Research Article

Journal of Environmental Nanotechnology

Enhancing Surface Quality and Tool Longevity in EDM of D2 Steel Using Copper Composite Tools

Navuluri Padma Sravya[1], R. Manimegalai[2], R. Rajeswari[3], M. Gowtham[4], R. S. Achsah[5] and S. Naveen[6*]

[1]Department of Mechanical Engineering, Geethanjali Institute of Science & Technology, Nellore, AP, India
[2]Department of Physics, K. Ramakrishna College of Engineering, Samayapuram, Trichy, TN, India
[3]Department of Biotechnology, P.S.R Engineering College, Sivakasi, TN, India
[4]Department of Electrical and Electronics Engineering, Karpagam Institute of Technology, Coimbatore, TN, India
[5]Department of Biotechnology, Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, Vellanur, Avadi, Chennai, TN, India
[6]Department of Mechanical Engineering, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, Saveetha University, Chennai, TN, India
Received: 29.07.2024 Accepted: 26.09.2024 Published: 30.09.2024
*naveenmurali33@gmail.com

ABSTRACT

Hard material machining and die manufacture are the main applications for electrical discharge machining (EDM). For EDM, conventional electrode materials include graphite, steel, brass, pure copper, and alloys based on copper. Unfortunately, excessive tool wear is a common problem with these materials, which raises the cost of machining. In this investigation, hardened D2 steel was machined using a composite tool made of 90% copper and 10% silicon carbide. The powder metallurgy method was used to create the composite tool. Surface roughness (SR) and electrode wear rate (EWR) were compared to a number of process variables. For experimentation, a response surface methodology based on CCD design in design of experts software was used. SR and electrode wear rate models were created using the CCD approach. Utilizing analysis of variance, the most important factors and their effects on EWR and SR were determined. The lowest tool wear rate of 0.39 gm/min is achieved with a current of 5 Amps, a pulse duration of 100 µs, and a pulse interval of 10 µs with an R2 of 0.9957, which accounts for 99.57% of the variability, the tool wear rate model fits the data very well and obtained lowest surface roughness of 2.8 µm.

Keywords: EDM; RSM; TWR; SR; Nano electrode.

1. INTRODUCTION

To achieve desired results in terms of machined SR and tool wear, electric discharge machining for D2 steel utilizing Cu-SiC composite tools requires process parameter modification. EDM is a popular non-traditional machining method for materials like D2 steel that are challenging to process using standard methods. The procedure makes use of silicon carbide and copper composite electrodes in an effort to increase tool durability and machining efficiency. Optimizing process parameters is a primary emphasis in EDM research and application because it is essential to achieving appropriate surface roughness and reducing tool wear, both of which are necessary for guaranteeing product quality and prolonging tool life.

Chaudhary *et al.* (2013) research investigated the ideal machining parameters of AISI D2 die steel Used Taguchi Methodology. Cu-SiC composite electrode was manufactured using a powder metallurgy method that combines grinding and electrical discharge machining. This approach provides insights into parameter correlations and validation via confirmation studies. Laibi and Shather, (2020) this investigation analyzed important areas such as MRR, electrode wear, and roughness in 304 stainless steel EDM using a composite electrode made of Cu and SiC. By methodically assessing the impact of changing current and pulse parameters on performance optimization, it provides insightful information on how to improve processes. Choudhary *et al.* (2014) experimental investigation investigated the production of metal matrix composite tool electrodes for electrical discharge surface grinding (EDSG) using powder metallurgy. It evaluates the output performance measures including by adding a rotary spindle attachment to an EDM machine and explains how these metrics relate to important input parameters. The results highlight how rotational speed and gap current affect material removal and wear rates, with surface roughness showing a different pattern. Haron *et al.* (2001) in EDM of AISI 1045 tool steel, copper electrodes with diameters of 9.5, 12, and 20 mm were used. It was shown that electrode diameter and current affected both metal removal and electrode wear rate, with low current being appropriate for smaller electrodes and high current for larger ones. Abdulwahhab and Ibrahim, (2023) The present study highlighted the benefits of a composite electrode

(Cu-1%Cr-0.5%WC-1%Ag) over traditional pure copper electrodes by examining its effectiveness in EDM. Tool wear rate and material removal rate are two performance indicators that are compared between the two electrode types to show how effective and wear-reducing composite electrodes may be during machining. The results highlight the need of using composite electrodes, which showed better MRR and reduced surface roughness as compared to electrodes made entirely of copper, indicating their potential as workable substitutes in EDM procedures. Mohanty and Routara, (2016) Precision machining is needed to achieve surface finish requirements as new, harder materials emerge and cutting technology progress. With the growing need for metal matrix composites in aerospace, marine, and other sectors demanding high accuracy and surface polish, electro-discharge machining has excelled at cutting hard materials. Powder mixed electro-discharge machining uses Nano-sized powders in the dielectric fluid to improve material removal rates.

Fig. 1: D2 die steel work piece

Jayahariharapranav *et al.* (2021) this research investigated on two major problems that arise in traditional processing methods: tool wear rate and surface quality. The drawbacks of conventional techniques are reduced by using Electrical discharge machining in conjunction with a unique copper titanium diboride ($Cu-TiB_2$) composite that is produced via powder metallurgy. Surface roughness and material removal rates are improved by optimizing process parameters using response surface methodology. Significant parameters are found via ANOVA analysis and used in multi-objective optimization to achieve ideal process conditions. At 14 A, 16(μs), and 0.6 MPa, the lowest roughness and highest removal rates of metal are reached. Kumar *et al.* (2021) studied the machining parameters for better output performance while using Cu, Cu-W, and graphite tools in electrical discharge machining on Zircaloy-2. With Taguchi L18 Design, the study examines five separate process parameters to maximize response parameters using entropy-integrated-gray-VIKOR and gray relation analysis techniques. The oxide layer deposition on the machined surface and the properties of the tool material are examined using a FESEM. A graphite tool with negative polarity yields the maximum material removal rate, according to the study's important discovery. Nagunoori *et al.* (2024) micro-sized SiC, B4C, and TiB2 reinforcements have been added to Cu-SCs to improve their mechanical characteristics, thanks to recent developments in friction stir processing. Cu-TiB2 composites' mechanical performance was greatly enhanced by process parameter optimization, especially at 1120 rev/min TRS and 40 mm/min TS. This resulted in higher tensile strength, yield strength, and hardness. Umair *et al.* (2023) ansys software was used to create and validate a thermal model for EDM, which revealed that the amount of SiC nanoparticles and pulse current had a noteworthy effect on MRR and SR in Al-SiC composites. With 6% SiC nanoparticles, 20–30 pulse-on times, and 6 A pulse current, the highest EDM performance was found by experimental optimization utilizing ANOVA and grey relational analysis. Zhu *et al.* (2023) the evaluation emphasized how well EDM works to overcome traditional machining problems like cracking and uneven edges when milling fragile semiconductor materials like Si, Ge, GaAs, and SiC. In order to provide light on upcoming machining methods, it also addresses current developments in dielectric fluids, multi-channel discharge phenomena, and thermal removal models. Prayogo *et al.* (2019) used copper electrode, this research investigated the effects of EDM process parameters on D2 steel.

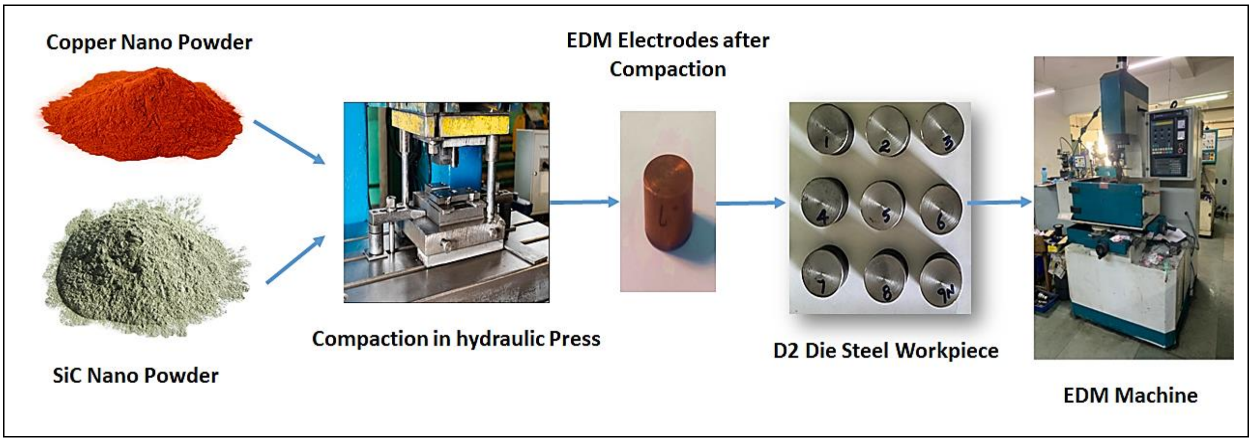


Fig. 2: Schematic diagram of EDM procedure

The results show how the input parameter have a substantial impact on MRR, TWR, and SR. By using a L9 Taguchi array, the best surface roughness was found at 10 A, 400 µs Ton, and 40 µs Toff, SEM analysis verified that the best MRR and TWR were attained at 20 A, 500 µs Ton, and 40 µs Toff. Raj *et al.* (2024) examined how different dielectric fluids and nanocomposite electrodes are used in EDM, with an emphasis on how they affect the machining of tougher materials. Analyzed are important technical features, which highlight improvements in EDM for challenging and complicated applications. Raj *et al.* (2024) used RSM and ANOVA for parameter optimization, this work examined the effects of aluminum Nano electrodes on surface integrity and machining time in Inconel 625 EDM. The findings provide valuable information for improving EDM efficiency and surface quality as they show that pulse-off time mostly impacts machining time, while current primarily effects surface roughness.

Literature studies are crucial in understanding the selection of suitable EDM variables and optimization techniques. The reviews above indicate that limited research has examined the effects of input factors such as electrode material, voltage, current, dielectric medium, pulse on and off times, and EWR and SR responses. This study stands out for its innovative use of the powder metallurgy process to create the Cu-SiC copper composite electrode. Then, the RSM- Central composite design is used to find the ideal parameters that would improve the results of EWR and SR. Responses from SR and EWR often rely on relevant input factors. The three elements we have selected for our research are current, pulse duration, and pulse interval. Twenty trials were conducted under CCD guidance, and the results showed a higher wear rate and meaningful correlations between certain factors. Our objective is to evaluate the composite material's wear rate and surface roughness performance using Design Expert software, pinpoint the most important factor influencing the wear rate.snd surface roughness.

2. MATERIALS AND METHODOLOGY

Hardened D2 steel was selected for the work piece material in this research because of its high hardness and superior abrasion resistance, which make it very difficult to process. The D2 steel finds widespread use in the manufacturing of industrial cutting tools, die and punch fabrications, and shear and planer blades. Samples of 30×10 mm were used for the testing (Fig. 1).

2.1 EDM Tool Materials

The P/M method was used to create the electrode. The base metal was copper (Cu) powder, which accounted for 90% of the weight, and the reinforcing material was silicon carbide (SiC), which made up 10% of the weight. SiC was picked for its high hardness and wear resistance, whereas copper was chosen for its outstanding thermal and electrical conductivity. The average particle size of both powders was 40 µm. The full procedure's schematic is shown in Figure 2. The particles were compressed into 10-mm-diameter cylindrical forms using a hydraulic press that operated at 250 MPa pressure for 30 minutes. After that, the pellets underwent three stages of sintering in a tube furnace. For the purpose of degassing, the temperature was raised frequently for stability and property recovery. The produced pellets were machined on a die-sinking EDM. Images of the Cu-SiC tool electrode are shown in Figure 3.

Fig. 3: Cu-SiC tool electrode

Fig. 4: EDM machine setup

2.2 Experimental Setup

As shown in Figure 4, the experimental setup used a die-sinking EDM machine with kerosene acting as the dielectric fluid. Research suggests that a number of input process factors, including peak current, gap voltage, and pulse duration and interval times, are important when it comes to EDM machining of hardened steel. Three variables were used for this study. Based on the machine's capabilities and early pilot tests, these process variables and their values were chosen. It was shown that the process variables included important processing conditions. The process variables and their corresponding levels used in the experiments are shown in Table 1. For every trial, the machining time was maintained at 30 minutes. Following the machining process, the tool's surface roughness (µm) and tool wear rate were assessed.

2.3 Design of Experiment

The experiment design was created using the Central Composite Design (CCD) method. The effects of different factors on the response that are quadratic, independent, and interactive may all be predicted by CCD using three sets of experiments.

Table 1. EDM input process parameters

Parameters	Levels		
Peak current, I_p (A)	3	5	7
Pulse duration, T_{on} (µs)	100	150	200
Pulse interval, T_{off} (µs)	10	20	30

Table 1 shows the three settings for each parameter used to maximize the EDM process for D2 die steel using a copper composite electrode. The discharge current (I_p) was varied at 3, 5, and 7 Amps, while the pulse ON time (T_{on}) was adjusted at 100, 150, or 200 microseconds. The pulse OFF time (T_{off}) was adjusted in increments of 10, 20, and 30 microseconds to determine the optimal machining conditions.

Fig. 5: D2 Die steel after machining with EDM

Table 2. RSM experimental output

Run	A: Current	B: Pulse ON	C: Pulse OFF	EWR	Surface Roughness
	Amps	µs	µs	g/min	µm
1	5	100	30	1.52	3.9
2	5	200	30	0.95	2.8
3	9	200	30	2.41	6.6
4	9	150	20	2.69	7.4
5	7	150	20	1.21	5.4
6	7	150	20	1.21	5.4
7	9	200	10	3.62	7.2
8	7	150	20	1.21	5.4
9	7	150	20	1.21	5.4
10	5	200	10	0.88	3.12
11	9	100	30	2.9	9.2
12	7	100	20	1.49	7.3
13	7	150	10	1.49	4.5
14	7	150	30	1.63	4.1
15	5	100	10	0.39	3.1
16	7	150	20	1.32	5.4
17	5	150	20	0.68	3.4
18	9	100	10	3.02	8.1
19	7	200	20	1.41	5.6
20	7	150	20	1.21	5.4

Table 3. ANOVA for electrode wear rate

Source	Sum of squares	df	Mean square	F-value	p-value	
Model	13.72	9	1.52	256.69	< 0.0001	significant
A: Current	0.0619	1	0.0619	10.42	0.0090	
B: Pulse ON	0.0037	1	0.0037	0.6186	0.4498	
C: Pulse OFF	0.4473	1	0.4473	75.33	< 0.0001	
AB	0.0045	1	0.0045	0.7599	0.4038	
AC	0.8001	1	0.8001	134.73	< 0.0001	
BC	0.5778	1	0.5778	97.30	< 0.0001	
A^2	0.3483	1	0.3483	58.66	< 0.0001	
B^2	0.0402	1	0.0402	6.77	0.0264	
C^2	0.1466	1	0.1466	24.69	0.0006	
Residual	0.0594	10	0.0059			
Lack of Fit	0.0493	5	0.0099	4.89	0.0532	not significant
Pure Error	0.0101	5	0.0020			
Cor Total	13.78	19				

Table 4. Fit statistical analysis of tool wear rate

Std. Dev.	0.0771	R^2	0.9957
Mean	1.62	Adjusted R^2	0.9918
C.V. %	4.75	Predicted R^2	0.9799
		Adeq Precision	58.7988

3. RESULTS AND DISCUSSION

When machining D2 steel with a copper composite electrode, the creation of 2 mm holes was the main goal. Tool wear and electrode performance were also evaluated. The goal of the input optimization and experimental investigation was to EWR and SR. The electrode's efficiency and the adjusted parameters are highlighted in the figure 5, that follow, which also show the machining results and optimization process.

The results from 20 experimental runs using response surface approach to optimize D2 die steel' EDM are shown in the Table 2. Discharge current (5–9 amps), pulse duration (100–200 µs), and pulse timings (10–30 µs) are among the variables that might change. The findings demonstrate how these factors affect machining performance and are expressed in terms of EWR and surface roughness.

With a p-value of less than 0.0001, the electrode wear rate ANOVA table 3 shows that the model is significant. The parameters with high F-values and low p-values that substantially impact the tool wear rate include Pulse Off Time, the interaction between Current and Pulse Off Time, and the quadratic terms. The model seems to fit the data well, as shown by the non-significant lack of fit.

With an R^2 of 0.9957, the tool wear rate fit data demonstrate an excellent model fit and 99.57% of the variability in the EWR explained by the model in Table 4. The model's dependability and predictive capacity are shown by the tight relationship between the Adjusted R^2 (0.9918) and Predicted R^2 (0.9799). The model may be utilized to efficiently traverse the design space, as shown by the Adeq. Precision value of 58.7988, which is significantly above 4.

$$\begin{aligned} EWR =& \\ &+0.499466 - 0.454057\,Current - 0.005522\,Pulse\ ON \\ &+ 0.099049\,Pulse\ OFF + 0.000238\,Current * Pulse\ ON \\ &- 0.015812\,Current * Pulse\ OFF - 0.000537\,Pulse\ ON \\ &* Pulse\ OFF + 0.088977\,Current^2 + 0.000048\,Pulse\ ON^2 \\ &+ 0.002309\,Pulse\ OFF^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1) \end{aligned}$$

Discharge current and pulse off time are the two most important parameters, and their interactions and quadratic terms also contribute to the overall behavior of EWR. This regression model illustrates the significant effects of the machining parameters on EWR, and an understanding of these relationships aids in optimizing the EDM process for improved tool wear performance. Shows in the equation (1).

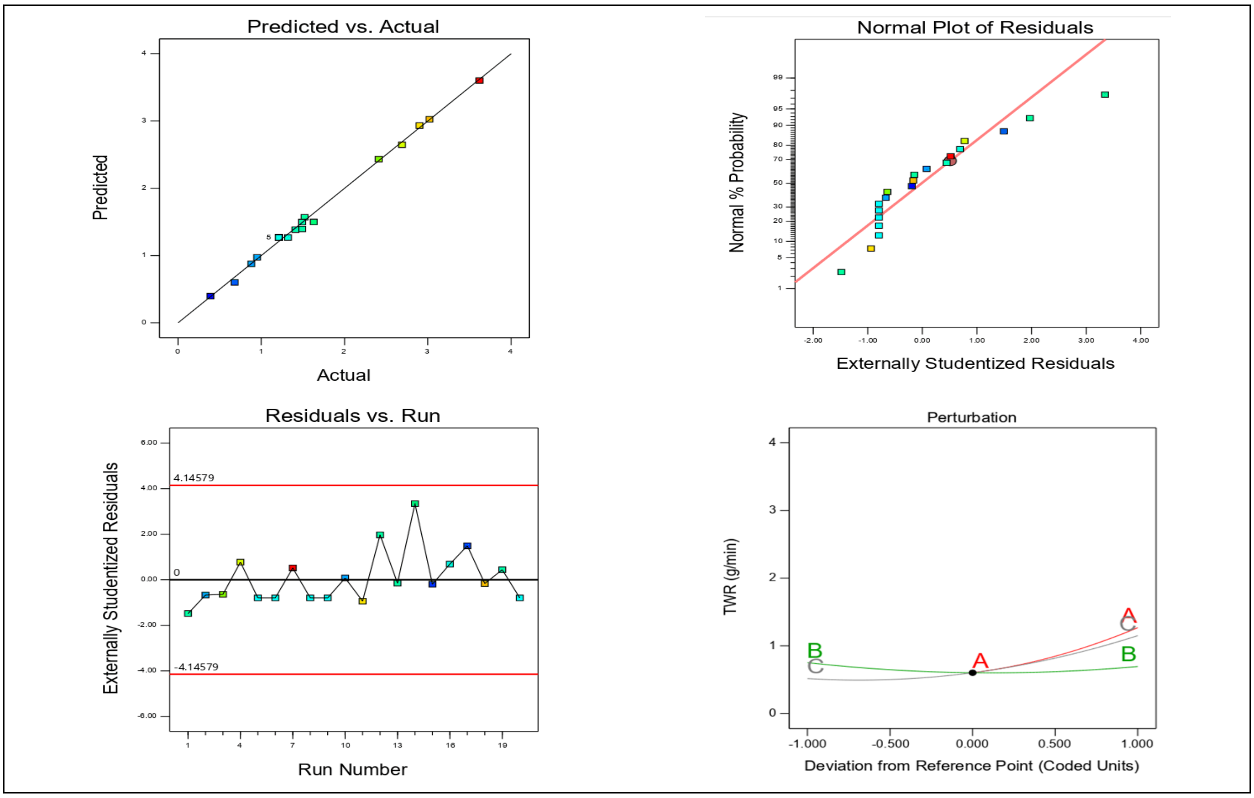


Fig. 6: RSM diagnostic plot analysis of electrode wear rate

In the electrode wear rate research using RSM, diagnostic charts evaluate the model's performance and highlight key experimental results. The normal distribution plot validates the model's statistical assumptions by ensuring that residuals, which compare predicted and actual TWR values, follow a normal distribution. Figure 6 illustrates the expected vs. Actual Plot comparing experimental data to predicted TWR values. Tight alignment along a 45-degree diagonal line indicates accurate predictions. Residuals vs. run plot compares experimental trial faults to find systemic trends or outliers that may impact model performance. Perturbation plots highlight TWR's sensitivity to input parameters and help identify the factors that most affect TWR. These diagnostic tools enhance modeling and experimental settings to reduce electrode wear and optimize EDM machining conditions.

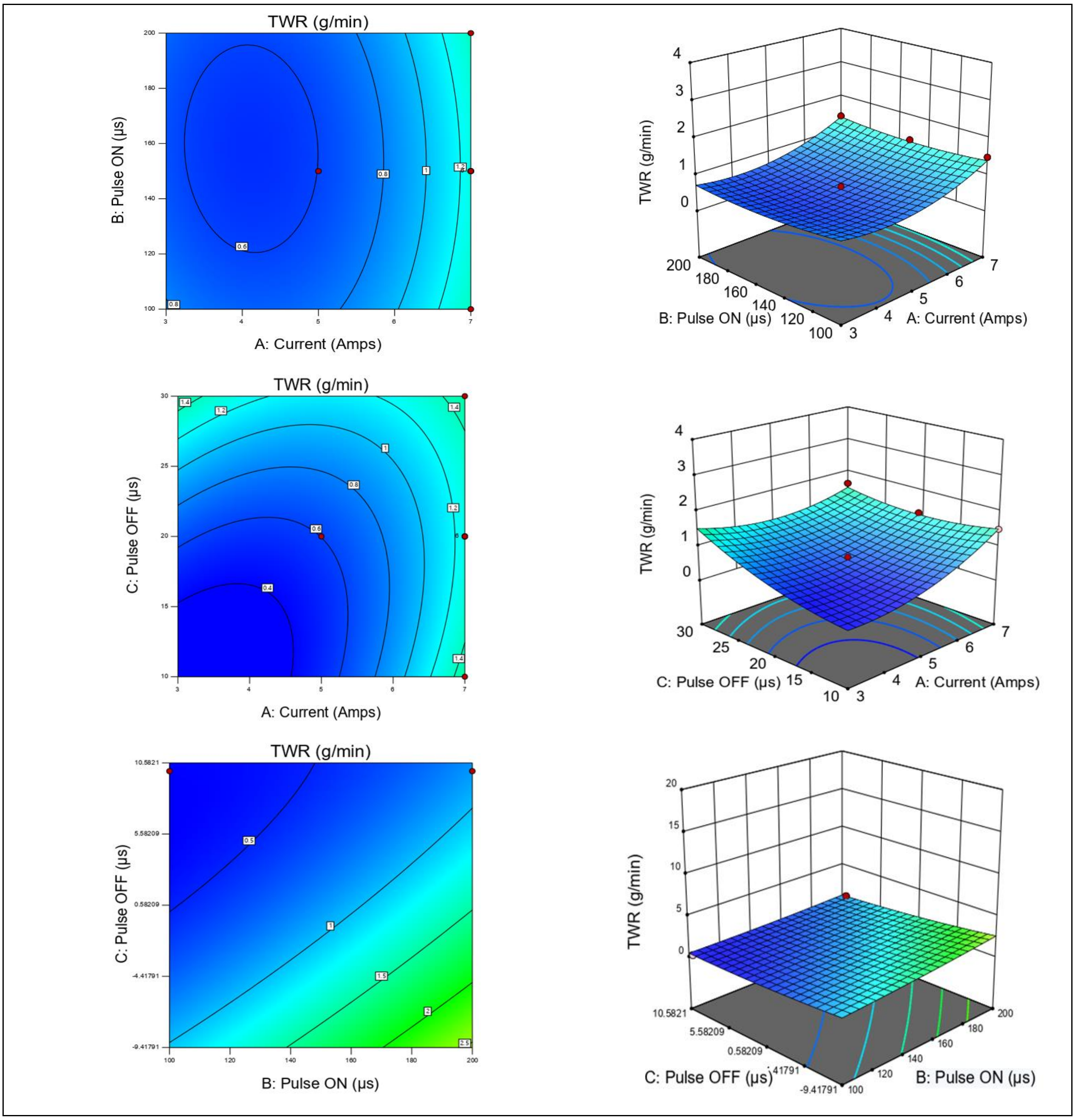


Fig. 7: RSM 3D plot analysis of electrode wear rate

The electrode wear rate 3D response surface methodology figure 7, which is based on the provided data, shows how variations in the input factors affect EWR. It displays the areas where TWR rises or falls in order to illustrate the interaction impacts between these factors. By emphasizing regions with low tool wear, the plot aids in the identification of ideal machining settings and offers a clear knowledge of the parameter interactions influencing TWR in EDM operations.

3.1 Effect of Process Factors on the EWR

The tool must be able to endure deformation from the impact forces produced during operation while it is being machined. Enhancing the resistance of the EDM tool against disintegration may be achieved by optimizing its mechanical, electrical, and thermal qualities. The results of the experiments showed that EWR is significantly increased by greater current, with higher TWR values being seen at 9 Amps. An inverse connection is often seen between EWR and pulse ON time, with shorter pulse ON periods typically resulting in greater EWR. Pulse OFF time has a less consistent influence on EWR, exhibiting variability among runs and not necessarily demonstrating a strong association with EWR variations. Overall, pulse ON and pulse OFF timings show more complicated relationships with EWR, while current has a predicted effect.

Table 5. ANOVA analysis table of surface roughness

Source	Sum of squares	df	Mean square	F-value	p-value	
Model	59.57	9	6.62	143.70	< 0.0001	significant
A: Current	2.86	1	2.86	62.00	< 0.0001	
B: Pulse ON	0.4709	1	0.4709	10.22	0.0095	
C: Pulse OFF	0.0137	1	0.0137	0.2972	0.5976	
AB	0.7321	1	0.7321	15.89	0.0026	
AC	0.0001	1	0.0001	0.0011	0.9744	
BC	0.9940	1	0.9940	21.58	0.0009	
A^2	0.0085	1	0.0085	0.1836	0.6774	
B^2	3.36	1	3.36	72.96	< 0.0001	
C^2	3.00	1	3.00	65.14	< 0.0001	
Residual	0.4606	10	0.0461			
Lack of Fit	0.4606	5	0.0921			
Pure Error	0.0000	5	0.0000			
Cor Total	60.03	19				

The surface roughness ANOVA table 5 indicates a significant model with an F-value of 143.70 and a p-value of <0.0001. Significant variables impacting surface roughness include Current (A), Pulse ON (B), interaction terms AB and BC, and squared terms B^2 and C^2 (p-values < 0.05). The parameters Pulse OFF (C), AC, and A^2 are not important. A low residual error indicates a strong model fit.

Table 6. Fit statistic analysis for surface roughness

Std. Dev.	0.2146	R^2	0.9923
Mean	5.44	Adjusted R^2	0.9854
C.V. %	3.95	Predicted R^2	0.9301
		Adeq Precision	42.1847

Table 6 shows the model's R^2 value of 0.9923 indicates a high degree of fit, explaining 99.23% of the variance in the data, while the Adjusted R^2 of 0.9854 accounts for the number of predictors used. The Predicted R^2 of 0.9301 shows strong predictive ability, and Adeq Precision of 42.1847 suggests an adequate signal-to-noise ratio.

$$
\begin{aligned}
&Surface\ Roughness\\
&= +0.559295 + 1.36616\ Current - 0.109940 Pulse\ ON\\
&+ 0.528493 Pulse\ OFF - 0.003025 Current\ *\ Pulse\ ON\\
&+ 0.000125\ Current\ *\ Pulse\ OFF\ - 0.000705\ Pulse\ ON\\
&*\ Pulse\ OFF + 0.013864 Current^2 + 0.000442\ Pulse\ ON^2\\
&- 0.010445\ Pulse\ OFF^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)
\end{aligned}
$$

This equation predicts Surface Roughness using input variables and their interactions, revealing how each element and their combinations affect the output. Show in equation (2).

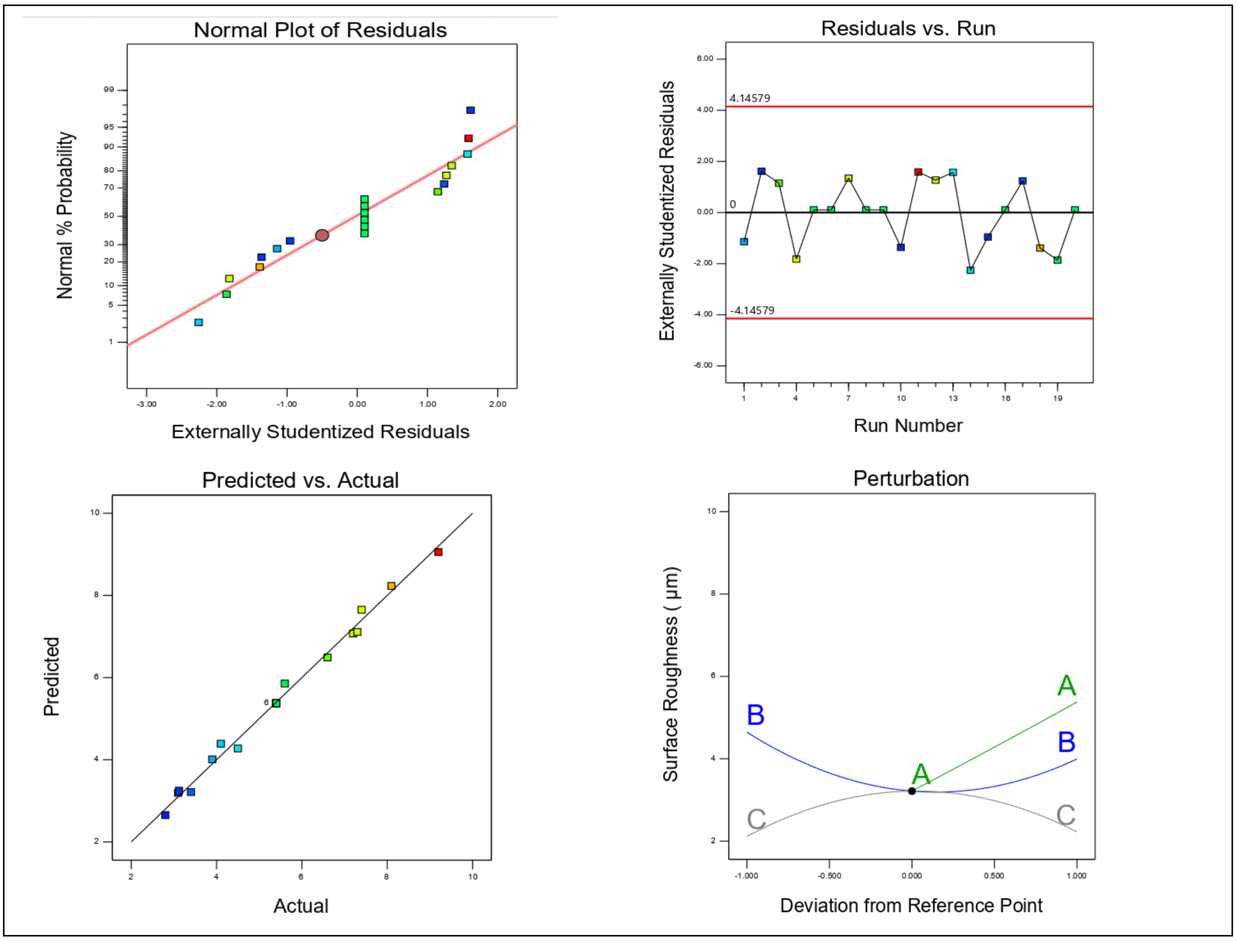
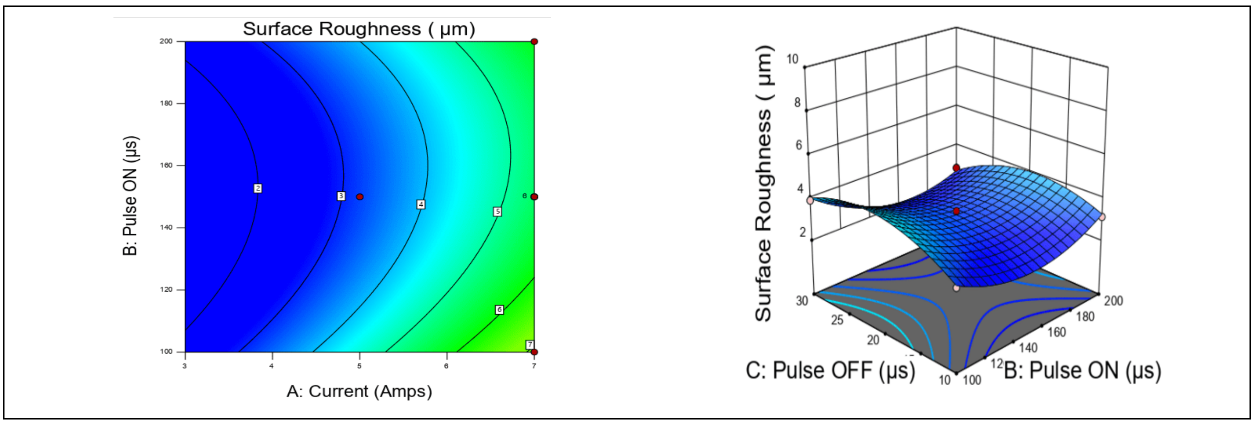


Fig. 8: RSM diagnostic plot analysis of surface roughness

When it comes to electric discharge machining, Figure 8 shows surface roughness as a crucial indicator of the quality of the machined surface. The degree of roughness and imperfections on the surface during machining may have a substantial effect on the functioning and performance of the machined component. The input parameters have an impact on the surface roughness, which ranges between 2.8 µm and 9.2 µm in the supplied data. With a current of 5 Amps, a pulse ON time of 200 µs, and a pulse OFF time of 30 µs, the lowest SR of 2.8 µm was attained, suggesting that these conditions result in the smoothest surface finish. Achieving a desired surface quality requires optimizing these parameters since lower surface roughness usually translates into higher fatigue resistance, less friction, and enhanced aesthetic appeal of the machined components. The model's dependability in enhancing EDM procedures for better surface quality is shown by the high R^2 values obtained from the analysis of the model, which also imply that the expected SR values closely correspond with the actual measurements.



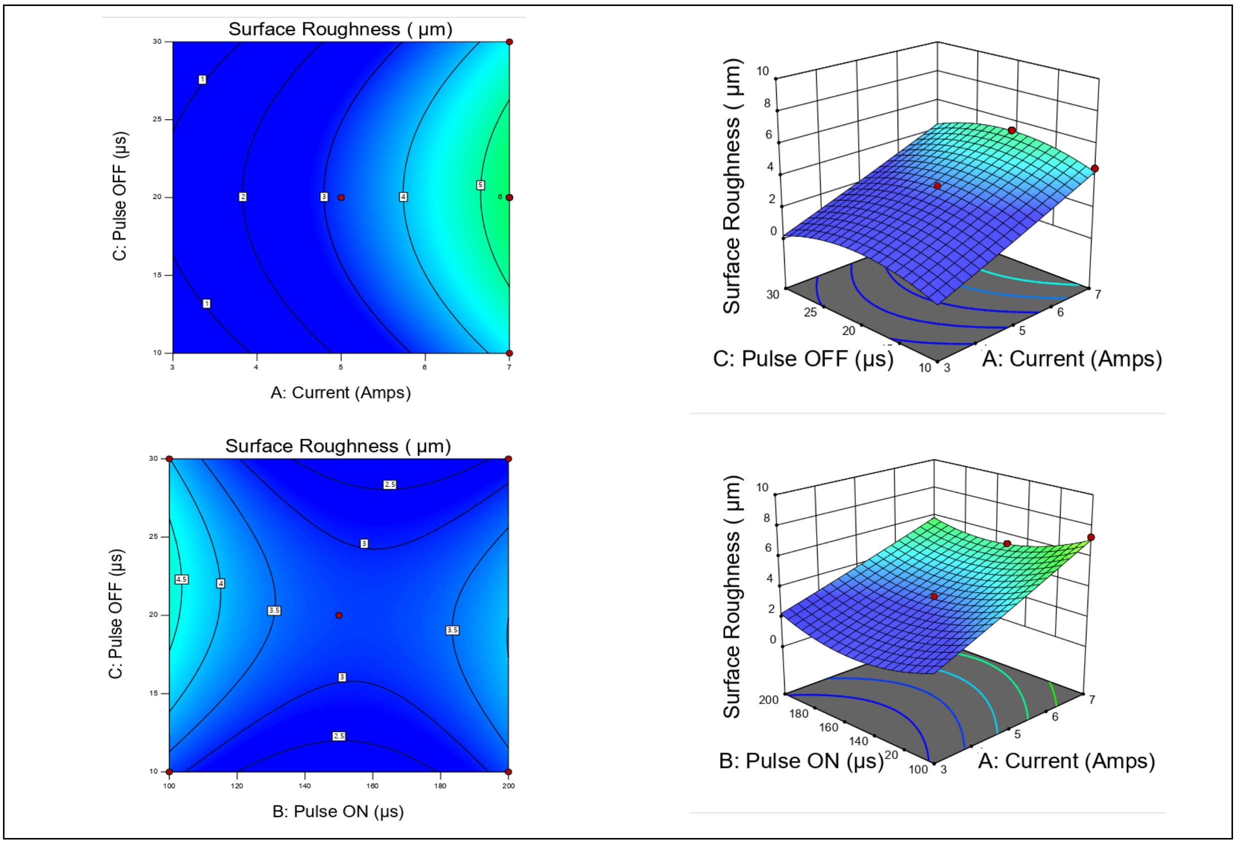


Fig. 9: RSM 3D plot analysis of surface roughness

The 3D response surface graph for SR in EDM shows complex correlations between these components and the final surface quality. The data shows in Figure 9 that variations in input factors have a considerable impact on surface roughness. Reduced surface roughness values, such the lowest of 2.8 µm recorded, are seen at lower currents (5 Amps) in conjunction with longer discharge durations (200 µs) and moderate pulse interval (30 µs). This suggests that smoother surfaces are a result of enough cooling time and longer discharge durations. On the other hand, surface roughness increases up to 9.2 µm for larger currents (9 Amps) and shorter pulse off durations (10 µs), suggesting that rougher textures are produced by too much energy and inadequate cooling in between discharges. In order to optimize the EDM settings and obtain the required surface quality by balancing the energy input and thermal management, this 3D analysis aids in understanding the interaction between these factors.

3.2 Effect of Process Factors on the SR

Higher SR on the tool corresponds to a rougher finish on the work material in EDM, where the geometry of the tool is reflected onto the work piece. I_p (current), T_{on} (pulse ON time), and flushing pressure were shown *via* experiments to be critical SR-influencing parameters. Surface roughness is significantly impacted by current with larger values (e.g., 9 Amps) and continuously raising SR (runs 3, 4, 7, 11, and 18). The effects of pulse ON time are not consistent, with SR being affected differently in various runs at both lower (100 µs) and higher (200 µs) values. In contrast to current and Pulse ON time, Pulse OFF time have variable effects on SR and lack a consistent pattern across studies, indicating a less predictable impact.

Table 7. Confirmation test analysis

Response	Predicted Mean	Predicted Median	Observed	Std. Dev
TWR	0.397114	0.397114	0.39	0.0770618
Surface Roughness	3.19368	3.19368	3.1	0.214623

3.4 Confirmation Test Analysis of SR and EWR

Table 7 shows the predicted and observed values for electrode wear and surface roughness are compared, it is clear that the predictive modeling was accurate because of the near alignment and low standard deviations.

4. CONCLUSION

The current study effectively sintered Cu-SiC composites using the powder metallurgy process and machining with hardened D2 steel. For optimization, the experiment was designed using the central composite rotatable design approach. The following results were obtained from the experimental studies:

- When employing a Cu-SiC composite tool for EDM of D2 steel, the best possible combination of parameters is 5 Amps of current, 200 µs of pulse on time, and 30 µs of pulse off time to obtain the lowest surface roughness of 2.8 µm. When compared to other parameter values in the dataset, this combination produces a much better surface quality.

- The lowest electrode wear rate of 0.39 gm/min is achieved with a current of 5 Amps, a pulse on time of 100 µs, and a pulse off time of 10 µs. This suggests that this combination is the most efficient for reducing electrode wear when EDMing D2 steel with a Cu-SiC composite tool

- With an R^2 of 0.9957, which accounts for 99.57% of the variability, the tool wear rate model fits the data very well. It also has strong prediction power and dependability, as seen by its Adjusted R^2 of 0.9918 and Predicted R^2 of 0.9799. Strong signal-to-noise ratios are shown by the Adeq. Precision values of 58.7988 and 42.1847, which validate the model's resilience and efficiency in traversing the design space.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

REFERENCES

Abdulwahhab, A. B. and Ibrahim, A. F., Improvement of Performance Evaluation Using Hybrid Composite Electrode (Cu/Cr/WC/Ag) in Electric Discharge Machining, *J. Eng. Technol.*, 41(12), 1516-1526 (2023). http://doi.org/10.30684/etj.2023.142962.1550

Choudhary, R., Kumar, H. and Singh, S., Effects of Machining Parameters on Performance of Electrical Discharge Surface Grinding of AISI D2 die Steel with Composite Tool Electrode, *In Proc. Int Conf Res. Innov. Mech. Eng. ICRIME-2013*, 201-211 (2014). https://doi.org/10.1007/978-81-322-1859-3_18

Choudhary, R., Kumar, H. and Singh, S., Machining performance and surface integrity of AISI D2 die steel machined using electrical discharge surface grinding process, *J. Mater. Eng. Perform.*, 22, 3665-3673 (2013). https://doi.org/10.1007/s11665-013-0679-8

Haron, C. C., Deros, B. M., Ginting, A. and Fauziah, M., Investigation on the influence of machining parameters when machining tool steel using EDM, *J. Mater. Process. Technol.*, 116(1), 84-87 (2001). https://doi.org/10.1016/S0924-0136(01)00846-9

Jayahariharapranav, P., Dinesh, D., MathanKumar, P., Rajamurugan, G. and Jayakumar, N., Effect of Titanium Di-Boride/Copper (TiB_2-Cu) Electrode on the Machinability of OHNS Steel by EDM Process, *IOP Conf. Ser. Mater. Sci. Eng.*, 1059(1), 012046) (2021). https://doi.org/10.1088/1757-899X/1059/1/012046

Kumar, J., Soota, T., Rajput, S. K. and Saxena, K. K., Machining and optimization of Zircaloy-2 using different tool electrodes, *Mater. Manuf. Process.*, 36(13), 1513-1523 (2021). https://doi.org/10.1080/10426914.2021.1905829

Laibi, Y. Q. and Shather, S. K., Effect of SiC-Cu electrode on material removal rate, tool wear and surface roughness in EDM process, *J. Eng. Technol.*, 38(9A), 1406-1413 (2020). https://doi.org/10.30684/etj.v38i9A.552

Mohanty, S. and Routara, B. C., A review on machining of metal matrix composites using nanoparticle mixed dielectric in electro-discharge machining, *Int. J. Automot. Mech. Eng.*, 13(2), 3518-3539 (2016). https://doi.org/10.15282/ijame.13.2.2016.18.0290%20

Nagunoori, R., Lam, S. R., Gurram, M., Borigorla, V. and Kaki, V. R., Experimental and optimization studies of friction stir processed Cu-TiB_2 surface composites, *Proc. Inst. Mech. Eng., Part C: J. Mech. Eng. Sci.*, 238(12), 5779-5792 (2024). https://doi.org/10.1177/09544062231223347

Prayogo, G. S. and Lusi, N., Determining the effect of machining parameters on material removal rate of AISI D2 tool steel in electrochemical machining process using the Taguchi method, *IOP Conf. Ser. Mater. Sci. Eng.*, 494(1), 012055 (2019). https://doi.org/10.1088/1757-899X/494/1/012055

Raj, Y. J., Bejaxhin, A. and Rajkumar, S., Review about removal rates and wear rate of EDM using nano composite electrodes with variant electrolytic solutions, *AIP Conf. Proc.*, 2853(1) (2024). https://doi.org/10.1063/5.0197422

Raj, Y. J., Bejaxhin, A., Kumar, B. H. and Balamurugan, G. M., Influence of Novel Al-Ni electrodes on Roughness and Machining Time in Inconel 625 EDM Machining: a Comprehensive RSM Performance Analysis, *J. Environ. Nanotechnol.*, 13(1), 243-253 (2024). https://doi.org/10.13074/jent.2024.03.241547

Umair, A., Imtiaz, A.K. and Faisal, H., Thermal modelling and Parametric optimization for Machining of Aluminum (Al-10%SiCmicro-SiCnano) based hybrid composite using Spark Erosion (2023). http://dx.doi.org/10.21203/rs.3.rs-3095363/v1

Zhu, X., Li, G., Mo, J. and Ding, S., Electrical discharge machining of semiconductor materials: A review, *Mater. Res. Technol.*, 25, 4354–4379 (2023). https://doi.org/10.1016/j.jmrt.2023.06.202