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Enhancing the performance of electrical discharge machining using nanotechnology

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ABSTRACT

The electrical discharge machining (EDM) process is a nontraditional method utilized to manufacture complicated and hard materials with high electrical conductivity. Since the tool wear usually has a high influence on EDM performance, it leads to a substantial increase in product precision. Thus, it is important to conduct an experimental study intended to minimize the tool wear rate (TWR) while increasing the material removal rate (MRR). Presently, nanocomposite electrodes represent a new solution for the EDM process. These electrodes have the potential to improve the operational performance and economic efficiency of EDM technology. This study experimentally analyzed and evaluated the performance of copper and copper-nanographene electrodes in the EDM process. TWR and MRR were used as quality pointers in this study. The results of this work demonstrated a significant enhancement in EDM performance and in improving economic efficiency. The experimental results represent hardness improvement with 42%, electrical conductivity with 23%, and thermal conductivity with 30%. Experimentally the nanographene in EDM assisted in reducing the TWR by 14.34% and increasing MRR by 15.39%, moreover, the surface quality of the workpiece was improved too with copper-nanographene electrodes in the EDM process.

Keywords: *EDM, Nanographene powder, Nanocomposite electrode, TWR, MRR, Stir casting method*

1. INTRODUCTION

Electrical discharge machining is a nonconventional and non-contact machining process that is used to sculpt the required part without demanding any other process after the EDM. The principal work depends on generating a high electrical spark between the workpiece and the electrode tool as shown in Figure 1. In many industrial manufacturing processes, EDM process was employed in various industries such as mold manufacturing, the aerospace sector, automobile manufacturing, etc. The electrode plays an effective and vital role in the EDM process. Graphite and copper are among the most important electrode materials because they have high mechanical and electrical properties. Manufacturing companies still offer various proposals to develop the electrodes' efficiency. Nanographene is one of the modern materials used to improve the mechanical and electrical characteristics of the electrode material and hence enhance the EDM performance [1].

The importance of the present study resides in the stir casting method for producing copper-nanographene electrodes. This study aims to check the effect of copper-nanographene electrodes on the EDM for machining AISI 1005 Carbon steel. The discharge current I_p (16–24 A), pulse on time T_{on} (150–300), and pulse off time T_{off} (75–125 gm) as process parameters, while the TWR and MRR were determined as an indicator of the efficiency of this study.

Electrical discharge machining is a very important technology that has attracted great interest in various sectors due to its unique characteristics [2]. This technology is used to process and machine hard and brittle materials that are difficult to process using traditional techniques [3]. EDM is the most efficient technique in precision manufacturing processes and can be utilized for electrically conductive materials and in operations that do not require contact between the workpiece and the tool [4]. The process of removing materials depends on the generation of sparks between the electrode and the workpiece [5]. Evaluating electrode wear is extremely important as it plays a major role in improving the performance of various manufacturing processes [6].

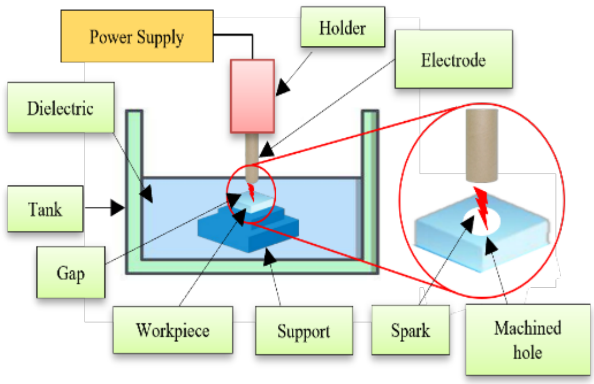

Figure 1. EDM Principle

Due to their great strength, superior hardness, resistance to corrosion, and resistance to high temperatures, metal matrix composites (MMCs) are among the most widely used materials in various applications [7]. Stir casting is one of the effective methods in the manufacturing process for producing metal composites. Copper-based matrix composites are the best-used materials due to their distinctive thermal and electrical properties, great corrosion resistance, and good machinability [8].

Many researchers have discussed the influence of nanomaterial on EDM performance. Shi *et al.* [9] observed the addition of multi-walled carbon nanotubes into WCu led to great optimization of the composite material's thermal conductivity. Tjong [1] explained in their research that nanographene has distinctive mechanical and physical characteristics and is considered a perfect nano stuffing in composite materials, providing huge possibilities for a broad variety of applications. Chen *et al.* [10] indicated that graphene mixed with copper powders assured a homogeneous dispersion and a good mix between graphene and copper matrix, as well as the valid structure of graphene powder, which was beneficial to its strengthening effect. Bashirvand and Montazeri [11] observed the graphene structure can play a significant role in improving the mechanical interrelatedness between the copper and graphene, which in role results in a better load transfer.

Dong *et al.* [12] Additionally, WCu/graphene composites have been noted to have enhanced resistance to wear. Shirguppikar *et al.* [13] used in their experiment electrodes of copper, which are coated with carbon nanotube CNT. The machining result observed that the electrodes of CNT coating led to a reduction in the TWR and a rise in the MRR when compared to the utilization of uncoated copper electrodes. Chindaladdha and Kaewdook [14] the tool wear rate (TWR), material removal rate (MRR), microhardness (HV), and workpiece surface topography with the multi-walled carbon nanotubes copper-coated electrodes have been highly optimized. Ishfaq *et al.* [15] discovered the optimization of dielectric (kerosene) due to nanoparticles of graphene. The experiment was done on the Aluminum, Brass, and Copper electrodes. The results of the work led to an increase in MRR.

Salecha *et al.* [16] proved that nanopowder performance is better than micro-powder and traditional EDM processes. Optimization of MRR was observed by 12.12% and 57.14% compared to micropowder and traditional EDM. The surface finish was also enhanced by 34.04% from traditional EDM. Ishfaq *et al.* [17] discussed the novel nanographene powders mixed with dielectric fluid that has been used to increase surface quality cutting speed. Different powders have been tested utilizing aluminium and copper electrodes, and significant performance enhancement has been achieved.

Rajaguru *et al.* [18] a novel copper-carbon nanotube tool at a varying part of the volume of carbon nanotube 0.35%, 0.70%, and 1.05% is improved. The performance of CNT-mixed electrodes in the EDM process is a higher MRR and good surface quality than the copper electrodes. Goyal *et al.* [19] observed in the case of nanographene mixed in the EDM process, the lower circularity and surface roughness achieved were 0.0126 mm and 1.590 µm, respectively These values represent an enhancement of 12.27% and 32.91% when compared to the outcome obtained from conventional EDM processes. Vora *et al.* [20] the insertion of nanographene in the dielectric fluid led to an enhancement in the MRR while decreasing the SR and the recast layer thickness RCL. Also, the introduction of nanographene at an amount of (2 g/L) led to a minimum of debris parts, micropores, microcracks, and globules. Pham Van *et al.* [8] the efficiency of the graphene-coated aluminium electrode in the EDM process for Ti–6Al–4V was studied and analyzed. TWR and MRR were utilized as quality pointers. The study outcome has explained a significant optimization in the quality properties of coated tools compared with uncoated tools.

From the past studies review, one can conclude that several papers have deduced experiments to enhance EDM performance using different materials of electrodes with varying operation conditions. According to the literature review, one can conclude that there is a scientific gap to fill in the effect of copper Nanocomposite electrode tool materials on process performance.

2. MATERIALS AND METHODS

2.1. Materials

The electrode used in the present work is a copper-based metal matrix composite material, which is mixed with nanographene reinforcement powder to produce a copper-nanographene composite, which was manufactured utilizing the stir casting process. The electrode in this work was selected in a cylindrical solid shape with a 10 mm diameter. While, the workpiece material that has been chosen is AISI 1005 Carbon Steel, as a piece of the plate 30×30 mm with a thickness of 2 mm, as shown the Table 1.

2.2. Manufacturing of the Electrodes

The copper-nanographene metal matrix composite (MMC) electrode is fabricated utilizing the stir-casting process

Table 1. Work materials

Electrode tool	Electrode geometry	Electrode end profile	Workpiece material (AISI 1005 Carbon Steel)
Copper electrode		 Diameter 10 mm	 30×30×2 mm
Copper-nano graphene electrode		 Diameter 10 mm	

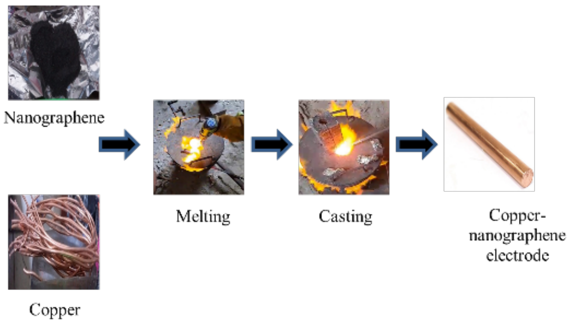

Figure 2. Manufacturing steps of nanographene electrodes

illustrated in Figure 2. Pure copper 99.9% with a weight of 250 g was used as the base metal matrix mixed with single-layer Nanographene powder 99% pure with a weight of 5 g with a two-dimensional lateral 1–10 µm and 3–9 thick nm. First, the mould is preheated to 503°C to moisture expulsion, reduce cracks, and achieve even heat distribution, then the nanocomposite electrode is produced by mixing the base copper matrix melted at a temperature of 1233°C and adding the single-layer Nanographene powder reinforcement which packaged by copper foil gradually to obtain highest homogeneity and to prevent agglomeration between the component.

2.3. Experimental Design

The experimental work of the copper and copper-nanographene was conducted on a CHEMER EDM machine model (CM 323+50N).

The trials were designed using Design Expert 13 software, and central composite design (CCD) was utilized to base the trials, various parameters selected to be investigated from the review of literature influencing the performance of the EDM process are I_p, T_{on}, and T_{off}, three input machining parameters with Three levels were chosen to perform trials. Table 2 lists the values for the various process factors and variables.

The TWR and MRR were calculated using Equations (1) and (2), respectively [21].

$$TWR = \frac{W_i - W_f}{D_t \times T} (mm^3/min) \quad (1)$$

where W_i: Tool initial weight (mg), W_f: Tool final weight (mg), T: Machining time (min), D_t: Tool density (gm/mm^3)

$$MRR = \frac{W_i - W_f}{D_w \times T} (mm^3/min) \quad (2)$$

where W_i: Workpiece initial weight (gm), W_f: Workpiece final weight (gm), T: Machining time (min), D_w: Workpiece density (gm/mm^3).

Table 2. Machining parameters and their levels

Parameters	Symbols	Levels		
		L1	L2	L3
Discharge current (A)	I_p	16	20	24
Pulse on time (µs)	T_{on}	150	225	300
Pulse off time (µs)	T_{off}	75	100	125

3. RESULTS

3.1. Evaluation of Nanographene Material

Experimental work was executed as per the Design Expert 13 software experiments and the response of TWR and MRR for two types of electrodes, as listed in Table 3.

The properties of electrode materials were measured before and after the addition of nanographene and observed as significant improvement in the material properties of Microhardness, Electric conductivity, and Thermal conductivity as listed in Table 4. This study covers the comparative study of the copper electrode and the copper-nanographene tool electrode.

3.2. Analysis of Variance (ANOVA)

Tables 5 and 6 show ANOVA for a comparison of the copper and copper-nanographene electrodes using the EDM process while assessing the TWR. The Design Expert 13 software was utilized to frame the ANOVA tables matching their mathematical models. Depending on the ANOVA tables, the Discharge current Ip has an important effect on the TWR, which contributes 73.07% with copper electrodes. As the Ip has a large effect on EDM [21], the I_p is important for evaluating spark energy over the processing region. The T_{on} is one of the EDM parameters having the

Table 3. Values of TWR and MRR

Operating parameters			Copper		Copper-nanographene	
I_p (A)	T_{on} (µs)	T_{off} (µs)	TWR (mm^3/min)	MMR (mm^3/min)	TWR (mm^3/min)	MMR (mm^3/min)
16	300	100	0.155	13.342	0.135	15.451
24	300	100	0.433	14.715	0.382	16.889
16	225	125	0.138	13.417	0.128	15.334
24	225	75	0.327	14.308	0.256	17.903
20	150	125	0.234	13.441	0.192	16.197
20	300	75	0.242	13.773	0.215	16.482
16	225	75	0.149	14.547	0.141	15.098
24	150	100	0.346	14.402	0.288	16.942
16	150	100	0.124	14.434	0.103	15.663
20	150	75	0.232	14.862	0.208	15.813
20	300	125	0.253	13.531	0.227	15.979
24	225	125	0.386	14.869	0.314	17.829

Table 4. Electrodes materials properties

Properties	Test name	Copper	Copper-nano graphene	Enhance (%)
Micro-hardness (HV)	Vickers	107	152	42
Electric conductivity (MS/m)	Keithley 2700	50.6	62.4	23
Thermal conductivity (W/mK)	Lee's Disc	400	520	30

second effect on the TWR, with a contribution of 22.86%. The T_{off} parameter demonstrated an insignificant effect on the TWR with a contribution of 2.6%. Figure 3 illustrates the percentage contributions of different parameters to the TWR of copper and copper-nanographene electrodes.

The higher correlation coefficient R^2 value is 96.27% for TWR of copper electrodes. As the copper-nanographene tool may prevent wear brought on through the spark energy, hence can reduce the TWR.

Tables 7 and 8 show the ANOVA results comparing copper electrodes to copper-nanographene electrodes it evaluating the MRR. The ANOVA table displayed that the I_p, which contributes 78.67% with copper-nanographene electrodes, has a significant influence on the MMR. T_{on}, with a contribution of 11.9%, has been the second main variable affecting the MRR. The T_{off} showed a minimum influence on the MRR from each of the other EDM process factors [22]. Figure 4 illustrates the percentage contributions of various parameters to the MRR, of copper and copper-nanographene electrodes. The higher R^2 correlation coefficient value is 91.51% for MMR of copper-nanographene electrodes.

Table 5. ANOVA for TWR of copper

Source	Sum of squares	DF	Mean squares	F-value	P-value
Model	0.0737	6	0.0106	6.93	0.025
A-I_p	0.0521	1	0.0521	38.20	0.001
B-T_{on}	0.0163	1	0.0163	1.02	0.043
C-T_{off}	0.0019	1	0.0019	0.011	0.917
AB	0.0056	1	0.0056	1.67	0.253
AC	0.0047	1	0.0047	0.530	0.499
BC	0.0012	1	0.0012	0.156	0.708
Residual	0.0077	5	0.0015		
Cor total	0.0713	11	R^2	0.9627	
Std. dev.	0.0391	Adjusted R^2		0.8639	
Mean	0.2759	Predicted R^2		0.6819	
C.V. %	14.18	Adeq Precision		7.4625	

Table 6. ANOVA for TWR of copper-nanographene

Source	Sum of squares	DF	Mean squares	F-value	P-value
Model	0.0733	6	0.0122	14.95	0.004
A-I_p	0.0352	1	0.0352	82.15	0.010
B-T_{on}	0.0195	1	0.0195	4.32	0.032
C-T_{off}	0.0102	1	0.0102	0.2570	0.633
AB	0.0110	1	0.0110	1.18	0.327
AC	0.0063	1	0.0063	1.54	0.269
BC	0.0042	1	0.0042	0.2397	0.645
Residual	0.0041	5	0.0015		
Cor total	0.0774	11	0.9472	0.9472	
Std. dev.	0.0286	Adjusted R^2		0.8838	
Mean	0.2157	Predicted R^2		0.6958	
C.V. %	13.25	Adeq Precision		10.640	

Table 7. ANOVA for MMR of copper

Source	Sum of squares	DF	Mean squares	F-value	P-value
Model	19.11	6	3.19	1.70	0.005
A-I_p	12.02	1	12.02	5.36	0.048
B-T_{on}	5.52	1	5.52	3.49	0.020
C-T_{off}	2.12	1	2.12	0.7583	0.423
AB	0.6243	1	0.6243	0.0664	0.806
AC	0.9837	1	0.9837	0.2587	0.632
BC	0.0469	1	0.0469	0.2924	0.611
Residual	9.35	5	1.87		
Cor total	28.46	11	R^2	0.9015	
Std. dev.	1.37	Adjusted R^2		0.8773	
Mean	12.55	Predicted R^2		0.6920	
C.V. %	10.90	Adeq Precision		3.8720	

Table 8. ANOVA for MMR of copper-nanographene

Source	Sum of squares	DF	Mean squares	F-value	P-value
Model	8.27	6	1.38	5.34	0.043
A-I_p	7.513	1	7.513	31.16	0.012
B-T_{on}	1.1372	1	1.1372	0.0168	0.012
C-T_{off}	0.2002	1	0.2002	0.0079	0.977
AB	0.1663	1	0.1663	0.0245	0.881
AC	0.1140	1	0.1140	0.0932	0.772
BC	0.0967	1	0.0967	0.0628	0.422
Residual	1.29	5	0.2579		
Cor total	9.55	11	R^2	0.9151	
Std. dev.	0.5078	Adjusted R^2		0.8031	
Mean	16.30	Predicted R^2		0.6227	
C.V. %	3.12	Adeq Precision		5.5673	

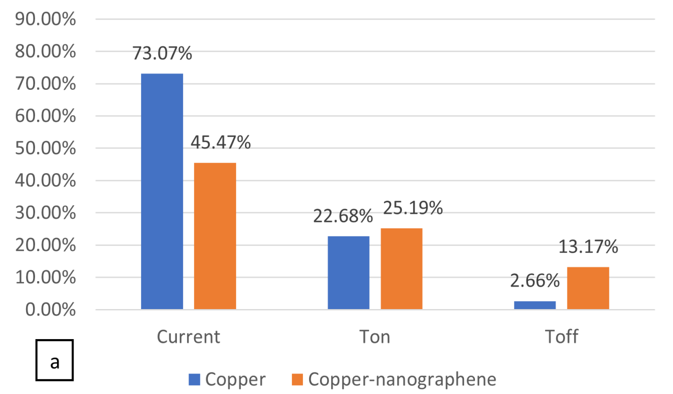

Figure 3. The percentage contribution of the parameters in TWR

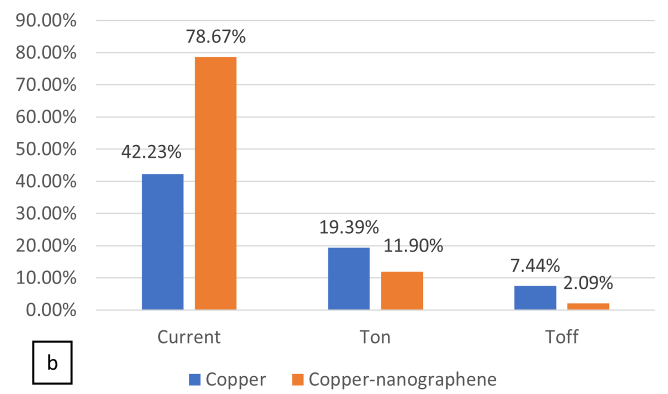

Figure 4. percentage contribution of the parameters in MRR

4. DISCUSSION AND ANALYSIS

4.1. Impact of the Nanographene Material on the Machined Surface

SEM micrographs of the workpiece surface machined utilizing the EDM using copper and copper-nanographene electrodes are illustrated in Figure 5. The material of the electrode affects the surface while machining, in terms of melting and vaporizing the material in contact and facilitating its removal before it obtains solidified.

The EDM process is composed of a large number of machining parameters that should be, dominated to gain substantial surface quality void of deposited layers, microcracks, micropores, globules, and other surface flaws. Higher values of discharge current and Ton result in a higher discharge energy amount due to a rise in spark density. This in turn increases the formation possibilities of surface defects [23].

The topography of the operated workpiece surface with copper and copper-nanographene electrodes is quite different, the globule sizes, microcracks, micropores, deposited layers, and some of the debris parts stick in the working area formed more readily when using copper electrodes in comparison with the workpiece surface topography observed at the copper-nanographene electrodes, Figure 5(a) the surface of the workpiece using copper electrodes shows many having of microcracks, micropores, deposited layers, and large globules compared with the copper-nanographene electrodes, as shown in Figure 5(b).

The reason for this is that generating a spark from the copper-nanographene electrodes is better than that in copper electrodes and outcome in a lower spark energy. Therefore, the amount of overcut in EDM with the copper-nanographene electrodes is less than that of the copper electrodes. Therefore, the processing accuracy of the surface finish in the EDM process with the copper-nanographene electrodes is better than that with the copper electrodes.

The recast layer thickness RCL and heat-affected zone HAZ are affected by the heat transfer to the workpiece material and the resulting microstructural changes during the EDM [24]. As shown in Figure 6(a) from SEM inspections, it was found that under high machining parameters, specifically, a current of (24 A), a pulse on time of (300 μs), and a pulse off time of (100 μs), the average thickness of recast layer on the workpiece reached (39.603 μm) when using a copper electrode.

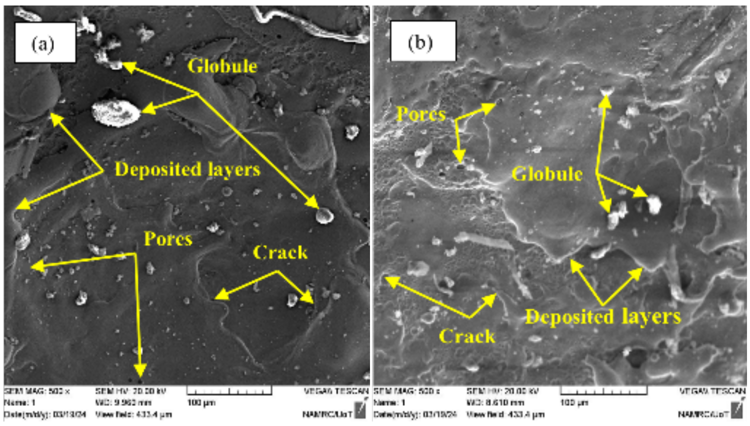

Figure 5. SEM micrograph of the operated surface using (a) Copper electrode and (b) Copper-nanographene electrode. I_p (24 A), T_{on} (300 μs), and T_{off} (100 μs)

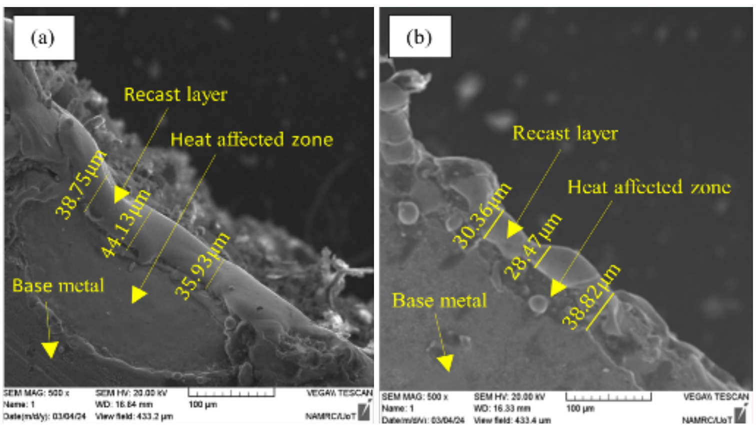

Figure 6. SEM micrograph of the workpiece (a) Copper electrode (b) Copper-nanographene electrode. I_p (24 A), T_{on} (300 μs), and T_{off} (100 μs)

According to Figure 6(b), using a convex electrode profile resulted in a thinner recast layer on the workpiece surface compared to machining with a flat electrode profile under the same operational conditions. The average thickness of the recast layer was (32.55 μm).

4.2. Morphologies of Electrodes

Regarding the EDM process, the term morphology of electrode indicates the surface characteristics and geometry of the electrode used in the machining process. Figure 7 shows the images by 3D laser scan technique of the surface of the electrodes using copper and copper-nanographene electrodes before and after machining, respectively.

It is evident from the 3D laser scan images that the geometry of electrodes, surface finish, electrode wear, and some of the pit defects observed on the electrode surface formed more readily when using copper electrodes in comparison with the surface morphology observed at the copper-nanographene electrodes, showing little presence of Electrode Wear, Surface Finish, and small deformities. This underscores an improvement in the microhardness of electrodes through the use of nanographene which is tough, durable, with high tensile strength and hardness which leads to increased wear resistance of electrodes at the sparks area. The morphology of the electrode surface is a good concept and is explained through the images of laser scanning.

4.3. A Comparative of This Study with Other Past Studies

This work aims to assess and check developed an enhancement in EDM performance using 2% nanographene powder in electrode manufacturing to improve mechanical and electrical properties, especially hardness, electrical, and thermal conductivity. This implies a substantial reduction in Energy consumption and an increased accuracy of the produced parts. Additionally, the process offers advantages such as optimal enhancement of EDM, ease of operation, and cost-effectiveness. These benefits provide clear advantages for the process considered in this study compared to other studies that were limited to partial optimization of the EDM process, as shown in Table 9.

5. CONCLUSIONS AND FUTURE WORKS

This experimental work resulted in several worthy findings. The findings obtained from the experiments introduced important information and helped to understand the topic. The main findings derived from the experimental work are summarized as follows:

Table 9. Comparison of this study with other past studies

Reference	Materials	Finding
[15]	Graphene nanoparticles addition to the kerosene-based dielectric	Enhancement of dielectric performance
[8]	Graphene-coated aluminium electrode	Improved the surface quality of the specimen
[17]	Nano-powder additive graphene to the aluminium electrode	Reduction in the machined specimen's roughness
This study	Nanographene mixed with the copper matrix for Electrode manufacturing	Enhancement of EDM performance measures

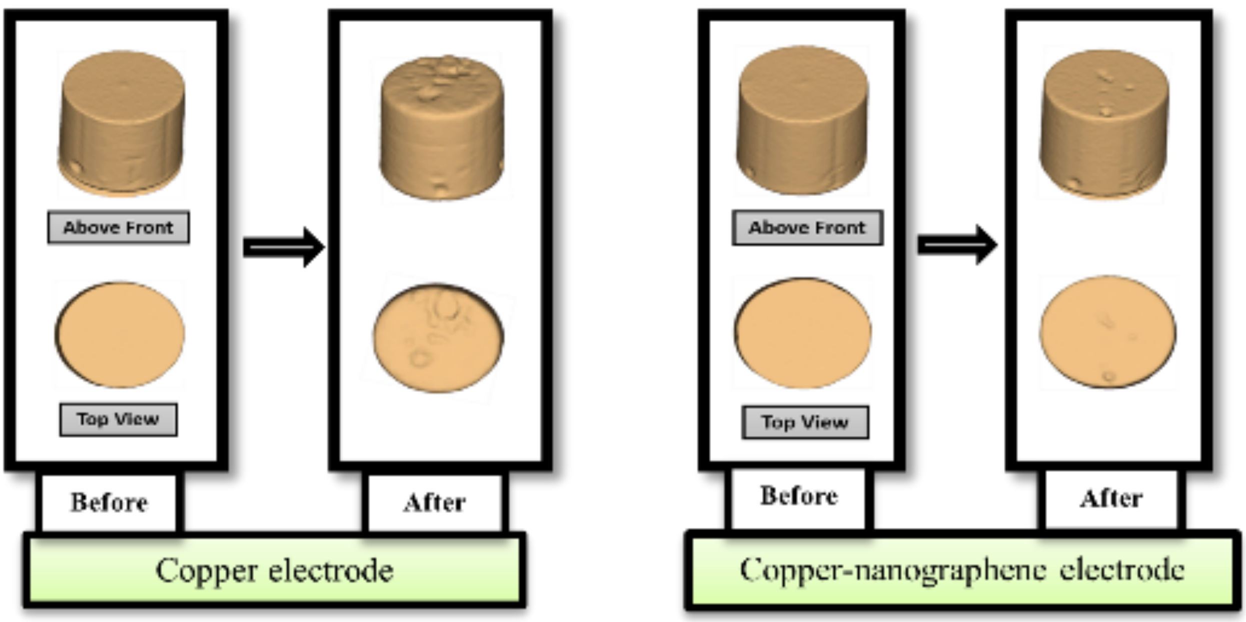

Figure 7. Comparing morphologies of electrodes by 3D scan

- The nanographene decreases the wear of the electrode due to its ability to increase wear resistance and hardness with minimized discharge energy.
- The nanographene powder increases the removal of metal due to its high electrical and thermal conductivity hence increasing the spark energy in the machining region.
- The copper-nanographene electrodes generate a better concentration of thermal energy in the operating area compared to the energy generated in the copper electrode.
- The copper-nanographene electrodes can decrease the configuration of microcracks, micropores, deposited layers, and small globules on the machining surface leading to improved surface roughness and surface integrity of the workpiece with reduced RCL and HAZ.
- The morphology of the copper-nanographene electrodes has lesser distortion and pits than that of the copper electrodes.
- Nanographene powder has contributed to the optimization of many quality pointers in the EDM process. Furthermore, electrodes containing nanographene are considered to have higher economic efficiency than copper electrodes, which will directly affect practical applications in this field.

Nanographene powder has shown many promising possibilities, so we suggest some future work to use nanographene in EDM process applications, such as reducing energy consumption, improving the cleaning and debris removal process, and increasing the manufacturing rate. However, there is a need for more studies and experimental research to explore the benefits of nanographene in EDM applications.

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