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Improvement of Performance Evaluation Using Hybrid Composite Electrode (Cu/Cr/WC/Ag) in Electric Discharge Machining

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HIGHLIGHTS

- The TWR for the pure copper electrode was 0.514 gm/min, while the composite electrode (Cu-1%Cr-0.5%WC-1%Ag) had the lowest TWR at 0.215gm/min.
- The pure copper electrode had a higher MRR of 54.5588 mm^3/min, while the composite electrode (Cu-1%Cr-0.5%WC-1%Ag) had the best MRR at 56.8689 mm^3/min.
- The composite electrode (Cu-1%Cr-0.5%WC-1%Ag) had an improved SR of 3.747 µm versus 3.967 µm for the pure copper electrode.
- Current, followed by pulse on/off time, significantly impacted the electrodes' TWR, MRR, and SR.

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ABSTRACT

Electrical Discharge Machining (EDM) is a non-traditional technique widely used in various industries to remove material using electrical discharges. Finding a suitable electrode material that can resist high temperatures and efficiently remove material from the workpiece is a major difficulty in electrical discharge machining (EDM). Due to their exceptional electrical and thermal properties, composite electrodes of various metals have become extremely popular. In this study, a composite electrode (Cu-1%Cr-0.5%WC-1%Ag) manufactured using the stir casting technique will be utilized to evaluate the electrical discharge machining (EDM) process. The study compares the performance between conventional pure copper electrodes and composite electrode utilization of stainless steel 304L as the workpiece material. The results indicate composite electrodes can increase machining effectiveness and reduce electrode wear. Utilizing a current of 10 A, with a pulse on time of 50µs followed by a pulse off time of 50 µs, reduced the tool wear rate to 0.215 gm/min for the composite electrode. By comparison, it was observed that the copper electrodes displayed a tool wear rate of 0.514 gm/min under the same conditions. While the pure copper electrode had the lowest material removal rate (MRR) at 54.5588 mm^3/min, the composite electrode had the greatest MRR at 56.8689 mm^3/min. The surface Roughness (SR) of the composite electrode was 3.747µm; this value was lower than that of the pure copper electrode, 3.967µm. As a result, composite electrodes present a potentially viable substitute for traditional EDM electrodes.

1. Introduction

Due to its distinctive capabilities, the non-traditional machining process known as Electrical Discharge Machining (EDM) has garnered considerable attention across diverse industries [1]. The process involves the utilization of electrical discharges to erode material from a workpiece, making it a proficient approach for severing hard and brittle materials, which present challenges when subjected to traditional machining methods. The utilization of EDM for producing high-precision parts and components has been extensively adopted by various industries, including aerospace, medical, automotive, and electronics [2,3].

The basic idea of Electrical Discharge Machining (EDM) includes using a voltage that causes erosion between the chosen tool, an electrode, and the workpiece. The distance between the electrode and the workpiece throughout the process is minimal, typically varying from 0.01 to 0.5 mm [4]. The electrode, generally made of a conductive material, connects to the power supply's negative terminal, whereas the workpiece, also consisting of a conductive material, is connected to the positive terminal. The generation of high-frequency spark discharges across a narrow gap is facilitated by applying an electrical voltage between the electrode and the workpiece. The aforementioned discharges generate the formation of a plasma channel, which leads to the vaporization of a small amount of the workpiece material and the consequent creation of a diminutive depression or crater [5]. Subsequently, the material transformed into vapor is removed using a dielectric fluid, which may include deionized water or oil. The repeated spark discharge phenomenon is employed to gradually form the electrode into the intended configuration by gradually removing the workpiece material [6]. An EDM (Electrical Discharge Machining) controller maintains the ideal

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distance between the electrode and the workpiece. This is significant in achieving efficient material removal and obtaining the desired surface finish. The EDM controller is responsible for monitoring the voltage and current levels throughout the machining process and making necessary adjustments to the gap [7].

Rajaguru et al. [8] used spark plasma sintering (SPS) to create a metal matrix composite electrode using copper and carbon nanotubes (Cu/CNT). According to their research, compared to pure copper electrodes, the CNT-infused electrodes had a greater Material Removal Rate (MRR) and a better surface smoothness when utilized as electrodes in EDM machining. Shather et al. [9] used a composite electrode composed of copper and silver and a high-speed steel plate as the workpiece material. The experiment results demonstrated that the Copper-Silver composite electrode, with a weight ratio of 70:30, yielded superior outcomes compared to the commonly used pure copper electrode. Furthermore, the tool wear rate was significantly lower when using the composite electrode, measuring at 0.0001gm/min. Beri et al. [10] used the Taguchi method to study the utilization of a CuW powder metallurgy (PM) electrode on Inconel 718. They aimed to determine the optimal parameter settings for achieving higher surface roughness. The research showed that using the powder metallurgy processed electrode improved the micro-hardness of the machined surface. XRD analysis revealed the formation of the Fe2W3C6 phase, which significantly contributed to the improved surface micro-hardness.

Balasubramanian et al. [11] conducted EDM on EN8 and D3 steels using cast copper and sintered powder metallurgy electrodes. The results indicated that the sintered copper electrode had a lower tool wear rate (TWR) and higher metal removal rate (MRR) for both steels than the cast copper electrode. The effectiveness of a green compact copper electrode produced via powder metallurgy (PM) to a normal copper electrode during aluminum EDM was compared by Jassal et al., [12]. The investigation showed that the surface quality was enhanced when the green compact PM copper electrode was used. According to microstructure analysis, higher current and longer pulse on times resulted in material transfer from the PM electrode to the workpiece surface.

The effect of deep cryogenic treatment (DCT) on tool wear rate during electric discharge machining of Ti-5Al-2.5S n titanium alloy was examined by Kumar et al., [13]. They discovered that the most important process variable was peak current. During the machining process, material transfer occurred, causing chemical compounds such as titanium carbide (TiC) to develop on both the tool and machined surfaces. The efficiency of Cu-SiC composite electrodes for cutting Ti-6Al-4V was investigated by Li et al., [14]. According to their research, surfaces machined with Cu-SiC electrodes had less microcracking than those treated with Cu electrodes. Using Cu-SiC electrodes also caused a continuous, uniform hardening layer on the machined surface. Cu-Gr composite materials have been investigated as EDM tools for cutting AISI 1020 mild steel by Uddin et al. [15] According to the study, adding more graphite to the Cu-Gr composite tool significantly reduced the tool wear rate (TWR) by up to 83% while keeping the metal removal rate (MRR) at 73%. TiC/Cu powder metallurgy (P/M) electrode was used in an experiment by Chundru et al. [16] to modify the surface of Ti6Al4V alloy. Numerous carbides, including TiC, Ti_2C, Fe_5C_2, and Fe_3C, and oxides, including TiO and Ti_3O, were found on the machined surface, according to the XRD examination. With no discernible increase in surface roughness, these carbides increased the hardness to 912HV. Rao et al. [17] investigated the surface modification of D_2 alloy steel using a WC/Co powder metallurgy (P/M) electrode made up of a mixture of nano-sized, micron-sized, and a combination of both sizes of particles. The work surface was found to have carbon particles deposited on it, oxygen particles diffused over the surface, and tungsten (W) and cobalt (Co) particles diffused across it from the electrode.

According to previous studies, the objective of the current study was to increase the effectiveness of the EDM process by utilizing a hybrid composite electrode with casting components to copper as the foundation material. The composite electrode contained 1% chromium, 0.5% WC, 1% Ag, and copper as a base material. The study aimed to evaluate the tool wear rate, material removal rate, and surface roughness when machining AISI stainless steel 304 L while varying input parameters like current, pulse on time, and pulse off time. The performance of the composite electrode was compared to that of a conventional copper electrode after its fabrication using the stir casting technique.

2. Experimental Work

The electrodes were created by combining different materials: copper (Cu) as the primary component with 99.9% purity, along with 1% chromium (Cr), 1% silver (Ag) by weight, and 0.5% tungsten carbide (WC). The manufacturing process involved melting pure copper at a temperature of 1280˚C. The additive components, placed in the foil, were added separately to the melted copper. The mixture was then stirred for 2 minutes using a steel rod to ensure an even distribution of the particles. Subsequently, the liquid mixture was poured into a preheated cast-iron mold at 500˚C and allowed to cool and solidify. Once solidified, the electrode was removed from the mold. To prepare it for use in the EDM process, the electrode was machined and finished to achieve the desired shape and dimensions using turning machining. The resulting electrode had a shaft diameter of 16mm and a length of 120 mm. Figures 1 (A and B) illustrate the shape of the electrode and its design, respectively. Examination results of the pure copper electrode by the State company for engineering rehabilitation can be found in Table 1.

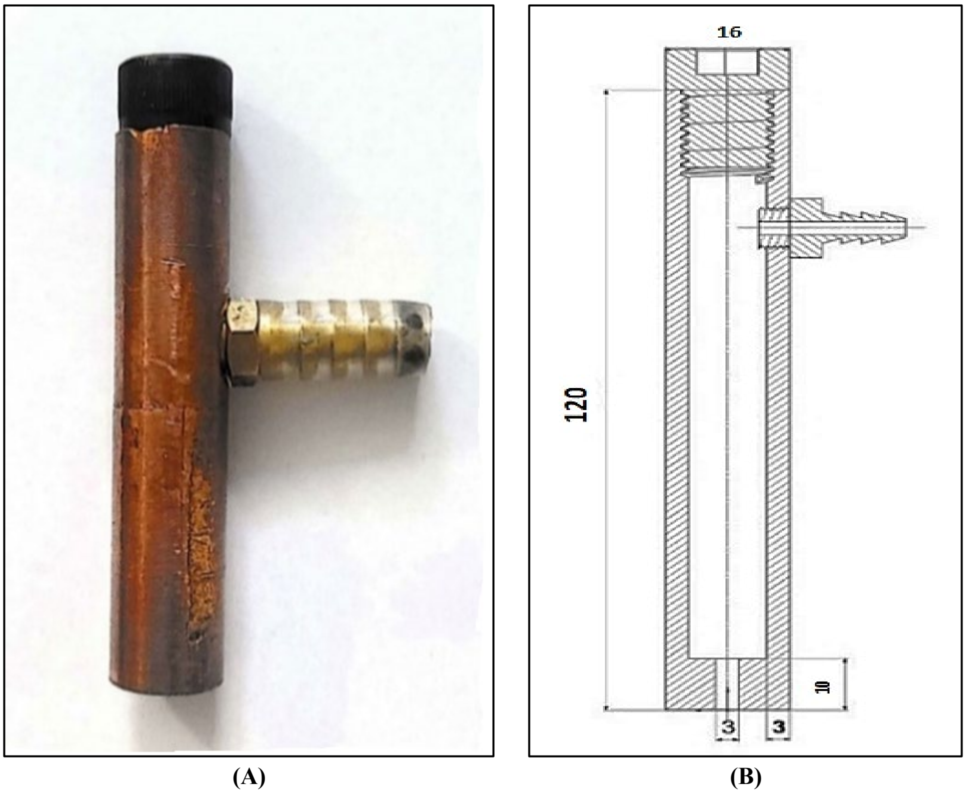


Figure 1: (A) Electrode used in experimental work, (B) Design of Tool electrode

Table 1: Chemical composition of pure copper electrode

Pb%	Sn%	P%	Fe%	Ni%	Si%	Cr%
0.0155	0.0073	0.0013	0.0458	0.0032	0.016	0.0007
Sb%	**Ag%**	**Al%**	**S%**	**Ti%**	**Cu%**	
0.005	0.0019	0.0017	0.0038	0.0002	99.9	

The experiments were conducted with a CHMER EDM machine (CM 232C) at the University of Technology-Iraq's Training and Workshop Centre. A 16 mm-diameter composite electrode and a pure copper electrode were both used in the tests. The composite electrode used in compositions: (Cu-1%Cr-0.5%WC-1%Ag). The workpiece chosen for the investigation was manufactured of stainless steel 304L, had dimensions of (40x40) mm, and was 6mm thick. Table 2 lists its mechanical and physical characteristics, while Table 3 lists its chemical composition. Each run of the workpiece was cut to a depth of 1mm to maintain consistency. The main goal of the research was to employ a pure copper electrode for EDM while altering the current levels (10, 30, and 50 Amp), pulse on time (50, 100, and 150 µs), and pulse off time (25, 50, and 75 µs). The machining parameters used in the investigation are shown in Table 4, and the Tool Wear Rate (TWR), Material Removal rate (MRR), and Surface Roughness (SR) were calculated for every experiment. The Minitab App with RSM analysis was also used to make the composite tool electrodes using the same parameters, allowing experiment design and result comparison. The workpiece is shown in Figures 2 (A and B) both before and after the machining operation.

Table 2: Mechanical and physical properties of Stainless steel 304L

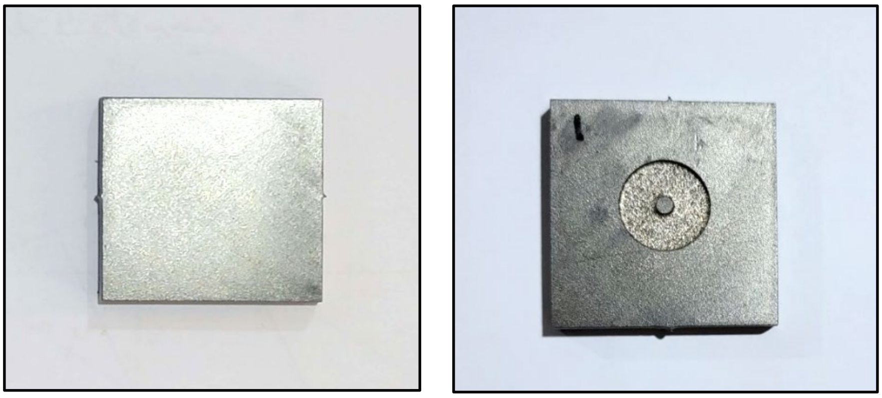
Properties	Stainless steel 304L
Tensile Strength	500 – 700 MPa
Elongation	45 %
Melting Point	1450 °C
Thermal Expansion	17.2 × 10-6 /K
Modulus of Elasticity	193 GPa
Thermal Conductivity	16.2 W/m.K
Electrical Resistivity	0.072 x 10-6 Ω .m
Density	8.0 (g/cm^3)

Table 3: The chemical composition of the AISI 304L stainless steel

Material	C	Si	Mn	P	S	Cr	Mo	Ni
Weight%	0.0249	0.452	1.174	0.0287	<0.0005	18.75	<0.002	8.670
Material	**Al**	**Cu**	**Co**	**Ti**	**V**	**W**	**Fe**	
Weight%	0.001	0.0258	0.272	0.0046	0.135	0.0233	Balance	

Table 4: Machining parameters used in experimental work

Working Parameters	Current, Pulse on time and Pulse off time
Workpiece	Stainless Steel 304L (6 mm)
Tool-electrode material	Pure Copper electrode & composite electrode
Shape of tool-electrode	Cylindrical bar
Electrode polarity	Negative (-)
Workpiece polarity	Positive (+)
Dielectric	Transformer oil
Dielectric temperature	40-80°C
Input voltage	380V (three-phase) AC
Output voltage	140V (two-phase) DC
Current	10-50 A
Pulse on time	50-150 µs
Pulse off time	25-75 µs
Gap	Code 10 (about 0.25 mm)
Depth of cut	1 mm



(A) (B)

Figure 2: (A) workpiece before machining, (B) workpiece after machining

3. Calculation of TWR, MRR, Ra

The electrode was firmly attached to the chuck for the experiments, which used the same kind of Transformer oil as the dielectric fluid. Following the electrode setup, the fluid level was checked, and the workpiece was set in the workpiece holder to guarantee accuracy. Using an accurate balance (Denver TP-214 electronic analytical balance, 4 Digit), the weight of the electrode was measured both before and after the machining process, and the results were recorded. The difference in weight between the tool's pre- and post-machining weights was divided by the length of the machining operation to provide the Tool Wear Rate (TWR) [18]. This calculation is described by Equation 1, which is given in reference [19].

$$\text{EWR (gm/min)} = (\text{W bef.} - \text{W aft.}) \times 100 \,/\, (\text{T}) \tag{1}$$

Where: TWR (gm/min) Tool Wear Rate, expressed as a percentage, W bef.: Weight of the electrode before machining, measured in grams (g), W aft. : Weight of the electrode after machining, measured in grams (g), T: Machining time, measured in minutes (min).

The weight difference between the workpiece before and after processing was divided by the machining time and the density of the metal being worked on, and the material removal rate (MRR) was calculated—Equation 2, which is provided in reference [20].

$$\text{MRR } (\text{mm}^3/\text{min}) = (\text{W bef.} - \text{W aft.})/(\text{T x D}) \tag{2}$$

Where:W bef. = Weight of workpiece before machining (g),W aft. = Weight of workpiece after machining (g),
T = Machining time (min), D = Density of workpiece.

Surface roughness (SR) was measured using the MarSurf PS1 Surface Roughness Tester. The accuracy is ±0.001µm, and the range of roughness values is (0-350 µm). The probe scans the surface before comparing peaks and valleys to identify the SR and measured in (µm).

4. Results and Discussion

The response surface methodology (RSM) was used to select three components, each with three levels. Table 5 illustrates the machining parameters and response variables determined by machining the pure copper electrode using Minitab -17.

The study evaluated the effects of three variables, each with three levels, on the machining process using the response surface methodology (RSM). Using the analysis of variance (ANOVA) technique, the effectiveness of the second-order model for each machining response was determined [21].

Table 5: Machining parameters and Response factors of pure Copper electrode

No. of experiments	Current (A)	Pulse on (Ton) µs	Pulse off (Toff) µs	Tool Wear Rate (TWR) (gm/min)	Material Removal Rate (MRR) (mm^3/min)	Surface Roughness (SR) µm
1	30	100	50	4.5246	26.8318	4.650
2	50	100	75	13.3363	35.7568	5.708
3	30	100	50	6.6984	27.6275	4.829
4	30	100	50	8.7792	26.7798	4.802
5	50	150	50	15.8549	54.5588	5.991
6	30	50	25	9.4433	51.2146	4.457
7	10	150	50	1.1299	8.96663	4.632
8	10	100	75	1.0521	6.55792	4.398
9	30	150	25	4.5036	35.7116	5.506
10	50	100	25	14.9607	52.7156	5.377
11	30	50	75	4.3770	13.5509	3.967
12	10	100	25	0.6335	8.50420	4.519
13	10	50	50	0.5141	5.37609	4.393
14	50	50	50	8.9291	24.5718	4.226
15	30	150	75	5.6519	30.0440	5.398

For the variables affecting the tool wear ratio (TWR), the main effect plot is shown in Figure 3. The results of the analysis are shown in Table (5), which indicates that the current is the most important factor. The findings show that TWR has a negative relationship with pulse off time, but TWR has a direct relationship with current and pulse on time. The main contributing factor was specifically named as the current. The mean TWR was 0.832 gm/min at a current of 10 Amp, 6.282 gm/min at 30 Amp, and 13.270 gm/min at 50 Amp, respectively. This is due to the fact that greater pulse currents induce more intense spark discharge between the electrode and workpiece, which increases the dielectric's flushing away of molten materials and degrades the erosion effect, as documented in a prior study [22]. The TWR was 5.815 gm/min at a pulse on time of 50 µs, as shown in Figure (3). TWR climbed to 7.140 gm/min with an increase of 1.325 in pulse on time, and then fell to 6.785 gm/min with a decrease of 0.355 in pulse on time. Furthermore, as the pulse-off time lengthened, the mean TWR decreased. The mean TWR was 7.385 gm/min at a pulse-off time of 25µs, and it marginally fell to 6.104 gm/min with a decrease of 1.281 in pulse-off time. This is due to lower temperatures in the machining zone caused by lower heat dissipation caused by increased pulse-off times. As a result, there are less little craters and molten materials created, which lowers the rate of tool wear [23].

According to Figure 4, the results indicate that MRR is directly proportional to both current and pulse on time. There is an inverse relationship between MRR and pulse-off time. The most important factor was specifically named as the current. The average MRR was discovered to be 7.3512 mm^3/min when the current was set at 10 Amp. The MRR grew as the current was raised to 30 Amp, reaching 30.2515 mm^3/min, then 41.9007 mm^3/min at 50 Amp. As a result, the material melts and evaporates more quickly and intensely. This is because a larger current increases the energy given to the workpiece. Figure 3 also shows that the Material Removal Rate (MRR) was measured at 23.6783 mm^3/min at a pulse on time of 50 µs. The MRR grew to 26.3962 mm^3/min with a pulse-on-time increase of 100 µs and 32.3203 mm^3/min with a pulse-on-time increase of 150 µs. Higher energy delivery to the workpiece and higher material removal rates result from extending the pulse-on time. This is because a longer pulse duration erodes more material with each discharge. Moreover, the pulse-off time was associated with decreased average MRR. By a pulse-off time of 25µs, the mean MRR was 37.0365 mm^3/min; however, by 50 µs, it significantly decreased to 24.9589 mm^3/min. Further, it dropped to 21.4774 mm^3/min at a pulse-off time of 75 µs. The stability and accuracy of the EDM process are improved by a longer pulse-off time because it enables a more thorough re-solidification of the molten material. However, this can result in a lower MRR.

The surface roughness (SR), as illustrated in Figure 5, is directly proportional to current and pulse on time and inversely proportional to pulse-off time. As observed, the SR is 4.485 µm at currents of 10 Amp and rises to 5.325 µm with currents of 50 Amp with an increasing value of 0.84 µm. Then observed a low SR of 4.261µm at the pulse on time of (50) µs, which increases to 5.382 µm when the Ton is 150 µs. This is because the spark density in the plasma channel is maximized due to the initial level of pulse-on time. More material melts on the workpiece's surface due to increased heat energy delivery to that area. The surface roughness will deteriorate if the molten material isn't flushed away from the machined surface using the dielectric solution. The molten material will solidify and create a resolidified layer [22]. As seen in the same figure, the SR decreases from 4.965µm at a pulse-off time of 25 µs to 4.867µm at a Toff time of 75 µs, with a decreasing value of 0.098 µm. This is because a lengthy Toff time results in a lower temperature, fewer small craters, and the ability to flush debris out of the machining zone.

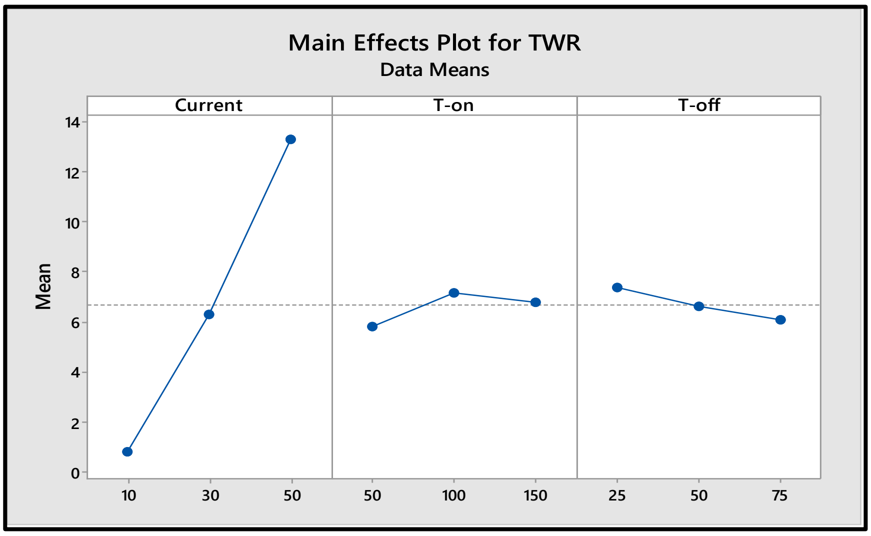


Figure 3: Main effects plot of Tool wear ratio using pure Copper electrode

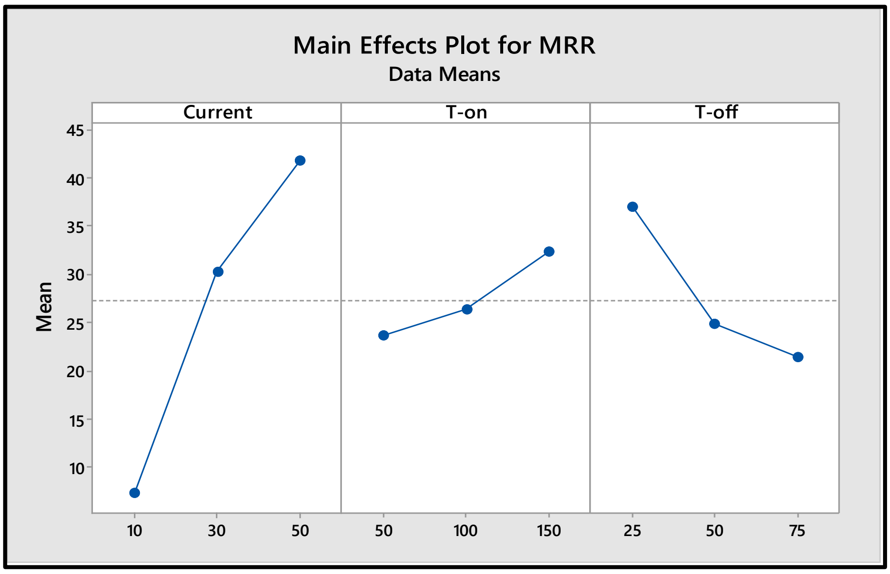


Figure 4: Main effects plot of material removal rate using pure Copper electrode

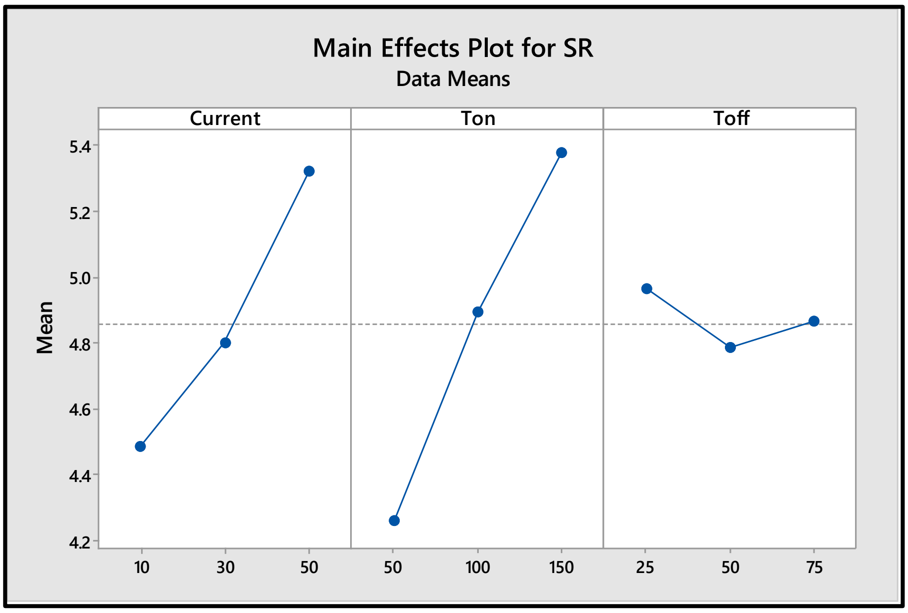


Figure 5: Main effects plot of surface roughness

The machining parameters and response variables from the ANOVA analysis performed in Minitab on the composite electrode (Cu-1 % Cr-0.5 % WC-1 % Ag) are shown in Table 6. It thoroughly analyzes the machining parameters and associated measured response parameters for the composite electrode.

The machining of the composite electrode is illustrated in Figure 6, and the main effects plot shows how the machining parameters affect the Tool Wear Rate (TWR). The current stands out as the most significant parameter in the process and has the greatest effect on TWR of all the process factors. The current, pulse on time (Ton), and pulse off time (Toff), in particular, significantly influence TWR.

TWR shows an inverse relationship with pulse off time but a direct relationship with the current and pulse on time. The current appears to be the main determining factor. It provides a lower mean TWR of 0.218 gm/min at a current of 10 Amp. TWR rises to 4.854 gm/min with an increase of 4.636 gm/min when the current increases to 30 Amp. Similarly, TWR reaches a mean value of 9.877 gm/min with an increase of 5.023 gm/min at a current of 50 Amp. This is because electrical discharges produced by larger currents are more powerful and energetic, which causes increased electrode wear. Figure 6 also shows how TWR and pulse on time are related. TWR is 5.067 gm/min at a pulse on time of 50µs. TWR increases to 5.107 gm/min with a 0.04 increase in pulse on time.

On the other hand, a reduction in pulse on time of 0.477 results in a TWR of 4.584 gm/min. Due to higher energy transfer and localized heating at the electrode-workpiece contact, longer pulse on times typically result in greater electrode wear. A higher TWR can occur from the electrode material being subjected to the electrical discharge for longer. Similarly, longer pulse-off times lead to lower machining zone temperatures, which create fewer tiny craters and less molten material, reducing the electrode wear rate. The mean effects of TWR, which go from 5.973 gm/min with a pulse-off time of 25µs to 4.664 gm/min with a drop of 1.309 gm/min in pulse-off time, serve as proof. The composite electrode's hardness and wear resistance are improved by including chromium and tungsten carbide. These elements have a part in the impacts on TWR seen throughout the machining process.

As shown in Figure 7, the MRR is directly proportional to both current and pulse on time. There is an inverse relationship between MRR and pulse-off time. The most important factor was specifically named as the current. The average MRR was discovered to be 8.0651mm^3/min when the current was set at 10 Amp. The MRR grew as the current was raised to 30 Amp, reaching 31.2314 mm^3/min, then 43.6445 mm^3/min at 50 Amp. This is because a larger current increases the energy input during each electrical discharge, which causes the workpiece material to melt and vaporize more quickly. As a result, more material is removed in a given amount of time, increasing the MRR. Figure 7 also shows that the Material Removal Rate (MRR) was measured at 24.6931 mm^3/min at a pulse on time of 50µs. The MRR grew to 24.4733 mm^3/min with a pulse-on-time increase of 100µs and 33.5932 mm^3/min with a pulse-on-time increase of 150 µs. A longer pulse on time enables a longer energy input into the workpiece, improving material melting and vaporization. This promotes a greater amount of material removal, which raises the MRR. Moreover, the pulse-off time was associated with decreased average MRR. By a pulse-off time of 25µs, the mean MRR was 38.4434 mm^3/min; however, by 50µs, it significantly decreased to 26.0304 mm^3/min. Furthermore, it dropped to 22.3680 mm^3/min at a pulse-off time of 75µs. During the EDM process, the pulse-off time predominantly impacts the flushing action and debris removal. A steady and effective material removal process is made possible by adequate flushing, which removes debris and molten material from the cutting gap.

As illustrated by Figure 8, the pulse-on time can be regarded as the most significant value when machining composite electrodes since it has a major effect on surface roughness compared to other process parameters (current and Toff). SR is directly proportional to current, pulse on time, and inversely proportional to pulse-off time. As shown, the SR is 4.236µm at currents of 10 Amp and rises to 4.966 µm with currents of 50 Amp with an increasing value of 0.73µm. Then observed a decrease in SR of 4.005 µm at the pulse on time of 50 µs, and reached 5.062 µm at the Ton 150µs with an increase of 1.058 µm. As noted in the same Figure, the SR decreases from 4.650 µm with a shorter pulse-off time of 25 µs to 4.585 µm at a longer Toff of 75 µs with a decreasing value of 0.065 µm. This is because the longer Toff caused the temperature to drop and flushed debris out of the machining zone.

Table 6: Machining parameters and Response factors of composite electrode (Cu-1%Cr-0.5%WC-1%Ag)

No. of experiments	Current (A)	Pulse on (Ton)µs	Pulse off (Toff)µs	Tool Wear Rate (TWR) (gm/min)	Material Removal Rate (MRR) (mm^3/min)	Surface Roughness (SR)µm
1	30	100	50	1.2092	28.2461	4.436
2	50	100	75	9.1912	37.1081	5.353
3	30	100	50	5.6052	28.5498	4.666
4	30	100	50	7.1948	27.0477	4.634
5	50	150	50	9.9385	56.8689	5.603
6	30	50	25	8.0246	52.4639	4.211
7	10	150	50	0.0955	9.2030	4.403
8	10	100	75	0.2793	7.0369	4.181
9	30	150	25	3.5976	36.9852	5.181
10	50	100	25	11.9880	53.8600	4.974
11	30	50	75	3.6388	14.0111	3.747
12	10	100	25	0.2832	10.4643	4.236
13	10	50	50	0.2151	5.5564	4.124
14	50	50	50	8.3929	26.7411	3.937
15	30	150	75	4.7076	31.3157	5.061

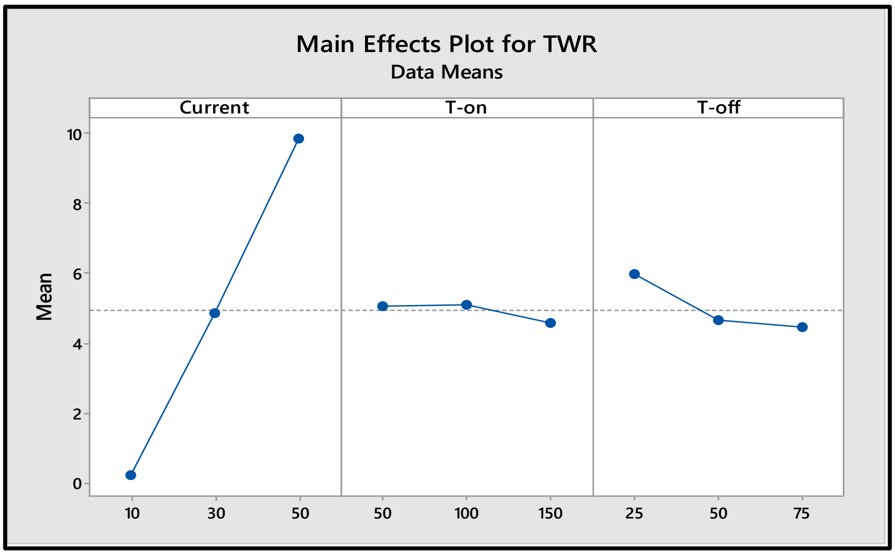


Figure 6: Main effects plot of TWR using composite electrode (Cu-1%Cr-0.5%WC-1%Ag)

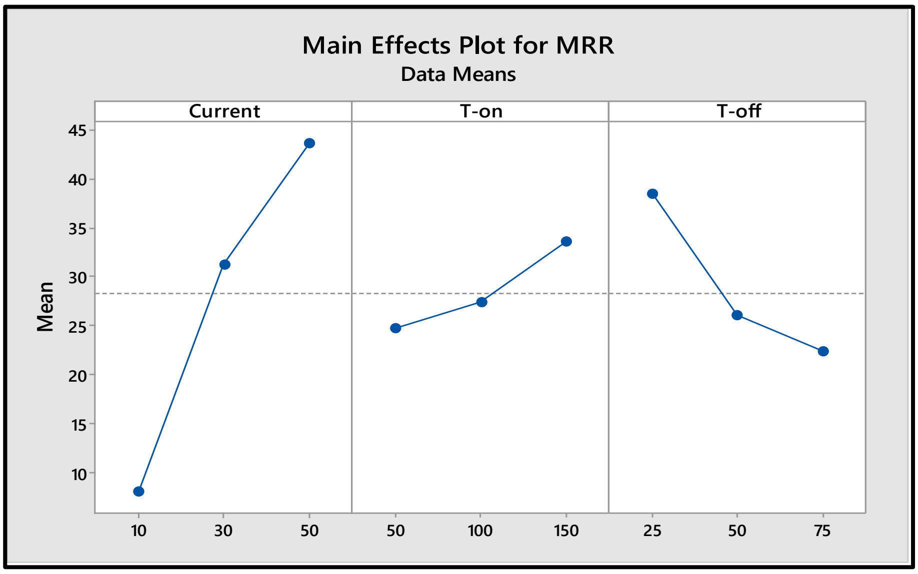


Figure 7: Main effects plot of MRR using composite electrode (Cu-1%Cr-0.5%WC-1%Ag)

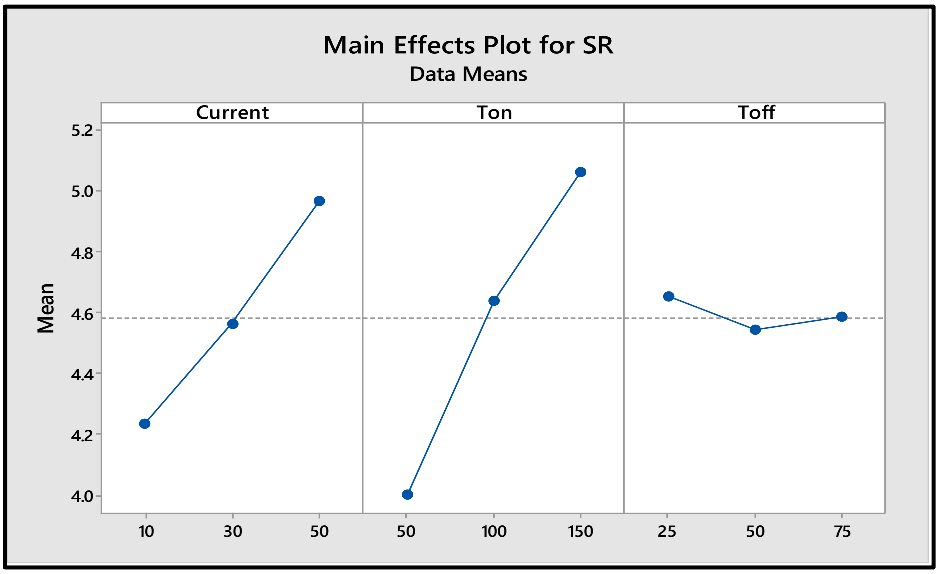


Figure 8: Main effects plot of SR using composite electrode (Cu-1%Cr-0.5%WC-1%Ag)

The tool wear rate (TWR) changes significantly, as seen by looking at the data in Figure 9 and comparing the pure copper electrode with the composite electrode. For the copper electrode, 15.854 gm/min is the highest reported wear rate, and 0.514

gm/min is the lowest. The maximum wear rate found is 11.9880 gm/min, while the lowest is 0.2151 gm/min for the composite electrode (Cu-1%Cr-0.5%WC-1%Ag). This difference can be due to the composite electrode's improved mechanical and physical characteristics, such as the hardness, electrical conductivity, and thermal conductivity of the additional metals. As a result, the electrode's wear is reduced. These findings support those of earlier research [24].

When comparing the results in Figure 10, it is clear that the composite electrode (Cu-1%Cr-0.5%WC-1%Ag) and pure copper electrode (Pure Cu) have very different material removal rates (MRR). The MRR values for the electrode made of pure copper are higher at 54.5588 mm^3/min and lower at 5.3760 mm^3/min. On the other hand, the composite electrode had higher MRR values at both ends of the removal rate range, with values of 56.8689 mm^3/min and 5.5564 mm^3/min, respectively. This is because composite electrodes may have greater electrical conductivity than copper-based electrodes. Due to this, the discharge energy may be larger than with copper electrodes, which could increase MRR.

It is clear from a comparison of the data in Figure 11, however, that the surface roughness (SR) of the composite electrode (Cu-1%Cr-0.5%WC-1%Ag) and pure copper electrode are significantly different. The SR values of pure copper electrodes are greater at 5.991μm and lower at 3.967μm. Conversely, the composite electrode showed rougher surface values at both ends of the roughness range, with values of 5.603μm and 3.747μm, respectively. This is because, compared to the copper electrode, the materials added to the composite electrode to provide more constant charge energy have reduced the surface roughness of the workpiece.

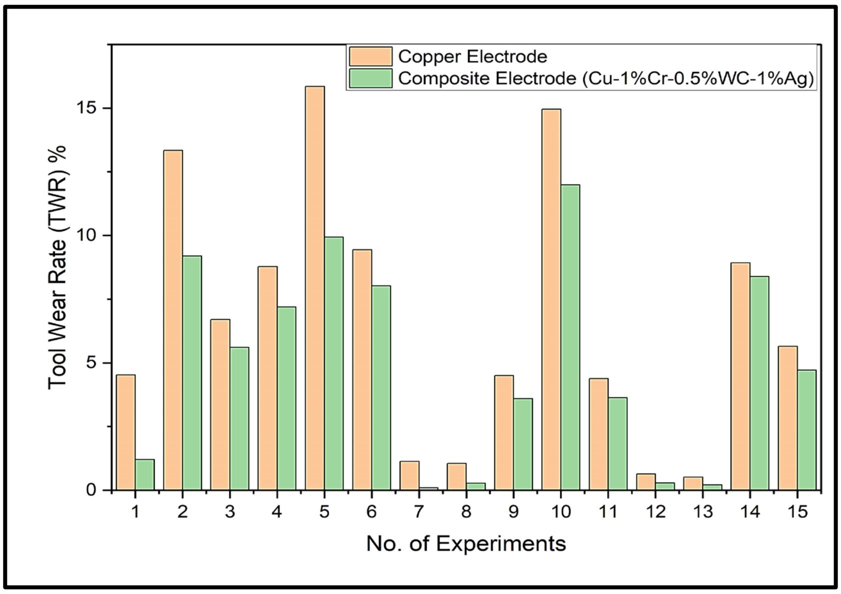


Figure 9: Comparison of TWR between the pure copper and the composite electrodes

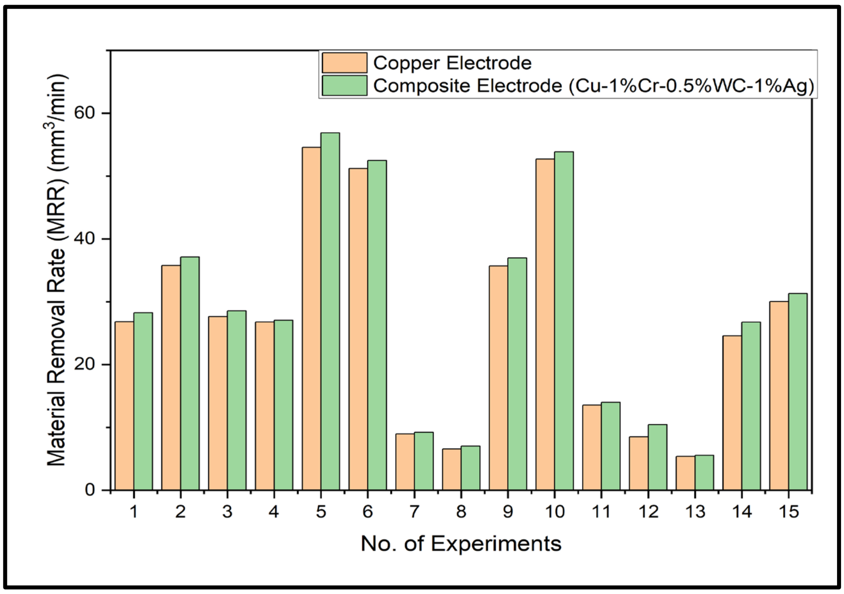


Figure 10: Comparison of MRR between the pure copper and the composite electrodes

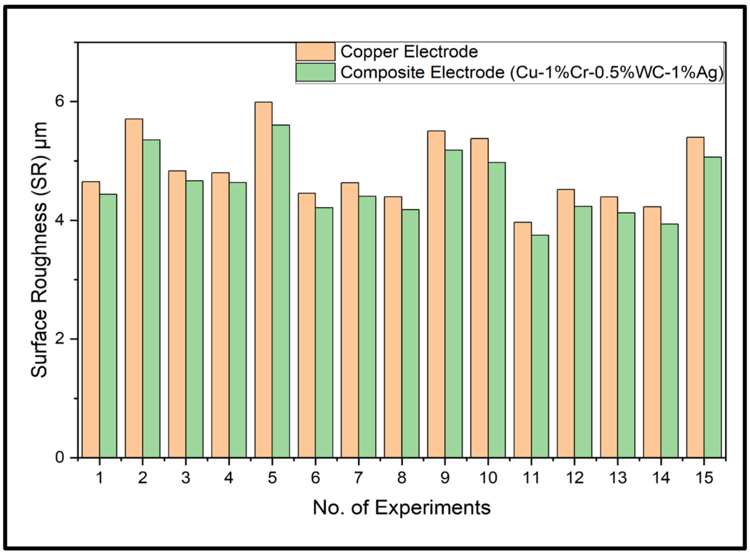


Figure 11: Comparison of SR between the pure copper and the composite electrodes

5. Conclusion

Based on the results obtained from the experiments, the novelty part can be concluded:

- The pure copper electrode's tool wear rate (TWR) was 0.514 gm/min, while the TWR of the composite electrode (Cu-1%Cr-0.5%WC-1%Ag) was 0.215 gm/min, considered the least.
- The pure copper electrode's material removal rate (MRR) was higher at 54.5588 mm^3/min, while the composite electrode (Cu-1%Cr-0.5%WC-1%Ag) had the best MRR at 56.8689 mm^3/min.
- The Surface Roughness (SR) of the composite electrode (Cu-1%Cr-0.5%WC-1%Ag) was 3.747µm, which is an improvement over the Surface Roughness (SR) of the pure copper electrode, which was 3.967µm.
- The current, followed by the pulse on time and pulse off time, had an important effect on pure copper and composite electrodes' TWR, MRR, and SR.

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Author contributions

Conceptualization, A. Abdulwahhab and A. Ibrahim; methodology, A. Abdulwahhab and A. Ibrahim; formal analysis, A. Abdulwahhab and A. Ibrahim; resources, A. Abdulwahhab and A. Ibrahim; data curation, A. Abdulwahhab and A. Ibrahim; writing—original draft preparation, A. Abdulwahhab and A. Ibrahim; writing—review and editing, A. Abdulwahhab and A. Ibrahim; supervision, A. Abdulwahhab and A. Ibrahim. All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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