on an EDM device. Figure 3 shows an illustration of the EDM Machine. EDM removes material from a part by frequently electrically discharging the object being machined, and the EDM electrodes (Al-Cu-ZrB_2) used to do it when a dielectric fluid is present.

2.5 Collection of Data

The maximum removal rate that can be achieved while remaining within the permitted mean current, electrode wear and surface integrity are typically taken into consideration while deciding on the pulse current. During the experiments, three different pulse current settings (4 amps, 8 amps, and 12 amps) were used with Al-Cu-ZrB_2 electrode materials and a 2 mm depth of cut. The ratio of the difference in electrode mass between prior to and following machining divided by running time and density is known as the electrode wear rate (EWR).

2.5.1 Evaluation of Tool Wear Rate (TWR)

It is defined as the mass of the electrode prior to and after EDM processing divided by the machining time and density.

$$\text{Electrode Wear Rate} = Ei - Ef / \text{time x density g/min}$$

Whereas,

Ei = Electrode weight before EDM machining.

Ef = Electrode Weight after EDM machining.

2.5.2 Evaluation of Surface Roughness

Determining surface roughness Ra (average roughness) on a surface profile includes computing the absolute value of the height deviations from the mean line's arithmetic mean.

2.6 Optimization Methods

2.6.1 Response Surface Methodology

A popular statistical method for streamlining intricate procedures is output Surface Methodology (RSM), which models the connection between input variables and the desired output. In RSM, mathematical models are created to simulate the underlying system behavior, and a series of experimental runs is planned to efficiently explore the design space. Finding the ideal conditions that produce the intended reaction is the main objective. RSM facilitates the investigation of the response surface to identify the optimal point and expedites the optimization process by means of a methodical technique that modifies input variables in accordance with the created models.

3. RESULTS AND DISCUSSIONS

The results for output responses are summarized in this part. Following that, a data analysis of the experimental results is done to discuss the correlations between the examined parameters and the output responses. Figure 4 Shows the D2 die steel after machining by EDM.

Fig. 4: The work piece of D2 Die Steel for machining EDM

Table 2. RSM Parameter Selected and their output response levels

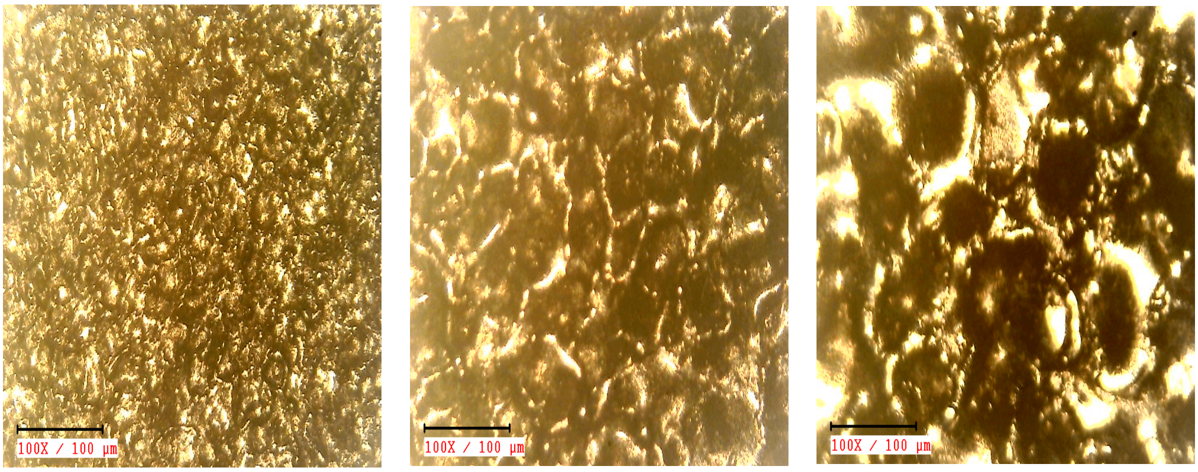
Std.	Current Amps.	Pulse ON µs	Pulse OFF µs	SR µm	TWR g/min.
1	8	30	90	4.871	0.001
2	12	30	80	1.922	0.0009
3	8	50	90	5.101	0.0013
4	8	50	90	5.101	0.0013
5	8	50	90	5.101	0.0013
6	4	50	90	2.835	0.0008
7	4	30	80	3.934	0.0007
8	8	70	90	5.044	0.0016
9	12	70	100	5.564	0.0007
10	4	30	100	4.034	0.0007
11	8	50	100	5.202	0.0015
12	4	70	100	6.17	0.001
13	8	50	90	5.101	0.0013
14	4	70	80	5.17	0.0009
15	8	50	90	5.101	0.0013
16	8	50	80	4.801	0.0016
17	8	50	90	5.101	0.0013
18	12	50	90	5.025	0.0006
19	12	30	100	1.71	0.001
20	12	70	80	5.364	0.0006

The innovative aluminum base composite electrode Al-Cu-ZrB2 was used to treat the previously disclosed Fig. 4 D2 Die Steel Hard Workpiece by EDM. The machining is carried out on a sinker EDM machine. For our performance analysis, make a 2 mm hole on each sample surface and calculate the EWR and SR. Using the above samples, the optimized input settings and higher MRR, as well as reduced tool wear, were analyzed, which is the main goal of this research.

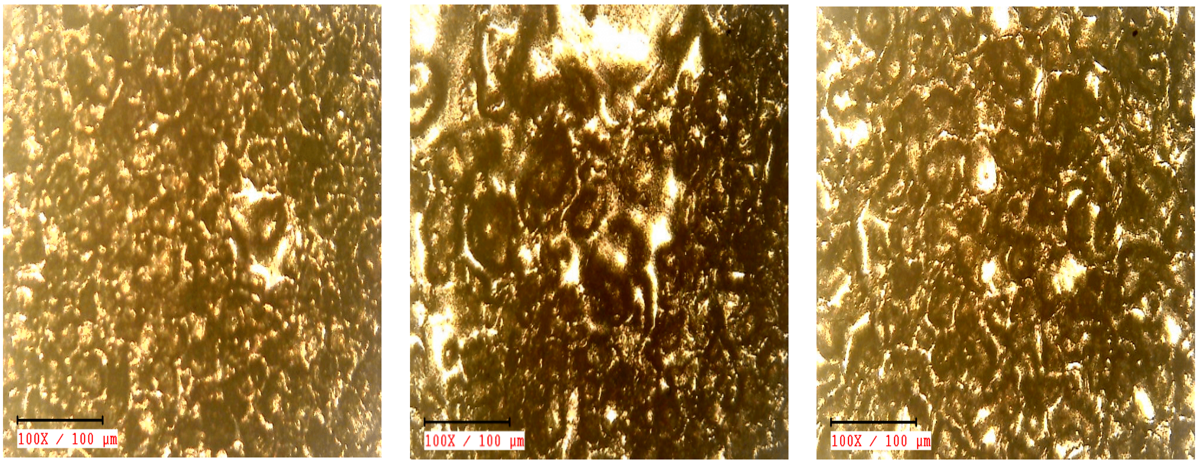
An experimental design with input variables is shown in the table below, along with the related responses in tool wear rate and signal-to-noise ratio. A particular combination of factor values is represented by each row, and the answers for SR and TWR are noted. The amounts of the elements in this experiment appear to be systematically varied according to a factorial structure. The information makes it possible to analyses how variations in input affect the response performance. Table 2 functions as a dataset for the statistical analysis, which may allow for the modeling and optimization of the relationship between the input elements and the observed responses for next experiments or process improvement through the use of methods such as RSM.

The optical microscopic images presented in Figure 5 offer a clear visual understanding of the influence of different input parameters on the machined workpiece surface and its finishing in EDM. The images depict notable variations, highlighting the crucial role of optimal input parameters in determining EDM output quality. Particularly, image 7, obtained with input parameters of 12A current, 70µs pulse on time, and 90µs pulse off time, showcases superior results compared to other samples. This configuration demonstrates a higher metal removal rate and lower electrode wear, indicating its efficiency in the machining process. These observations underscore the significance of precise parameter selection for achieving optimal EDM performance.

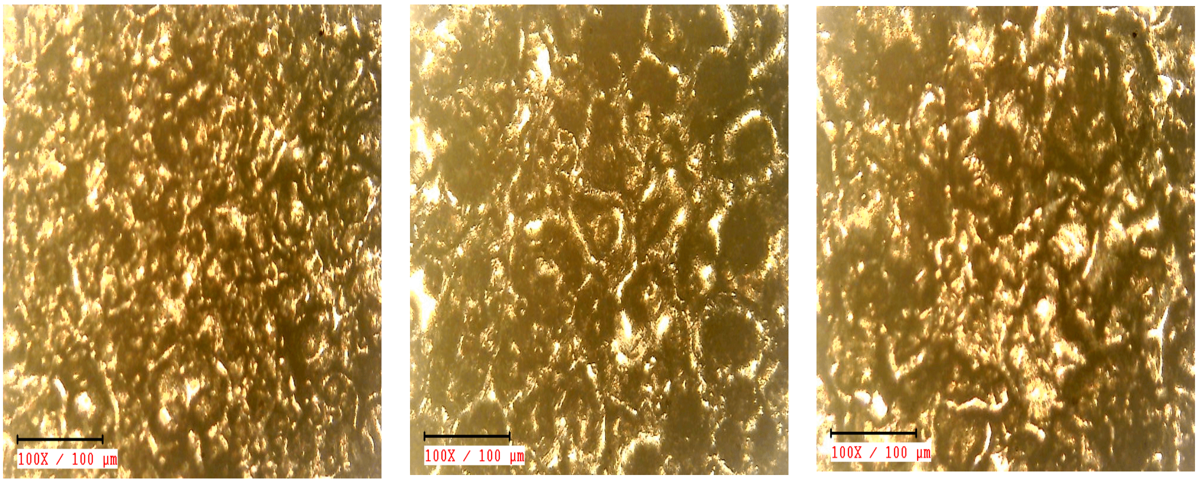
This study investigates EDM process parameters' influence on surface roughness using optical microscopy. Combinations of current, pulse on, and off times were explored for D2 die steel. The 7th combination demonstrated the lowest Ra (1.710µm) and superior surface quality. Other combinations exhibited varying levels of surface roughness and features like cracks. These findings offer insights into optimizing EDM for improved surface finish. Further research can explore additional parameters to enhance machining outcomes. Ra values demonstrate the influence of input factor. Higher current and specific Ton-Toff combinations, notably 12A current, 30µs Ton, and 100µs Toff lead to significantly lower Ra, indicating improved surface quality. Conversely, certain Ton-Toff combinations, such as 8A current, 70µs Ton, and 80µs Toff, result in higher Ra, indicating rougher surfaces.



(a) Ip 4 amps TON 30µs TOFF 80 µs (b) Ip 4 amps TON 50µs TOFF 90 µs (c) Ip 4 amps TON 70µs TOFF 100 µs



(d) Ip 8 amps TON 30µs TOFF 80 µs (e) Ip 8 amps TON 50µs TOFF 90 µs (f) Ip 8 amps, TON 70µs, TOFF100 µs



(g) Ip 12 amps TON 30µs TOFF 80 µs (h) Ip 12 amps TON 50µs TOFF 90 µs (i) Ip 12 amps TON 70µs TOFF 100 µs

Fig. 5: Optical microscopic images of experimental samples after EDM machining

Table 3. ANOVA analysis table for EWR

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	1.872E-06	9	2.080E-07	10.93	0.0004	significant
A-Current	9.000E-09	1	9.000E-09	0.4731	0.5072	
B-Pulse ON	2.500E-08	1	2.500E-08	1.31	0.2784	
C-Pulse OFF	4.000E-09	1	4.000E-09	0.2102	0.6564	
AB	1.513E-07	1	1.513E-07	7.95	0.0182	
AC	1.250E-09	1	1.250E-09	0.0657	0.8029	
BC	1.250E-09	1	1.250E-09	0.0657	0.8029	
A^2	1.162E-06	1	1.162E-06	61.07	< 0.0001	
B^2	6.875E-09	1	6.875E-09	0.3614	0.5611	
C^2	1.100E-07	1	1.100E-07	5.78	0.0370	
Residual	1.903E-07	10	1.903E-08			
Lack of Fit	1.903E-07	5	3.805E-08			
Pure Error	0.0000	5	0.0000			
Cor Total	2.062E-06	19				

3.1 Analyzing the Best Parameters for Better EWR

The findings of a statistical analysis in table 3, most likely from a planned experiment employing Response Surface Methodology (RSM), are displayed in the table. With a large F-value (10.93) and a low p-value (0.0004), the "Model" row presents the model's overall fit and suggests that it is statistically significant. For every factor, there are coefficients, sum of squares, degrees of freedom, mean square, F-value, and p-values available. The words "A^2," "B^2," and "C^2" indicate the elements' quadratic impacts. The "Pure Error" and "Lack of Fit" elements. The p-value of 0.8035, which indicates lack of fit, indicates that the model fits the data well.

Table 4. Fit statistics for EWR

Std. Dev.	0.0001	R^2	0.9077
Mean	0.0011	Adjusted R^2	0.8247
C.V. %	12.89	Predicted R^2	0.2887
		Adeq. Precision	9.2277

3.1.1 Fit Statistics

In Table 4. The average variability of the observed data points around the mean is indicated by the Standard Deviation of 0.0001. The average of the answer variable is shown by the "Mean" value of 0.0011. The percentage of the response variable's variability that the model can account for is indicated by the coefficient of determination (R^2), which is at 0.9077. After taking into consideration the number of predictors and modifications made to the model, the "Adjusted R^2" comes out as 0.8247. How effectively the model predicts fresh data is shown by the "Predicted R^2" of 0.2887. Last but not least, the signal-to-noise ratio-related "Adeq. Precision" score of 9.2277 indicates that the model is accurate enough for practical use.

3.1.2 Regression Equation of EWR

$$\mathrm{EWR} = +0.014181 + 0.000700\ \mathrm{Current} + 0.000023\ \mathrm{Pulse\ ON} - 0.000364\ \mathrm{Pulse\ OFF} - 1.71875\mathrm{E}-06\ \mathrm{Current} * \mathrm{Pulse\ ON} + 3.12500\mathrm{E}-07\ \mathrm{Current} * \mathrm{Pulse\ OFF} + 6.25000\mathrm{E}-08\ \mathrm{Pulse\ ON} * \mathrm{Pulse\ OFF} - 0.000041\ \mathrm{Current}^2 - 1.25000\mathrm{E}-07\ \mathrm{Pulse\ ON}^2 + 2.00000\mathrm{E}-06\ \mathrm{Pulse\ OFF}^2$$

On the normal probability plot, the residuals in Figure 6 show a linear distribution, indicating that errors have a normal distribution. In addition, every observed value is contrasted with its matching anticipated value from Figure 6, which is produced by the model. It is clear that there is a significant ratio between the highest and lowest values, with responses ranging from 0.0006 g/min to 0.0016 g/m. All things considered, the regression model fits the observed data rather well.

RSM research with different values of the input factors and related responses. A three-dimensional plot with the levels of the factors represented by the axes is what you would see while interpreting the RSM 3D graph for input factor vs Electrode Wear Rate (EWR). The response variable, EWR, would be affected by changes in these parameters, as the Figure 7 would show. Depending on the experimental purpose, the goal is to find the best possible combination of input factor levels that minimize the response. The 3D graph's peaks and valleys represent areas of interest for getting the intended reaction. Understanding the links between the variables and streamlining the procedure to get the intended result can be aided by graph analysis. The results of the study highlight a significant achievement in the decrease of wear rates during EDM, with a low value of 0.0006 g/min attained. The use of certain EDM parameters, namely a pulse duration set at 50µs, a pulse interval set at 80µs, and a Current of 12A, is credited with this accomplishment.

One important measure of the effectiveness of these optimized settings is the wear rate of 0.0006 mm³/min that has been recorded. Crucially, the industrial sector will be directly and significantly impacted by this result. Manufacturers might potentially reduce wear during EDM operations by using these optimized parameters since the discovery of certain EDM parameter values that lead to lower wear rates has practical ramifications.

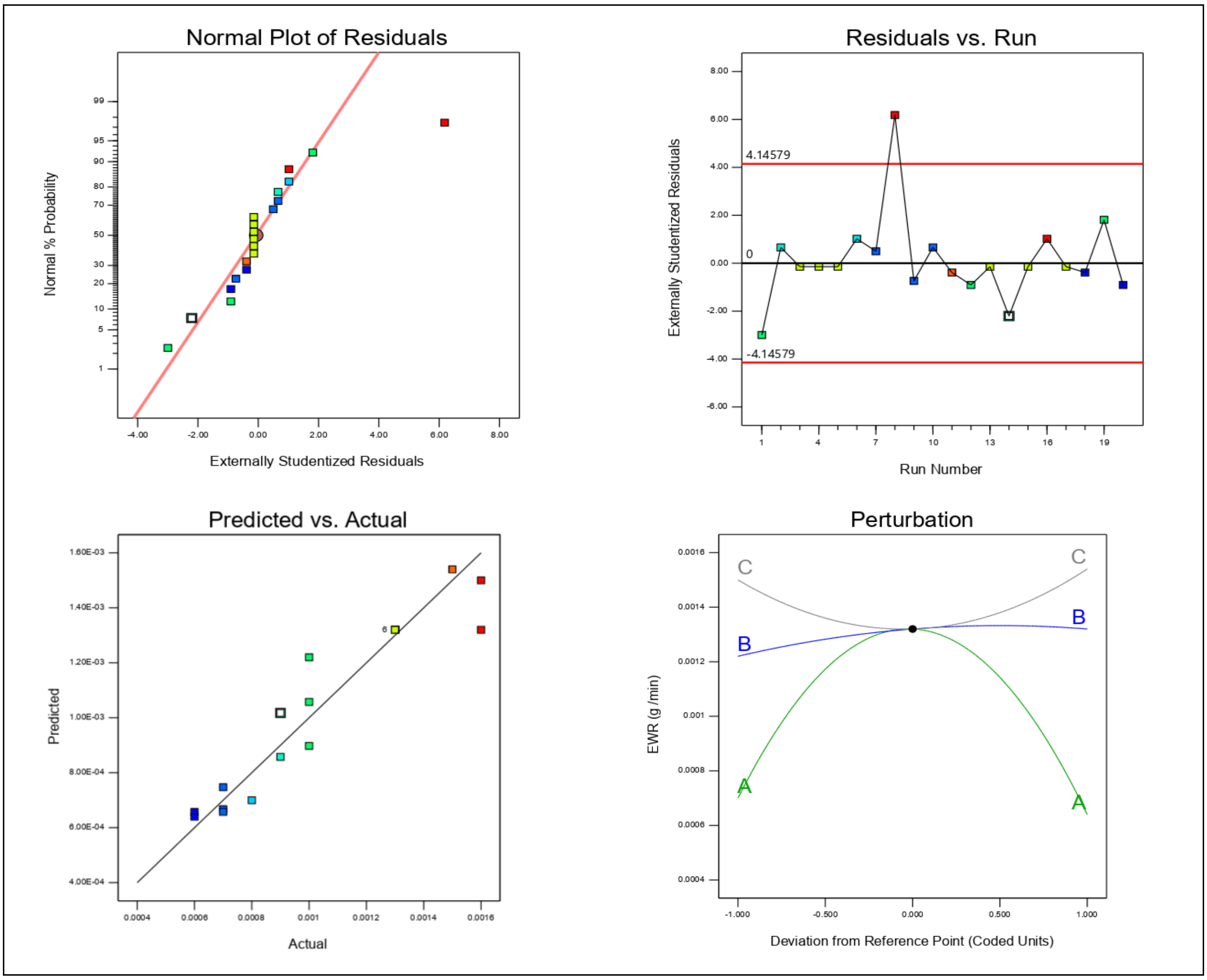


Fig. 6: Diagnostic plot for Electrode wear rate

3.2 ANOVA Analysis for SR

With a substantial F-value of 5.01 and a low p-value of 0.0122, the "Model" row presents the model's overall fit and suggests that it is statistically significant, as shown in table 5. The impacts of each individual factor on the response variable are shown in the following rows. The "A-Current" element does not significantly add to the model, as shown by its non-significant p-value (0.3904). By comparison, "B-Pulse ON" has a low p-value (0.0018) and a highly significant F-value (14.00), indicating a strong influence on the reaction. The statistical significance of "C-Pulse OFF" is not present (p-value: 0.6144). The p-value of 1.22, which indicates a lack of fit, indicates that the model fits the data well.

3.2.1 Fit Statistics

The observed data points' average variability around the mean, which is 4.61, is shown in table 6 by the Standard Deviation of 0.9163. The amount of variability in the response variable that the model explains is indicated by the coefficient of determination (R^2), which is at 0.4846. With 0.3879, the "Adjusted R^2" takes into consideration the number of predictors and model changes. The 19.87% Coefficient of Variation indicates how variable the data are in relation to the mean. The model's ability to forecast fresh data is indicated by the "Predicted R^2" of 0.1175. In terms of the signal-to-noise ratio, the "Adeq Precision" rating of 7.2663 indicates that the model is deemed to be quite accurate for practical applications.

Table 5. ANOVA analysis for Surface Roughness

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	12.63	3	4.21	5.01	0.0122	significant
A-Current	0.6543	1	0.6543	0.7793	0.3904	
B-Pulse ON	11.75	1	11.75	14.00	0.0018	
C-Pulse OFF	0.2217	1	0.2217	0.2641	0.6144	
Residual	13.43	16	0.8396			
Lack of Fit	13.43	11	1.22			
Pure Error	0.0000	5	0.0000			
Cor Total	26.06	19				

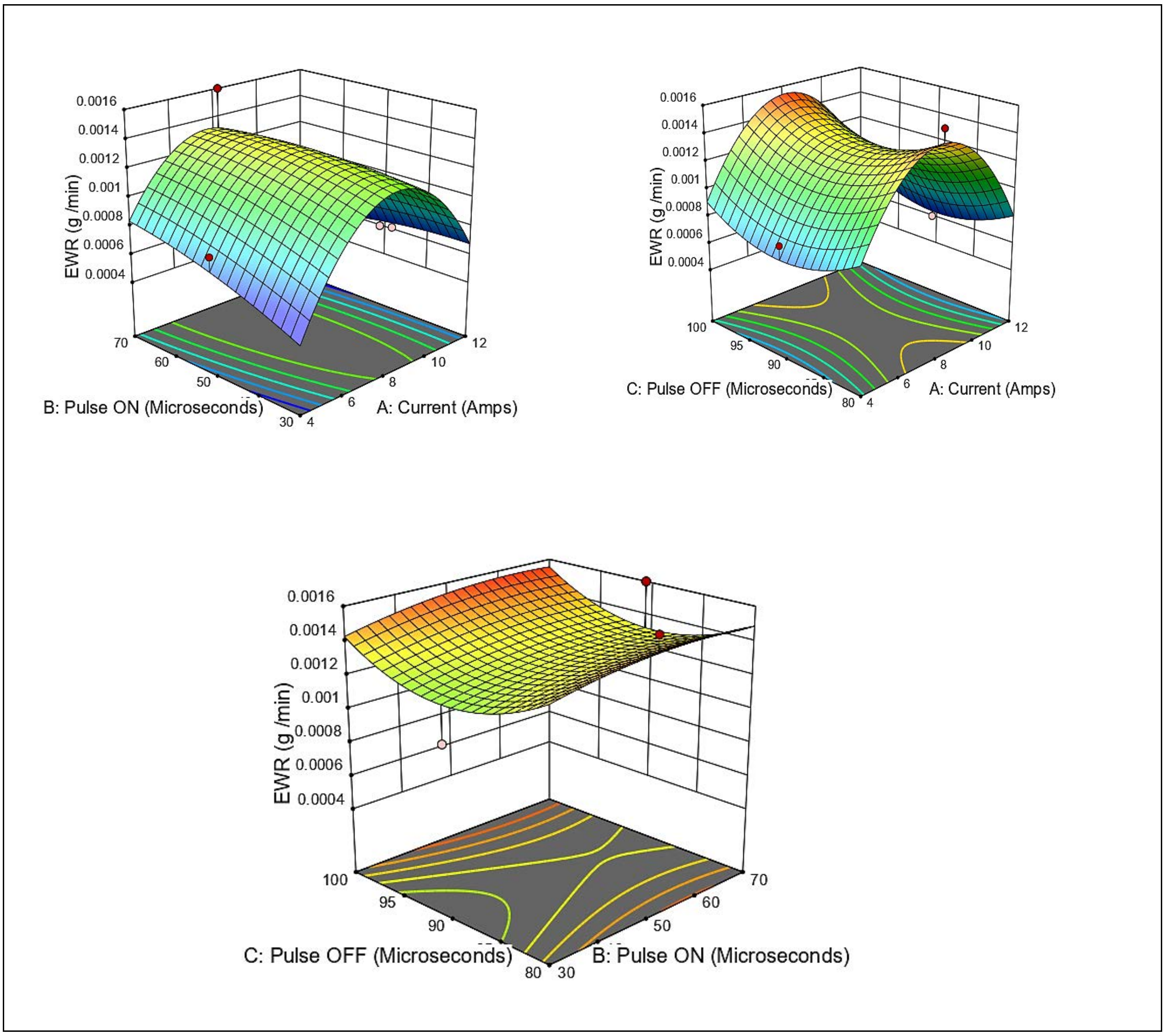


Fig. 7: 3D graph analysis for Electrode Wear Rate

Table 6. Fit statistics for surface roughness

Std. Dev.	0.9163	R²	0.4846
Mean	4.61	Adjusted R²	0.3879
C.V. %	19.87	PredictedR²	0.1175
		Adeq Precision	7.2663

3.2.2 Regression Equation of SR

SR = +1.07385 -0.063950 Current+0.054205 Pulse ON+0.014890 Pulse OFF

The errors are distributed normally, as seen by the straight line residuals in Figure 8's normal probability plot. The response ranges from 1.71 to 6.17 µm, with a greatest to lowest ratio, and the regression model provides a good match to the actual data. The Residual vs. Run plot, which is based on conventional residual analysis, assesses the variation between observed and predicted values and provides information on the model's goodness-of-fit and accuracy.

Based on the given table, a 3D graph showing the levels of input factors would be created by displaying the three axis values together using SR as the response variable. Showing in Figure 9

A particular combination of the input levels, as well as the associated SR value, are represented by each point on the graph. The link between these variables and the SR response may be seen in a multidimensional space thanks to the graph. The graph's peaks and valleys may represent areas of interest where particular levels of input produce either ideal or suboptimal SR values. The study highlights a noteworthy accomplishment in surface roughness reduction by Electrical Discharge Machining, achieving a specified surface roughness value of 1.710µm. The achievement may be ascribed to the use of certain EDM settings, namely establishing pulse length at 30µs, pulse interval at 100µs, and upholding a Current of 12A. The optimized settings effectively provide a smoother surface finish, as evidenced by the reported surface roughness value of 1.710µm. This discovery has important ramifications for EDM applications as it implies that using these optimized settings might result in better surface quality. In manufacturing processes, lower surface roughness is frequently preferred since it can lead to better product functioning, aesthetics, and possibly less wear and friction.

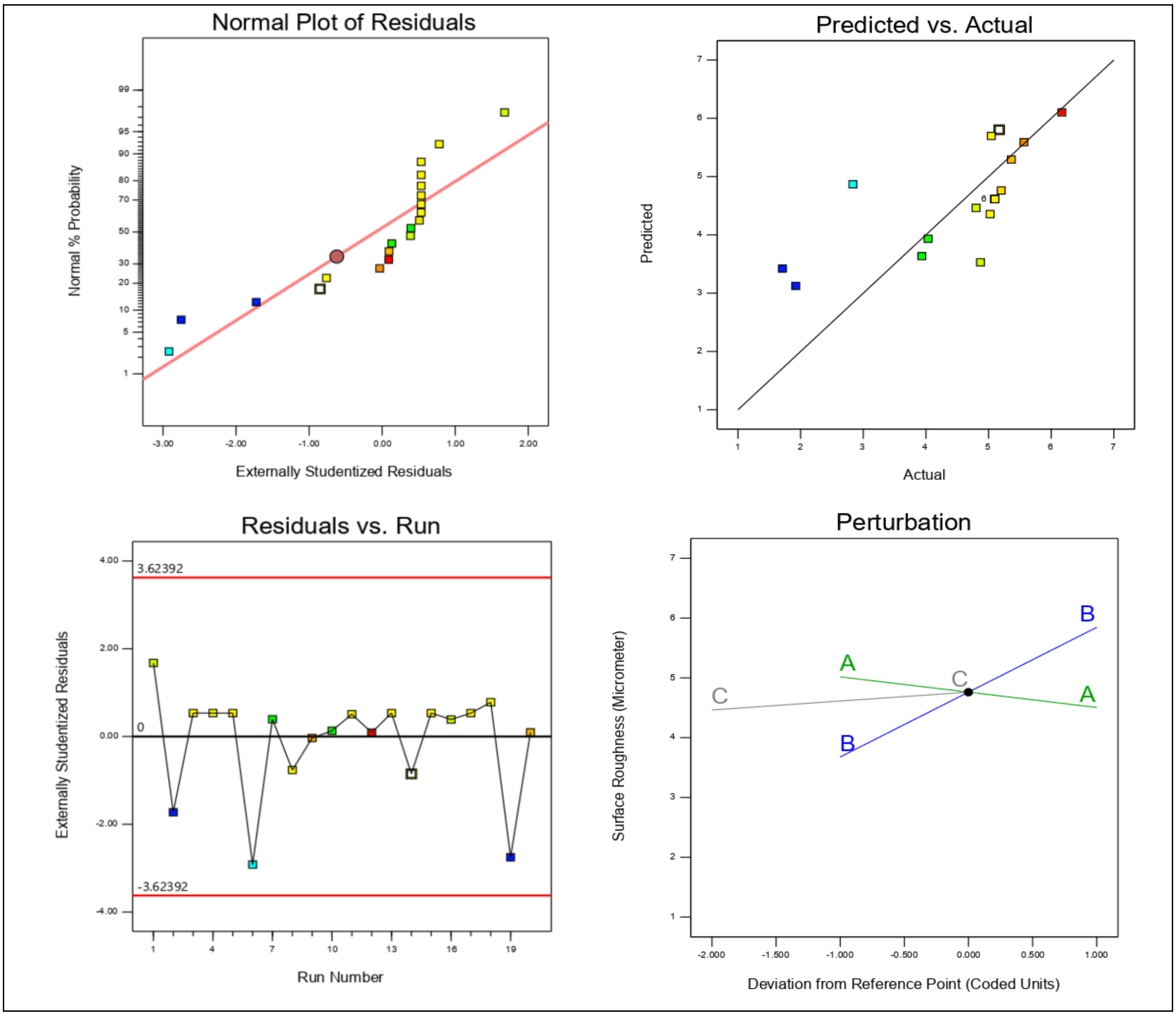


Fig. 8: Diagnostic plot for Surface Roughness

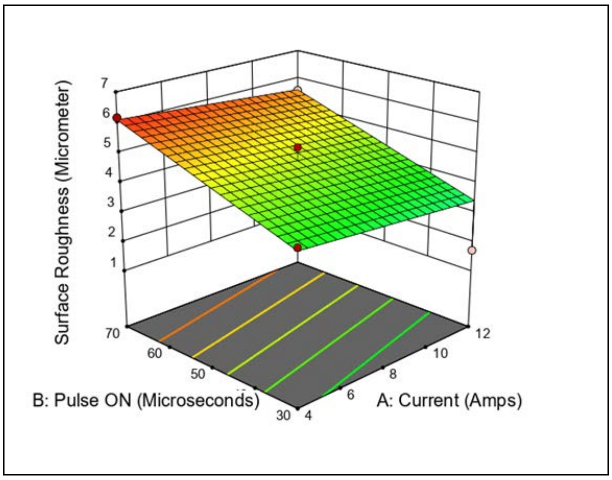


Fig. 9: RSM 3D graph for Surface Roughness

4. CONCLUSION

A tool made of Al, Cu and ZrB_2 has been created for EDM research. This is a summary of the conclusions drawn from the various experimental findings. The Al-Cu-ZrB2, Al composite decreased TWR compared to the pure Al tool due to changing process parameters and diameter overcut created on D2 Die steel. The tool's machined surface exhibits the presence of fine particle aggregation, porosity, etc. During the EDM, a sizable quantity of mass is transported between the electrodes. The Al Nano Composite tool surface demonstrates how, during the EDM, preferred orientation developed. Utilizing an Al-Cu-ZrB2 composite electrode, die-sinker EDM can save manufacturing costs and wear. To improve machining performance, the following input variables must be used.

- The research findings highlight the achievement of lower wear rates (0.0006 g/min) by utilizing specific EDM parameters: Ton at 50µs, Toff at 80µs, and Current at 12A. This outcome has direct implications for the manufacturing industry, suggesting that implementing these optimized parameters can significantly reduce wear rates during EDM operations.

- TWR tends to grow as the pulse ON time increases, and it is greater when the pulse OFF time is 80 µs as opposed to 90 µs. Both SR and TWR may be greatly impacted by the interaction effects between the pulse ON and pulse OFF timings as well as the amps. It seems advantageous to lengthen the pulse ON duration while carefully modifying the pulse OFF duration and amps in order to reduce SR and TWR.

- The research highlights the attainment of lower surface roughness values (1.710µm) by utilizing specific EDM parameters: Ton set at 30µs, Toff at 100µs, and Current at 12A. This finding is significant for EDM applications, indicating that employing these optimized parameters can lead to a smoother surface finish.

- As the pulse ON time grows from 30 to 70 µs, SR tends to decrease. There is no clear pattern in the relationship between pulse OFF time and SR; in general, SR is greater when pulse OFF time is 80 µs as opposed to 90 µs. Greater SR is often caused by greater amps.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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