

Experimental and Theoretical Analysis of Surface Roughness in Electrodischarge Machining (EDM) Performance

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Abstract

Non-traditional machining techniques are extensively utilized for manufacturing parts with intricate shapes or composed of materials that are difficult to machine using conventional methods. Among these techniques, Electrical Discharge Machining (EDM) stands out due to its ability to overcome the limitations faced by traditional machining approaches. EDM removes material through controlled electrical discharges occurring between the electrode and the work piece. This research investigates the influence of EDM process parameters on machining high-speed steel AISI M2, employing both copper and graphite electrodes. The study emphasizes the effect of various machining parameters on surface roughness (Ra). The key factors considered in the experiments include discharge current, pulse-on time, and pulse-off time. Experimental outcomes reveal that the minimum surface roughness was obtained with copper and graphite electrodes at a current of 10 A, pulse-on time of 100 μ s, and pulse-off time of 25 μ s, producing Ra values of 2.18 μ m and 1.67 μ m, respectively. In contrast, the maximum surface roughness occurred at a current of 42 A, pulse-on time of 200 μ s, and pulse-off time of 4 μ s, yielding Ra values of 6.37 μ m for copper and 5.98 μ m for graphite electrodes. The results further indicate that graphite electrodes consistently achieve smoother surfaces than copper electrodes under identical machining conditions.

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1. INTRODUCTION

1.1 Electro Discharge Machining

Electrical Discharge Machining (EDM) is a non-conventional manufacturing technique designed for machining electrically conductive materials. It is particularly effective for hard and tough materials that are challenging to process with traditional cutting methods. The material is removed through controlled electrical discharges between the tool electrode and the workpiece, enabling precise shaping and high dimensional accuracy. A deep understanding of the EDM process is crucial for enhancing operational efficiency, minimizing processing time, and reducing overall production costs. Due to the inherently stochastic nature of EDM and the influence of numerous interacting parameters, developing accurate analytical models based solely on theoretical or numerical approaches is challenging. Consequently, researchers have increasingly relied on experimental and data-driven modeling techniques to better capture and predict process behavior. Over the past two decades, a variety of modeling strategies have been proposed and refined, with notable approaches including statistical regression models and response surface methodology (RSM), reflecting their evolution across different regions and time periods. It is especially suitable for hard materials and allows accurate shaping without direct contact between the tool and the workpiece. This work also discusses optimization strategies that are often integrated with these models. While RSM has historically been the most frequently used empirical method, recent research trends show increased reliance on ANN due to their higher predictive capability for EDM performance measures. Additionally,

published studies indicate that much of the experimental work on EDM modeling has originated from Asian research communities. Electrical Discharge Machining (EDM) is a thermal process in which material is removed through heat. An electrical spark is generated between the tool and the workpiece while machining, facilitating material removal, creating high temperatures that melt and vaporize small portions of the material. This phenomenon leads to several surface-related effects, including increased surface roughness, changes in micro hardness, formation of a recast (white) layer, development of a heat-affected zone, microstructural alterations, Electrical Discharge Machining (EDM) is a thermal-based machining technique characterized by a complex mechanism of material removal. In this process, an electrical spark generates a plasma channel between the electrode and the work piece, causing localized melting and vaporization of the material. This phenomenon can also induce surface imperfections, including micro cracks. Collectively, these surface features define the surface integrity of the component, which plays a crucial role in determining the performance and lifespan of the machined parts. Electrical Discharge Machining (EDM) has traditionally been a key process in the manufacturing sector. However, recent technological advancements have introduced machining methods that surpass conventional EDM in terms of efficiency, offering higher material removal rates (MRR) and enhanced surface quality while preserving strict dimensional accuracy. Despite these developments, EDM remains a vital non-traditional machining technique for shaping hard, electrically conductive materials with intricate geometries. The process involves the generation of a plasma spark between the tool and the workpiece, which melts and vaporizes small quantities of material. This action can produce surface defects, such as microcracks, collectively referred to as surface integrity, which significantly influences the component's performance. EDM is particularly advantageous for machining materials and geometries that are challenging or impossible to process using conventional methods. Furthermore, advanced computational approaches, including fuzzy logic systems, artificial neural networks (ANN), and adaptive neuro-fuzzy inference systems (ANFIS), have been employed to optimize and control the EDM process, enhancing its overall effectiveness. Numerous studies have investigated the influence of EDM process parameters on machining performance. For instance, Daneshmand et al. [5] examined the effects of discharge current, voltage, pulse-on time, and pulse-off time on material removal rate (MRR), tool wear, and surface roughness during the machining of NiTi alloys. Their findings indicated that increasing current, voltage, and pulse-on duration led to higher MRR, while extending the pulse-off time contributed to reduced tool wear. In a similar study, Prajapati and Prajapati [6] evaluated the performance of different electrode materials—graphite, copper, and brass—when machining EN-9 steel. The results revealed that graphite electrodes achieved the highest MRR, whereas brass electrodes produced the smoothest surface finish. Chikalthankar et al. [7] examined the effects of voltage, current, and pulse parameters on material removal rate (MRR) and surface roughness during EDM of DIN 1.2379/AISI D2 tool steel using copper electrodes. Their results highlighted that discharge current exerts the most significant impact on both MRR and surface finish. EDM is extensively employed in mold making and the aerospace sector; however, electrode wear remains a critical issue, often compromising the dimensional accuracy of machined components. Most existing wear prediction models are tailored for conventional drilling or milling, with limited studies addressing multi-axis EDM involving complex electrode geometries. Recently, point cloud-based simulation methods have been developed to predict electrode wear by modeling the geometries of both the electrode and the workpiece, identifying spark locations, and simulating material removal. The efficiency of these simulations has been enhanced through KD-tree search algorithms and parallel discharge strategies for handling dense point clouds. Further research has investigated the effects of peak current, voltage, and pulse timing on surface quality, MRR, and electrode wear. For example, Tomadi et al. [9] employed design of experiments (DOE) and analysis of variance (ANOVA) to evaluate surface roughness, MRR, and electrode wear rate, while Rahman et al. [10] developed an optimized model to improve MRR in the machining of titanium alloys using copper-tungsten electrodes under positive polarity. Other research has focused on surface modification and microhardness prediction. Studies employing powder-mixed EDM (PMEDM) and artificial neural networks (ANN), combined with Taguchi design methods, have demonstrated that peak current has a strong influence on surface microhardness. Furthermore, investigations comparing conventional kerosene-based dielectric fluids with vegetable-based oils, Studies on materials such as refined palm oil have shown that electrode wear rate increases with higher peak current but decreases when the pulse duration is longer. Although EDM can machine only electrically conductive materials, electrode wear is unavoidable, which raises tooling costs and extends machining time. Therefore, ongoing research is focused on developing more efficient and accurate EDM systems that reduce these losses, as illustrated in Figure 1. This research focuses on optimizing the EDM process for stainless steel 304 by employing copper and graphite electrodes. The primary objective is to assess the impact of electrode material on machining performance, with a particular emphasis on surface quality, evaluated through the surface roughness of the machined components.

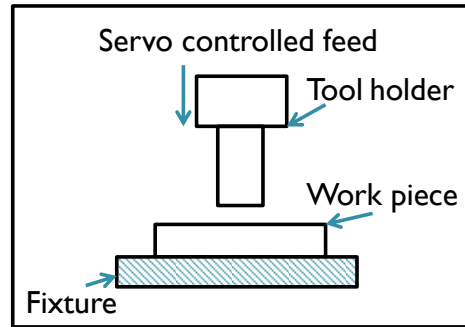


Figure 1. Schismatic of Electro Discharge Machining.

2. PRINCIPE OF EDM OPERATION

Electrical Discharge Machining (EDM) is a non-traditional manufacturing method in which material is removed through a series of rapid electrical discharges between a shaped tool electrode and the workpiece. These discharges take place within a dielectric fluid, which regulates the process and stabilizes spark formation. EDM is extensively applied in industry for the precise machining of electrically conductive materials, including metals, alloys, graphite, and certain conductive ceramics. It is particularly suitable for fabricating components with intricate geometries or materials that are challenging to machine using conventional cutting techniques. A key advantage of EDM is its ability to machine materials regardless of hardness by utilizing thermal energy, making it ideal for producing molds, dies, aerospace parts, and medical devices. Optimizing machining parameters can enhance material removal rates, improve surface finish, and minimize electrode wear. The process involves generating heat through electrical discharges that melt and vaporize small areas of the workpiece surface. The tool and workpiece are connected to a direct current (DC) power source, separated by a small distance called the spark gap. Typically, the workpiece is linked to the positive terminal (anode) and the tool electrode to the negative terminal (cathode). During EDM, the spark gap generally varies between 0.01 and 0.5 mm. Both the electrode and workpiece are submerged in a dielectric fluid, such as kerosene, transformer oil, or paraffin oil. This fluid is stored in a tank and continuously circulated through nozzles by a pump to the gap, facilitating debris removal and maintaining stable sparking conditions. When the power supply is activated, thousands of short-duration sparks occur every second. These sparks ionize the dielectric fluid. The electrical current flows between the electrode and the workpiece, with the dielectric fluid being constantly flushed through the gap to stabilize the process. A servo-controlled system constantly monitors and adjusts the electrode position to keep a consistent spark gap. When a voltage, typically between 50 and 450 V, is applied, the dielectric breaks down, forming an ionized plasma channel. This happens through electron emission from the cathode and a chain of ionization collisions, creating a stable discharge channel that enables controlled material removal. When enough electrons build up in the spark gap, the electrical resistance drops, allowing a discharge to occur between the tool and the workpiece. Each spark sends a burst of high-energy electrons from the cathode to the anode, producing intense localized pressure waves on the surfaces. These pressure waves sharply increase the temperature at the impact point, which can reach up to around 10,000 °C, causing rapid melting and softening of the material. Additionally, The spark generates electric and magnetic fields, which create tensile stresses that remove molten and softened material from the work piece, resulting in material removal.

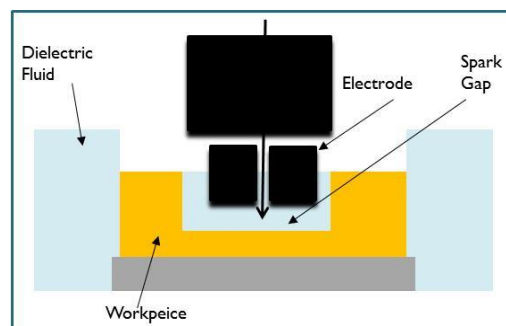


Figure 2. Schismatic EDM process in this work.

3. EPERMENTAL WORK SETAP

The material removal rate (MRR) in EDM is affected by several parameters, including discharge current, pulse-on time, and pulse-off time. In the present study, experiments were carried out on a CM 323C CNC EDM machine using kerosene as the dielectric fluid, as illustrated in Figure 3, with copper and graphite electrodes of 4 mm diameter.



Figure 3. A CM323C CNC EDM machine was employed for the experiments conducted in this work. The work material used in this study is high speed steel AISI M2 with nine specimens dimensions (60×45×3 mm). The chemical composition and mechanical and physical properties of the work material is given in Table 1 and Table 2 respectively.

Table 1. Chemical composition of AISI M2 work material.

Material	C	Si	Mn	P	S	Cr
Weight (%)	0.855	0.305	0.28	0.001	0.001	4.71
Material	Mo	Ni	Cu	V	W	Fe
Weight (%)	5.43	0.14	0.175	1.88	5.73	Balance

Table 2. Mechanical and physical properties of work materials.

Properties	AISI M2
Bending Strength (MPa)	4700
Modulus of Elasticity (GPa)	207
Specific Heat Capacity (J/g-°C)	17.2x10 ⁻⁶
Thermal conductivity (W/m-K)	19
Compressive yield strength (MPa)	3250
Melting point (°C)	4680
Elastic modulus (GPa)	210
Electrical Resistivity (ohm-cm)	54x10 ⁻⁶
Density (g/m ³)	8.14
Hardness (HRB)	65
Charpy Impact (J)	36
Poisson's ratio	0.30

Experimental findings of this study are presented in Table 3, which summarizes the results obtained under different voltage conditions. The experimental design was established to identify the input parameters that have the greatest effect on the EDM process outcomes. Table 3 summarizes the design of experiments, listing the main control factors and their respective levels, For this investigation, discharge current, pulse-on time, and pulse-off time were chosen as the primary parameters, with each evaluated at three separate levels.

Table 3. Design of experiment (Parameters and Levels).

Factors of consideration	Symbols	Levels		
		1	2	3
Current (A)	I	10	24	42
Pulse on time (μs)	P _{on}	100	150	200
Pulse off time (μs)	P _{off}	4	12	25

For the experiments, copper and graphite electrodes were used, fabricated as rods with a diameter of 4 mm and a length of 100 mm. Table 4 lists the process parameters considered in the study.

Table 4. Working factors used in the experimental work.

Working Factors	Description
Workpiece	AISI M2 (60×45×3 mm)
Tool-electrode material	Copper and Graphite (4 mm diameter)
Tool-electrode polarity	Negative (-)
Workpiece polarity	Positive (+)
Dielectric	Kerosene
Dielectric temperature	40-80°C
Input voltage	380V (three phase) AC
Output voltage	140V (two phase) DC
Current	10-42A
Pulse on time	100-200 μs
Pulse off time	4-25 μs

Table 5. Analysis of Experimental Results for Machining Parameters.

No. of sample	Copper Electrode				Graphite Electrode			
	Ra1	Ra2	Ra3	Ra(average) (mm)	Ra1	Ra2	Ra3	Ra(average) (mm)
1	2.40	2.43	2.42	2.41	1.90	1.93	1.90	1.91
2	2.36	2.38	2.40	2.37	1.83	1.82	1.90	1.85
3	2.14	2.16	2.18	2.16	1.68	1.66	1.67	1.67
4	2.61	2.64	2.62	2.63	2.14	2.13	2.09	2.12
5	2.55	2.57	2.59	2.57	2.05	2.07	2.06	2.06
6	2.48	2.44	2.47	2.46	1.89	1.92	2.01	1.94
7	2.98	2.97	3.00	2.99	2.47	2.45	2.52	2.48
8	2.83	2.85	2.81	2.83	2.37	2.34	2.34	2.35
9	2.63	2.62	2.65	2.64	2.13	2.18	2.20	2.17
10	4.61	4.63	4.62	4.62	4.10	4.13	4.13	4.12
11	4.55	4.50	4.54	4.53	3.98	3.99	4.06	4.01
12	4.39	4.37	4.35	4.37	3.84	3.85	3.92	3.87
13	4.69	4.70	4.65	4.68	4.10	4.10	4.13	4.12
14	4.61	4.63	4.62	4.62	3.98	3.99	4.06	4.01
15	4.59	4.60	4.55	4.58	3.84	3.85	3.92	3.87
16	4.80	4.82	4.84	4.82	4.10	4.10	4.13	4.11
17	4.79	4.78	4.76	4.77	4.16	4.11	4.09	4.12
18	4.62	4.66	4.67	4.65	4.02	4.02	2.05	4.03
19	5.93	5.94	5.92	5.93	4.32	4.43	4.27	4.34
20	5.73	5.72	5.70	5.71	4.23	4.26	4.28	4.25
21	5.13	5.14	5.10	5.12	4.14	4.14	4.11	4.13
22	5.85	5.81	5.78	5.82	5.43	5.51	5.47	5.47
23	5.79	5.78	5.77	5.76	5.31	5.22	5.25	5.26
24	5.33	5.31	5.30	5.32	5.77	5.78	4.85	4.80
25	6.38	6.36	6.40	6.37	5.84	5.93	5.90	5.98
26	6.14	6.17	6.19	6.16	5.61	5.69	5.78	5.66
27	5.87	5.91	5.88	5.89	5.45	5.58	5.53	5.52

4. EXPERIMENTS SETUP

4.1 Workpiece and Electrode Materials

In this study, a high-purity copper electrode (99.9% Cu) was used, with dimensions of 82 × 40 × 5 mm. The workpiece material was AISI 444 stainless steel, Samples were fabricated measuring 40 × 30 × 2 mm, with their chemical composition presented in Table 1, The constant operating settings of the EDM machine are listed in Table 2, while the variable machining parameters and their levels for the experiments are presented in Table 3.

4.2 Results and dissection

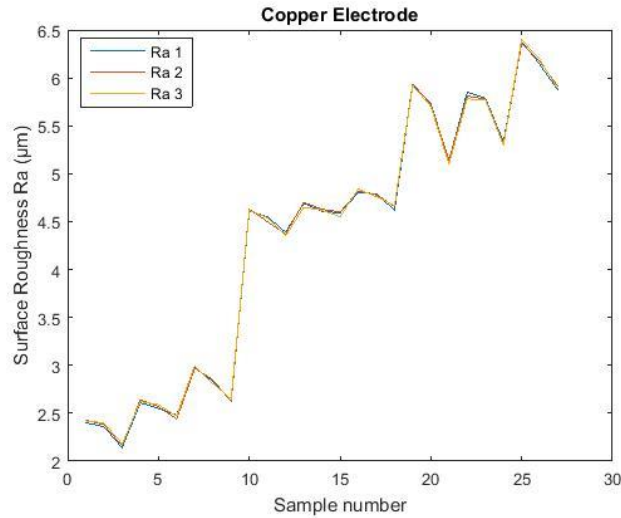


Figure 4. Surface Finish Analysis of Parts Machined by EDM Using Three Copper Electrodes

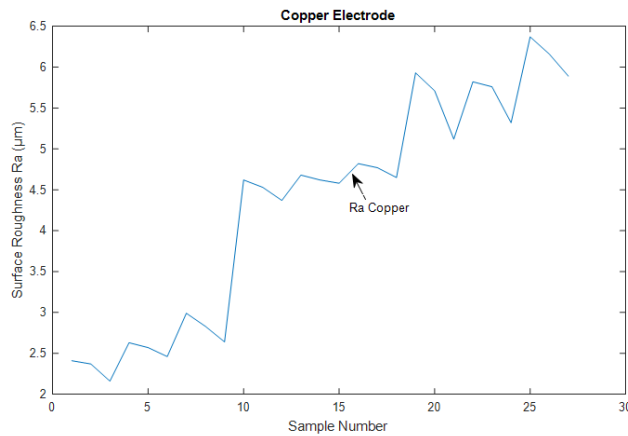


Figure 5. Evaluation of surface roughness for workpieces machined using a copper electrode in this study.

The results indicate that the surface roughness of the machined specimens increased progressively as the EDM process advanced. For copper electrodes, the roughness values rose from approximately Ra 2.41 µm to Ra 5.89 µm across the three samples tested, as shown in Figure 4, with the average surface roughness displayed in Figure 5. In contrast, specimens machined with graphite electrodes exhibited lower surface roughness than those machined with copper. The roughness values for graphite electrodes ranged from about Ra 1.91 µm to Ra 5.52 µm across 27 samples, as illustrated in Figure 6, with the average results presented in Figure 7.

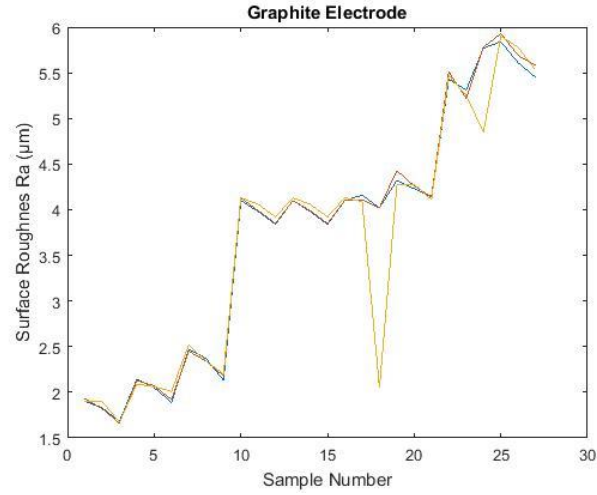


Figure 6. Effect of Three Graphite Electrodes on Surface Roughness in EDM

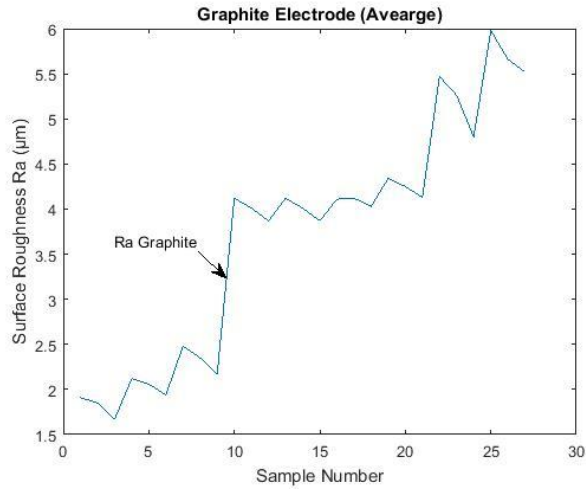


Figure 7. Evaluation of surface roughness for workpieces machined with a graphite electrode in this study.

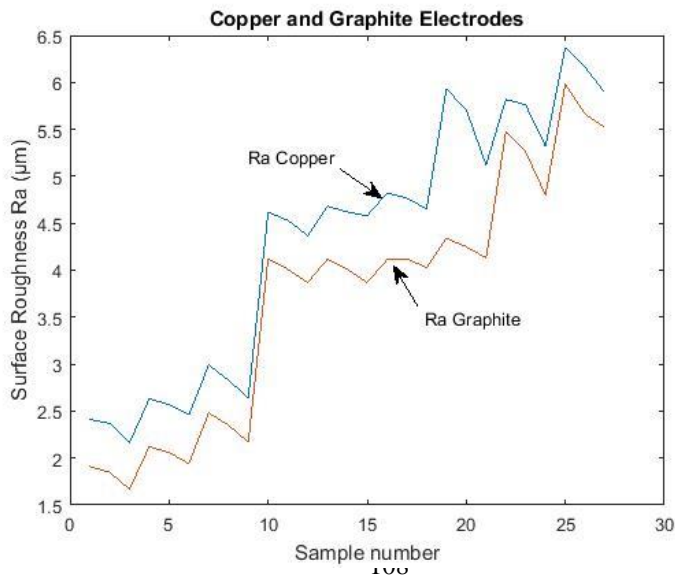


Figure 8. Comparison of surface roughness for EDM-machined workpieces with copper and graphite electrodes.

As illustrated in Figure 8, the electrode material significantly affects the surface quality of the machined components, Choosing the right machining conditions is therefore crucial to achieve high-performance components with the desired surface finish. Adjustments in operating parameters can further enhance overall machining performance. Each electrode material and experimental setup requires specific control settings. The parameters, including discharge current, pulse-on time, pulse-off time, and the measured surface roughness (R_a , μm) for copper and graphite electrodes, are illustrated in Figure 9.

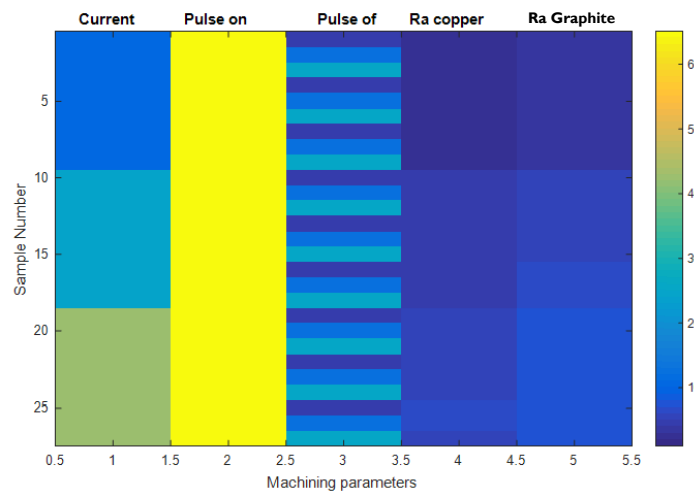


Figure 9. Impact of Process Parameters on Machining Performance with Emphasis on Surface Finish

5. CONCLUSION

This study investigated Electrical Discharge Machining (EDM), a widely employed non-traditional machining method capable of producing components with intricate geometries. A primary limitation of EDM is its reliance on electrically conductive workpieces. However, recent advancements in EDM technology, assisted processes, and optimization strategies have broadened research possibilities in this field. Previous research has also demonstrated that factors beyond electrical parameters can substantially influence EDM performance. In the present work, AISI M2 high-speed steel was selected as the workpiece, with copper and graphite electrodes serving as the machining tools. The maximum surface roughness (R_a) recorded was $6.37 \mu\text{m}$ for the copper electrode and $5.98 \mu\text{m}$ for the graphite electrode, corresponding to a current of 42 A, a pulse-on time of 200 μs , and a pulse-off time of 4 μs . These findings indicate that copper electrodes generate a rougher surface compared to graphite, underscoring the significance of electrode material selection and machining parameter optimization in enhancing EDM performance.

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