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Research Article

Influence of Coated Electrode in Nanopowder Mixed EDM of Al–Zn–Mg–Si_3N_4 Composite

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Machinability investigation of new material is one of the mandatory investigations to complete the purpose of creation of it. Electrical discharge machining (EDM) is one of the promising unconventional machining processes for highly accurate machining performance in difficult-to-cut material even machining complicated profiles. The powder-mixed EDM and nanopowder-mixed EDM are the improved versions of the EDM. The Al–Zn–Mg composite is reinforced with Si_3N_4 (9 wt. %) for meeting automotive and marine applications. The aluminium nanoparticles enhanced deionised water was used in NPMEDM. The nickel-coated brass and uncoated brass tube electrode were considered for the investigation. Pulse on time (μs), voltage (V), input current (A), and capacitance (nF) were independent variables and varied at 3 levels. The microhole machining performance with a coated and uncoated electrode was investigated. The L18 orthogonal array involved in the experimental design, material removal rate, and electrode wear rate were analysed. The SEM analysis was employed in the surface morphological study of electrodes before and after machining. The input parameters were optimised for the coated electrode for the responses of MRR and EWR.

1. Introduction

Due to the increasing demands of the aerospace and tooling industries, EDM can be used to machine modern alloys and composites with high toughness, high strength, and high rigidity [1]. However, it has some limitations such as low machining rates and poor surface finishes, this can be addressed by various methods such as electron orbiting, rotating the tool, applying ultrasonic vibrations to the tool, and mixing conductive particles with dielectric fluid [2]. Introducing conductive particles in the dielectric fluid known as powder mixer EDM (PMEDM) is a new development that increases the gap between tools and the workpiece while providing a bridge between the electrodes, resulting in an even distribution of spark energy, which makes the process more stable and as a result, it significantly enhances the machining performance such as tool wear, surface roughness [3]. In the PMEDM process, the abrasives were uniformly mixed with dielectric fluid. It has been inferred that adding powdered particles to a dielectric medium such as copper, aluminium, iron, and carbon improved the machining rate as the concentration of the powdered particles increased [4–6]. The addition of the fine graphite powder in the range of 4 g/l improves the material removal rate by 60% and reduced the tool wear ratio by 28% [7]. The addition of silicon carbide particles to H-13 die-steel resulted in a fine surface finish of 2 μm as well as an improvement in corrosion resistance. [8] Use a different concentration of tantalum carbide with the concentration value of 5 g/l, 10 g/l, and 15 g/l. Peak current increased both material removal rate and surface roughness. However, there is no consistency in the concentration of abrasive particles. [9] Observed microcracks and craters after using the PMEDM process. The role of abrasive particles in the dielectric medium has advantages and disadvantages based on the abrasive particles used. As a result, in this study, a thorough investigation was carried out by using aluminium nanoparticles in combination with dielectric fluid to conduct experimentation using the PMEDM process.

The length and side wear of the electrode in EDM affects the process machining accuracy [10]. The electrode wear rate can be reduced by providing coating or using composite material electrodes. [11] Investigates the coated electrode material results in reduced electrode wear and increased aspect ratio. The secondary spark can also be avoided using the coated electrode. [12] Compared commercially available brass electrode to composite tool electrode. For the manufacturing of composite electrodes, chromium and copper were used as the same material. The machining rate of the composite electrode is double that of the brass electrode, with better surface finish accuracy [13] observed that coating the copper electrode with NIP improved MRR and reduced electrode wear and overcut. Smooth and burr-free images were observed on the SEM image of the microholes. Copper electrodes were coated with zinc, chrome, and silver materials. The zinc-coated electrode had the highest rate of material removal out of the three [14].

It is clear from the literature review that coating highly conductive material over the tool electrode reduced dimensional inaccuracies, surface irregularities, and secondary spark. Hence in this study, the high electrical conductivity of nickel is coated over the brass electrode to assess the machinability of microholes in Al–Zn–Mg/Si_3N_4 composites using the PMEDM process has not been carried out for manufacturing application. Considering this as a major constraint an attempt has been made to PMEDM on Al–Zn–Mg/Si_3N_4 composites and compare its outcome with the coated and uncoated tool.

This research is unique by investigating the microhole machinability investigation of specially prepared Al–Zn–Mg/Si_3N_4 composites on the advanced machining technology of nano-PMEDM with the conventional brass electrode and nickel-coated brass electrode (by electroless plating) to suggest the best electrode for machining microholes in high material removal rate and lower electrode wear. To the best of our knowledge, this kind of investigation is not reported in the literature.

2. Experimental Methodology

The present study made use of Al–Zn–Mg composites reinforced with Si_3N_4 (9 wt. %) of a thickness of 10 mm because these composites have higher mechanical properties than Al–Zn–Mg alloys and they have been successfully used in automotive and marine applications [15]. The test was carried out on an ocean OCT-3525NA electrical discharge machine with nickel-coated brass, uncoated brass, and tube electrodes as tool materials. PMEDM was performed using deionised water as a dielectric fluid and aluminium nanoparticles in a ball mill to create a nanodielectric fluid. The process parameters used in this study are shown in Table 1 while the MRR and EWR were calculated based on equations (1) and (2) [16].

The Weight of the workpiece before and after machining was calculated by using 'OHAUS' make high precision weight balancing device. An optical microscope is used to measure the diameter of the machined hole on the workpiece. The electroless plating method was used in this work to coat the nickel of 2 μm thickness on the brass tube to evaluate the effectiveness of the coating on MRR and EWR.

$$\text{MRR} = \frac{(W_a - W_b)}{t}\left(\frac{\text{mg}}{\text{min}}\right), \tag{1}$$

$$\text{EWR} = \frac{(E_a - E_b)}{t \times \rho}\left(\frac{\text{mm}^3}{\text{min}}\right). \tag{2}$$

The chemical composition of the brass tube electrode and nickel coating material with a diameter of 14 mm is shown in Table 2.

The properties of aluminium nanoparticles and dielectric fluid is inferred in Tables 3 and 4.

In the present study, the machining parameters of micro-EDM such as current, voltage, pulse on time, and capacitance were studied. The effect of input process parameters has been evaluated by using machining time, MRR, and EWR. The experiment was carried out using an L18 orthogonal array as shown in Table 5 [17]. All process parameters were set to an equal level of three.

3. Outcome of the Experiment

3.1. Material Removal Rate (MRR). MRR is expressed as the amount of material removed from the workpiece per unit of time [18]. MRR was calculated by using equation (1). The Unit of MRR is mm^3/min. The effect of various input process parameters on MRR is shown in Figures 1(a)–1(d). It has been observed that an increase in current boosts the intensity of electrical sparks, resulting in a higher MRR, and the same results were observed with uncoated and coated electrodes for different input currents, as shown in Figure 1(a). Higher MRR was observed for the coated electrode. The MRR improved significantly when the current increased from 3 A to 9 A, but the nickel-coated electrode has better workability. When the input process parameter was set to 3 A with a coated tool, MRR increased by 74% when compared to the uncoated tool. Similarly, under current 6 A and 9 A conditions, the coated tool can enhance MRR by 28% and 38%, respectively. Figure 1(b) shows the comparison of MRR with the uncoated and coated electrodes under various voltage conditions. In this project, voltages were selected at three levels (25 V, 50 V, and 75 V). From the graph, it can be seen

Table 1: Process parameter variables.

Process variables	Description
Workpiece	Al–Zn–Mg/Si_3N_4 composites
Tool	Nickel-coated brass and uncoated brass tube electrode
Diameter of the hole	50 μm
Current (A)	3, 6, 9
Voltage (V)	25, 50, 75
Pulse on time (μs)	20, 40, 60
Capacitance (nF)	3, 6, 9

Table 2: Chemical properties of electrode.

Properties	Brass electrode	Nickel coating
Electrical conductivity (s/m)	1.67 × 107	1.43 × 107
Melting point (°C)	930	1455
Thermal conductivity (W/m°K)	159	975
Electrical resistivity (ohm-cm)	4.7 × 10−8	6.99 × 10−8
Specific heat capacity (J/g-°C)	0.38	0.444

Table 3: Properties of aluminium powder.

Properties	Aluminium
Density (g/cm^3)	3.9
Melting point (°C)	650
Electrical conductivity (s/m)	3.69×10^7
Thermal conductivity (W/m°K)	239
Electrical resistivity (ohm-cm)	2.82×10^{-8}

Table 4: Properties of dielectric fluid.

Properties	Kerosene oil
Dielectric constant, K	1.8
Electrical conductivity (s/m)	1.6×10^{-14}
Mobility, m^2/Vs	2.2×10^{-8}
Electric field, MV/m	16.6
Mass density, kg/m^3	728

that the MRR decreases with increasing voltage. But the MRR of the coated tool was quite high, compared with the uncoated tool. MRR can be improved drastically with the coated tool by about 49%. In this condition, the machine tool was operated under 75 V. MRR can be improved up to 39% and 34% by the coated tool, under the machining conditions of 25 V and 50 V. The comparison of MRR with the uncoated and coated electrodes under various pulses on time is shown in Figure 1(c). Abnormality was observed in this graph. When the machine tool was run at a pulse on time of 40 μs, it gave a low MRR compare to the other two levels. But normally, the MRR of the coated tool is high compared to that of the uncoated tool. Here, MRR can be improved up to 46% with this machine tool operating on a pulse on time of 60 μs. MRR can be improved by 31% and 35% by the coated tool, under the pulse on time of 20 μs and 40 μs.

Figure 1(d) shows the comparison of MRR with the uncoated and coated electrodes under various capacitance

Table 5: Experimental run order.

Exp run	Material of electrode	Current (A)	Voltage (V)	Pulse on time (μs)	Capacitance (nF)
1	Brass	3	25	20	3
2	Brass	3	50	40	6
3	Brass	3	75	60	9
4	Brass	6	25	20	6
5	Brass	6	50	40	9
6	Brass	6	75	60	3
7	Brass	9	25	40	3
8	Brass	9	50	60	6
9	Brass	9	75	20	9
10	Nickel-coated brass	3	25	60	9
11	Nickel-coated brass	3	50	20	3
12	Nickel-coated brass	3	75	40	6
13	Nickel-coated brass	6	25	40	9
14	Nickel-coated brass	6	50	60	3
15	Nickel-coated brass	6	75	20	6
16	Nickel-coated brass	9	25	60	6
17	Nickel-coated brass	9	50	20	9
18	Nickel-coated brass	9	75	40	3

conditions. From the graph, it can be seen that coated electrode gives a high MRR, compared to the uncoated electrode. Normally, MRR increases with increasing the capacitance from 3 nF to 9 nF, but here, tremendous changes were produced by the coated electrode. When the machine was run at 6 nF with the coated tool, it gave a 43% improvement in MRR, compared to the uncoated tool. Similarly, MRR can be improved by 49% and 32% with the coated tool under the capacitance conditions of 3 nF and 9 nF.

The graphs in Figure 1 show that the current, voltage, and capacitance exhibited good sensitivity with MRR. The increase in Current and Capacitance improves the MRR [19]. The decrease in voltage decreases the MRR [20, 21]. So the process could be controlled by varying these parameters. The pulse on time can be used for fine-tuning the process for more accuracy. The coated electrode recorded a significant improvement in MRR [22]. The nano-PMEDM is a promising process for a better surface finish. The coated electrode supported well in higher material removal rate. This result is supported by previous investigations. The ANOVA results (Table 6) helped to rank the influence of factors on the MRR. A lower p value indicates a higher influence. Hence factor current is rank 1 (As $p = 0.001$), voltage Rank 2 (current is rank 1 (As $p = 0.0364$), and finally, rank 4 for pulse on time. The same could be ensured by observing the F value in that Table 6. The Higher F value is indicated as a more influencing input parameter.

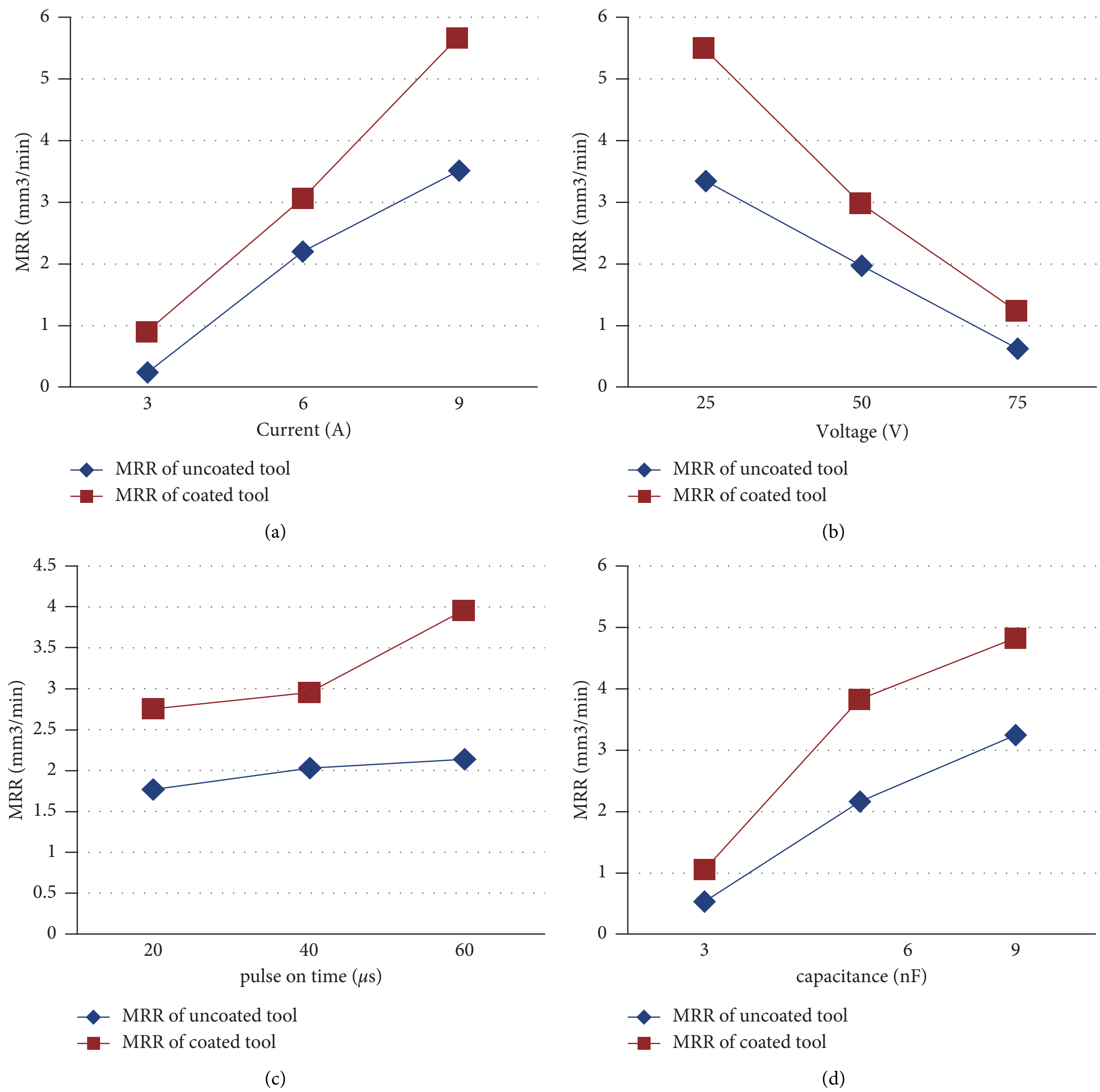

Figure 1: The MRR response with the variation of (a) input current, (b) voltage, (c) pulse on time, and (d) capacitance.

Table 6: ANOVA of MRR.

Source	DF	Adj SS	Adj MS	F value	p value
Electrode	1	0.095048	0.095048	35.37	0.001
Current (A)	2	0.217744	0.108872	40.51	0.001
Voltage (V)	2	0.008565	0.004283	1.59	0.0261
Pulse on time (μs)	2	0.001269	0.000635	0.24	0.0495
Capacitance (nF)	2	0.002887	0.001443	0.54	0.0364
Error	8	0.021499	0.002687		
Total	17	0.347013			

3.2. Analysis of Machining Time. Machining a microhole on the aluminium composites with the coated tool takes less time compared to the uncoated tool. Figure 2 represents the machining times of a coated and uncoated tool; the graph shows that the machining time of the coated tool is minimal. The machining time changed significantly in the first three experiments. Machining nine holes with an uncoated tool took 50 minutes and 88 seconds, but machining those same nine holes with a coated tool takes only 18 minutes and 11 seconds. In the remaining experiments, slight time

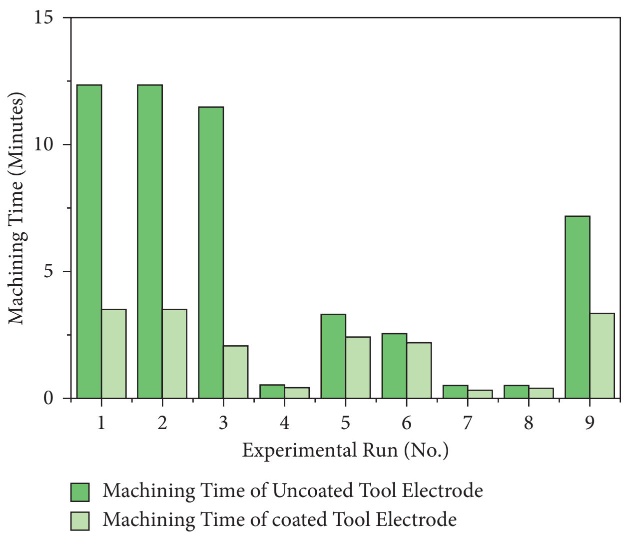

Figure 2: Machining time of composites.

variations were observed. The coated tool can reduce machining time by 64% in this particular scenario.

3.3. Electrode Wear Rate (EWR). One of the most important characteristics of an electrode to be used in EDM is higher material removal with lower electrode wear. The amount of material removed from the electrode material per unit of time is expressed as EWR. It is a major factor that contributes to achieving better productivity. The primary goal of this project is to reduce electrode wear rate to increase productivity. In this study, two kinds of electrodes were used: coated electrodes and uncoated electrodes. This pioneering investigation shows that the coated electrode has a higher EWR than the uncoated electrode. The unit of EWR is mm^3/min.

Figure 3(a) shows the comparison of EWR in the uncoated electrode and coated electrode under various current conditions. The graph shows that the coated electrode has a lower EWR than the uncoated electrode for the increase in current from 3 A to 9 A. When the current was set to 3 A with the coated tool, EWR improved by 63% when compared to the uncoated tool. Similarly, under current conditions of 6 A and 9 A, the coated tool can improve EWR by 5% and 29%. The main reason for the lower EWR in nickel-coated electrodes is that they are exposed to a higher energy electric spark for a shorter period than uncoated electrodes. Figure 3(b) shows the comparison of EWR with the uncoated and coated electrodes for various voltage conditions. In this study, voltages were selected at three levels, namely, 25 V, 50 V, and 75 V. [23] Observed that increasing gap voltage causes the formation of larger craters, which reduces the EWR linearly. The graph clearly shows that EWR decreases with increasing voltage, and the EWR of coated tool resulted in less wear than the uncoated tool. EWR has been reduced by approximately 76% with the coated tool for a voltage of 75 V, but by 26% and 32% for 25 V and 50 V, respectively.

The comparison of EWR with the uncoated and coated electrodes for various pulses on time is shown in Figure 3(c). Higher spark energy was produced with the increase in pulse on time, resulting in a higher EWR. For the pulse on time of 60 μs, the EWR of the nickel-coated tool has been improved to 38%. EWR has been improved by 24% and 7% with the coated tool under the machining conditions of pulse on time of 20 μs and 40 μs. Moreover, the comparison of EWR with the uncoated electrode and coated electrode for various capacitance conditions. As the capacitance value increases, the discharge energy of this spark increases linearly. As a result of the increased material removal, EWR begins to increase. From the graph, it can be seen that the coated electrode gives a high EWR compared to the uncoated electrode. Normally, EWR increases with increasing capacitance from 3 nF to 9 nF, a significant improvement was observed with the coated electrode. When the machine tool was run at 6 nF with the coated tool, it gave a 36% of improvement in EWR compared to the uncoated tool. Similarly, EWR has been improved by 27% and 15% by coated electrodes under the capacitance conditions of 3 nF and 9 nF.

3.4. Volume of Electrode Saved by Coated Tool. The volume of material removed from the electrode was used to calculate the amount of material electrode consumed by both uncoated and coated tools for machining with various process parameters, as shown in Figure 4. The uncoated tool consumed a large amount of material to make the 50 μm holes on Al–Zn–Mg/Si_3N_4 composites under various machining conditions, whereas the coated tool consumed a small amount of tool material to make the 50 μm holes. The uncoated tool used 7.527 mm^3 of material to make the nine holes in the Al–Zn–Mg/Si_3N_4 composites whereas the coated tool used less material (5.75 mm^3). Eventually, the coating process saved 24% of the material volume in the tool/electrode.

4. Analysis of Variance (ANOVA)

Analysis of variance (ANOVA) of the response can be used to investigate the significance of the process parameter [24]. ANOVA of MRR revealed that the electrode (coated and nickel-coated) and current were the most significant parameters, followed by voltage and capacitance as shown in Table 6.

The pulse-on-time process parameter is the least significant for MRR. The most important process parameter for EWR is an electrode (coated and nickel-coated) followed by pulse on time, voltage, and capacitance which is found to be the least significant as shown in Table 7. The linear regression model can be used to develop the relationship between input and output process parameters. In this study, Minitab software is used to create the linear regression model. Equations (3) and (4) show the relationship between the input parameter and the response of MRR. Equations (5) and (6) show the relationship between inputs and response of EWR. Both models were accurate and followed normality based on the residual plot of MRR and EWR as shown in

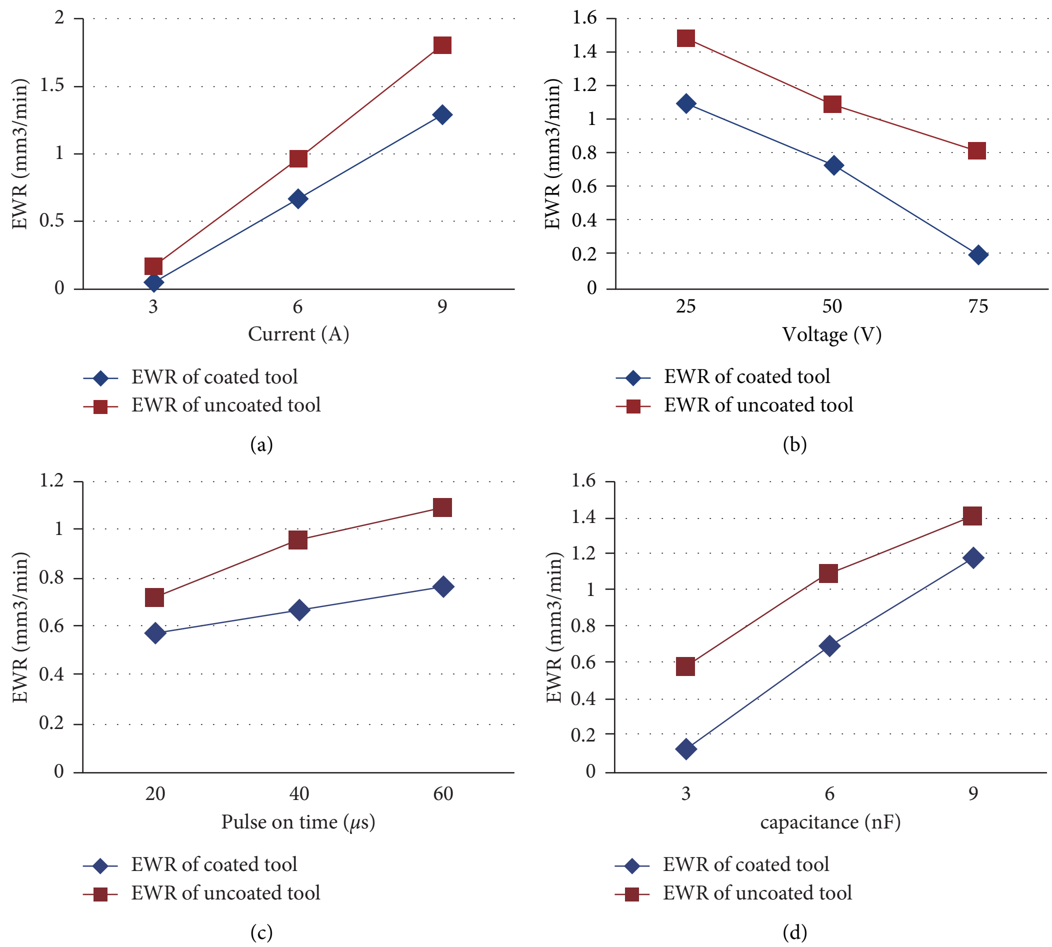

FIGURE 3: Effect of input process parameters on EWR.

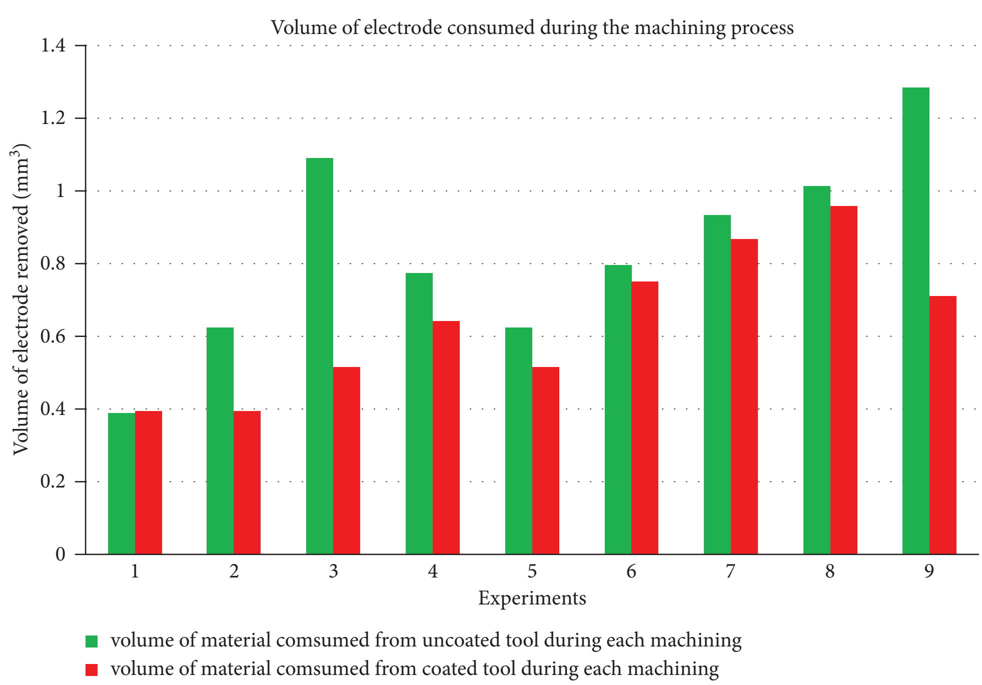

FIGURE 4: The volume of electrodes removed by coated and uncoated electrodes.

Table 7: ANOVA of EWR.

Source	DF	Adj SS	Adj MS	F value	p value
Electrode	1	0.042491	0.042491	3.5	0.0098
Current (A)	2	0.033721	0.016861	1.39	0.0304
Voltage (V)	2	0.02381	0.011905	0.98	0.0416
Pulse on time (μs)	2	0.036301	0.018151	1.49	0.0281
Capacitance (nF)	2	0.00286	0.00143	0.12	0.0389
Error	8	0.097155	0.012144		
Total	17	0.236339			

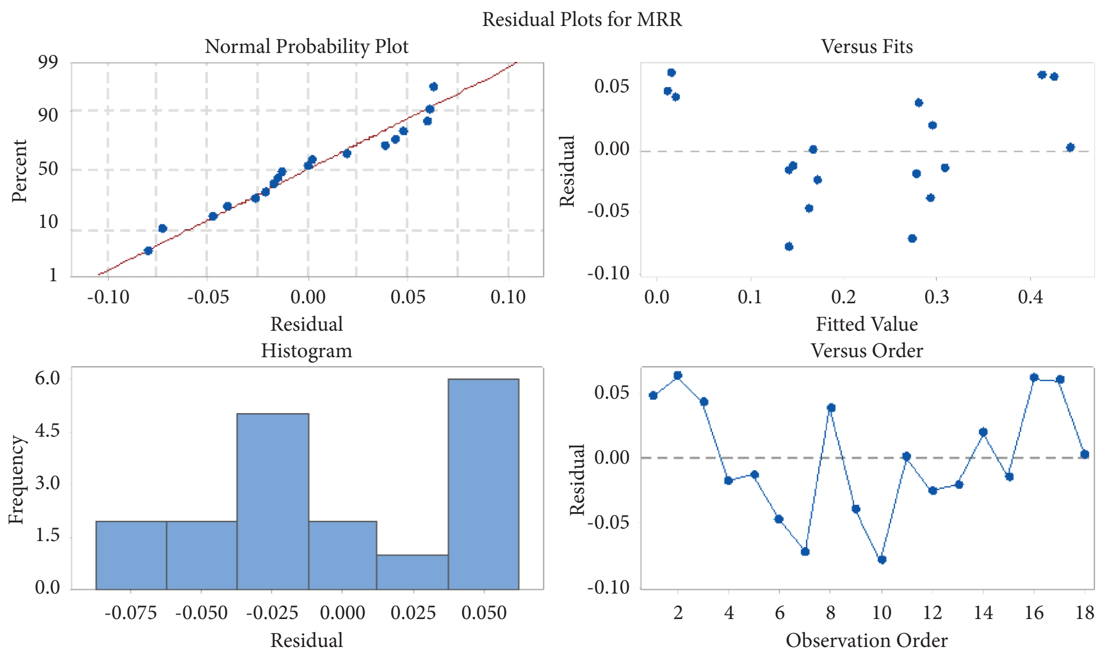

Figure 5: Residual plots for MRR.

Figures 5 and 6. In addition, no deviations or improper patterns were observed.

$$\text{MRR with Brass electrode} = -0.1298 + 0.04467\,\text{Current}\,(\text{A}) + 0.000477\,\text{Voltage}\,(\text{V}) - 0.000146\,\text{Pulse on Time}\,(\mu\text{s}) - 0.00136\,\text{Capacitance}\,(\text{nF}), \quad (3)$$

$$\text{MRR with Nickel Coated Brass electrode} = 0.0156 + 0.04467\,\text{Current}\,(\text{A}) + 0.000477\,\text{Voltage}\,(\text{V}) - 0.000146\,\text{Pulse on Time}\,(\mu\text{s}) - 0.00136\,\text{Capacitance}\,(\text{nF}), \quad (4)$$

$$\text{EWR with Brass electrode} = 0.157 + 0.0173\,\text{Current}\,(A) - 0.00164\,\text{Voltage}\,(\text{V})0.00063\,\text{Pulse on Time}\,(\mu\text{s}) - 0.0025\,\text{Capacitance}\,(\text{nF}), \quad (5)$$

$$\text{EWR with Nickel Coated Brass electrode} = 0.060 + 0.0173\,\text{Current}\,(\text{A}) - 0.00164\,\text{Voltage}\,(\text{V}) - 0.00063\,\text{Pulse on Time}\,(\mu\text{s}) - 0.0025\,\text{Capacitance}\,(\text{nF}). \quad (6)$$

5. Tool Morphology

5.1. Analysis of the Surface of the Uncoated Tool by Scanning Electron Microscope (SEM). The surface of the uncoated and coated tools was scrutinised using a scanning electron microscope (SEM). Following the machining process, erosion occurred on the brass tube, resulting in a small crater on the tool surface in both coated and uncoated electrodes as shown

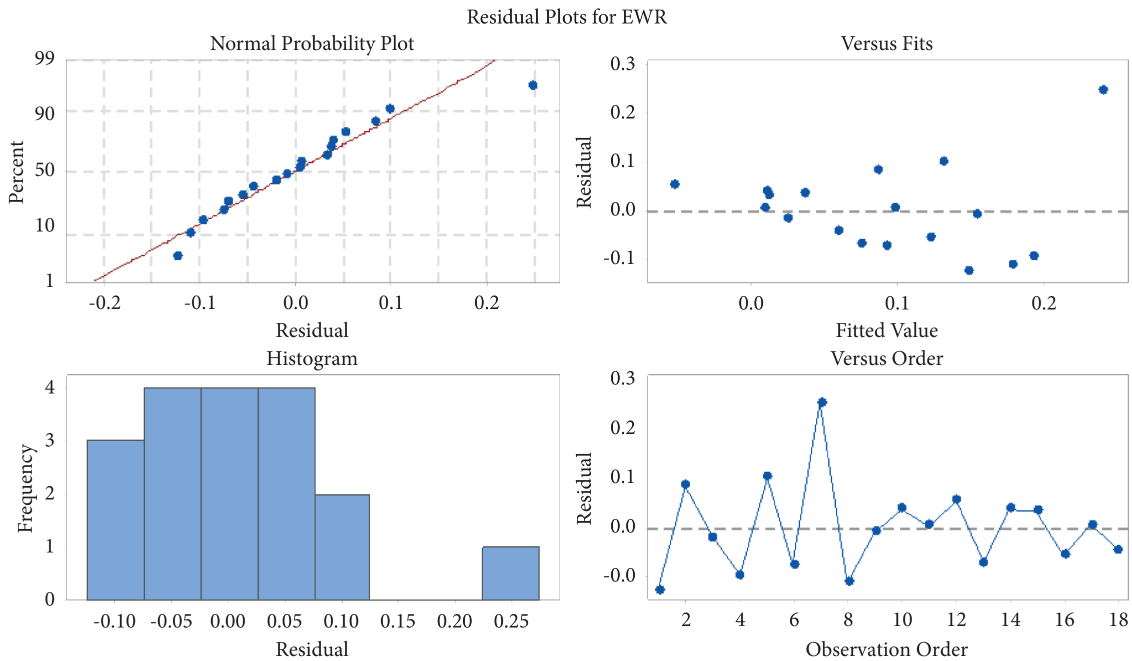

Figure 6: Residual plot for EWR.

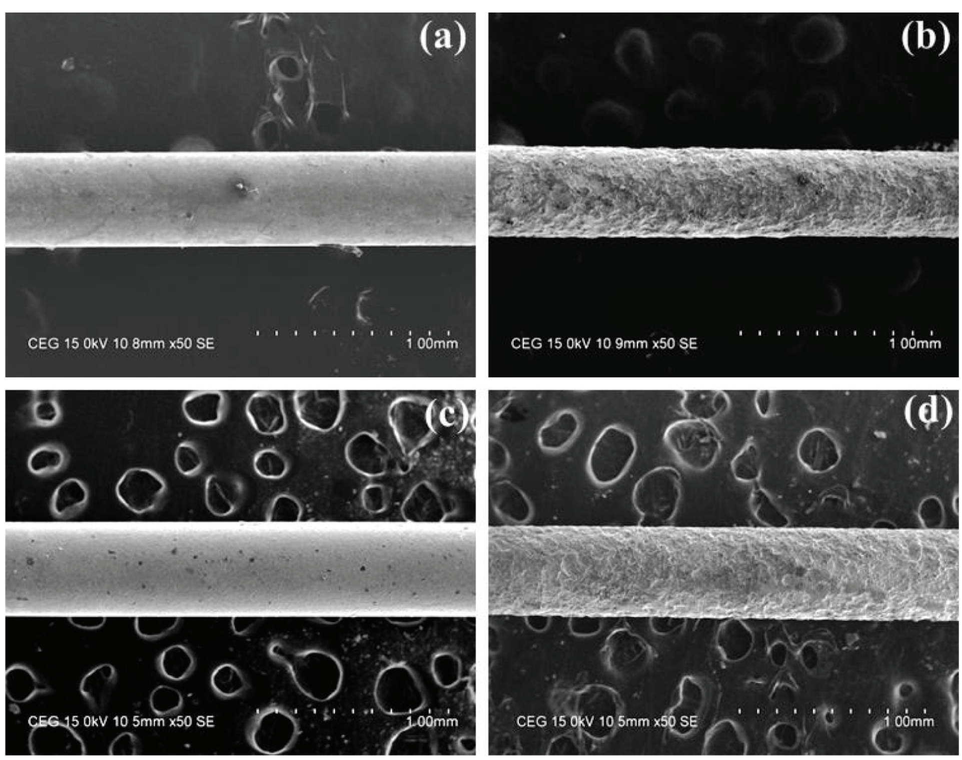

Figure 7: (a) Uncoated electrode before machining; (b) uncoated electrode after machining; (c) coated electrode before machining; (d) coated electrode after machining.

in Figures 7(a)–7(d). The Size of the crater is more with the uncoated electrode, which affected the life of the electrode as shown in Figure 7(b). From the SEM image, electrode wear in the coated tool has been reduced, with the ragged surface being the least in the case of coated tool electrode when compared to the uncoated electrode, as shown in Figures 7(b) and 7(d). The coated and uncoated electrodes effects are similar to those used for the machining of the D2 steel [25].

5.2. Analysis of the Edge of the Tool. Initially, the edge of the brass tube is the taper section that is shown in Figure 8(a) with small dust particles seen on the tool surface. After the

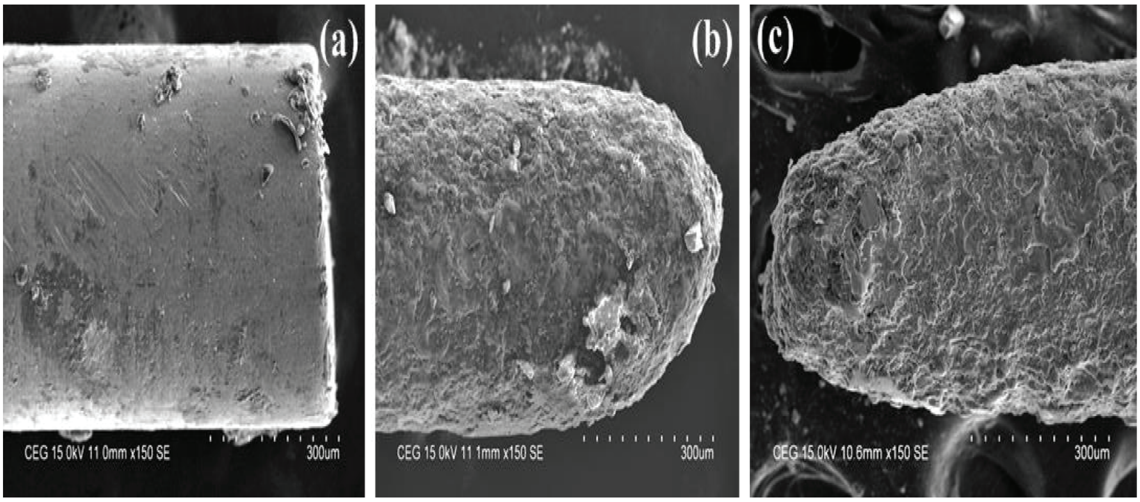

Figure 8: (a) Electrode before machining, (b) uncoated electrode edge after machining, and (c) coated electrode edge after machining.

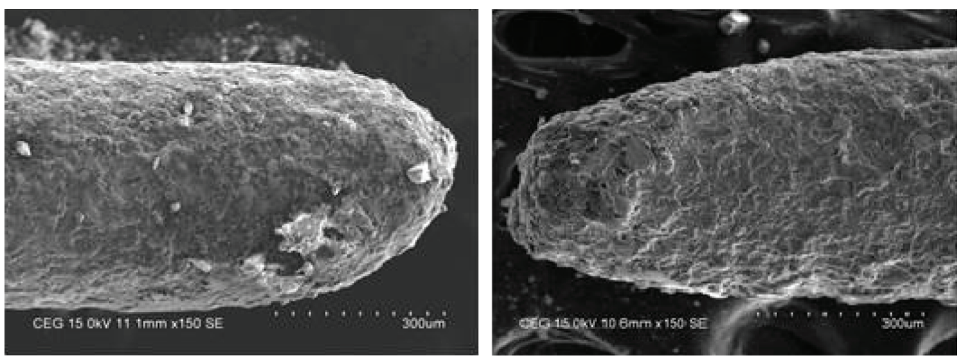

Figure 9: Uncoated (parabola section) and coated tools (elliptical section) were used for Al–Zn–Mg/Si_3N_4 composites.

machining process, erosion takes place on the tool surface, so a conical section was observed on the edge of the tool as shown in Figures 8(b) and 8(c). From the SEM image, EWR is more on the bottom section of the brass tube. The effects have good agreement with the machining of D2 steel [25].

5.3. Surface Analysis of the Coated Tool. Nickel is coated on the brass tube with a thickness of 2 microns as shown in Figure 8(c). Nickel particles look like small bubbles on the brass tube's substrate material. SEM analysis shows that nickel is uniformly distributed on the tool surface during the coating process. During the metal removal process, the nickel particles were eroded. Craters were observed on the machined tool surface as shown in Figure 8(c). When compared to an uncoated electrode, the size of the crater is smaller in the coated tool, indicating that the tool life is increased. The result supported for justification as it was used for machining D2 steel [25].

5.4. Comparison of the Coated Tool and Uncoated Tools. Figure 9 portrays that more metal removal occurs on the side wall of the uncoated tool. This causes a secondary reaction during machining, preventing the uncoated tool from providing the necessary spark energy. This results in a low MRR for the uncoated electrode, but because the coated tool provides concentrated spark energy during machining, more material was removed, as evident from the coated electrode edge. The coated electrode showed an elliptical section, but the uncoated tool showed a parabola section due to the secondary reaction as it was used for machining the D2 steel [25].

6. Conclusions

Powder-mixed micro-EDM experiments on Al–Zn–Mg/Si_3N_4 composites were carried out with a nickel-coated brass electrode and an uncoated brass electrode. The coated tool has increased tool life additionally, the coated tool provides more benefits than the uncoated electrode which are as follows: the electroless plating on the brass electrode coated with nickel reduced the machining time by 63.86%. The volume of material removal from the electrode has been reduced from 7.6227 to 5.39 mm^3 for the coated electrode. In comparison to an uncoated tool, a nickel-coated brass electrode improves MRR by 48.34%. High MRR was achieved due to more concentrated spark energy during machining with the nickel-coated electrode. The coated tool improves electrode life by 23.26% when compared to the uncoated tool. The superior properties of the nickel-coated electrodes provided high thermal stability during the machining process. This extends the life of the electrode. The electrode wear rate was minimised by using nickel-coated electrodes to about 21.92%. From ANOVA tables, the electrode material is an important factor in maximising MRR and minimising EWR. The investigation shall be extended by optimising the nanoparticles variety, effects of hybrid nanoparticles, and optimising the size of nanoparticles for improving the machinability.

Data Availability

The data used to support the findings of this study are included in the article. Should further data or information be required, these are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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