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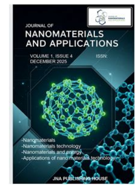

Influence of Copper Electrode Material on Surface Quality in Electrical discharge machining Drilling of Heat-Treated C45 Steel

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Abstract: Electrical Discharge Machining (EDM) has become a key manufacturing technology in Vietnam's mold and tool industry, particularly for producing components with complex geometries such as punches, dies, and plastic molds. However, conventional machining methods for nut punches often suffer from low productivity and limited surface quality. Consequently, there is a growing need for more efficient and reliable machining alternatives. This study aims to optimize the EDM process for fabricating complex components—specifically nut holes—with enhanced productivity and superior surface finish. The research focuses on evaluating the influence of red copper electrodes on the surface roughness of holes machined in heat-treated C45 steel, a widely used material that remains insufficiently explored in this context. The experimental results provide valuable insights to help manufacturing enterprises optimize EDM parameters, reduce production costs, and improve overall product quality.

Keywords: Copper electrode; C45 steel nut processing; Electrical discharge machining; Nut blank processing; Spark pulse

1. Introduction

In modern industry, the continuous development of superhard materials and wear-resistant alloys has created significant challenges for traditional machining methods. Since the first half of the 20th century, the growing demand for high-strength materials has driven the development of non-traditional machining technologies. Among these, Electrical Discharge Machining (EDM), developed by Boris and Natalya

Lazarenko in the Soviet Union in 1943, has emerged as a prominent solution. This technology enables the machining of conductive materials regardless of hardness by removing material through an electrothermal process using electrical pulses [1]. Over the decades, EDM has become an essential technology in many sectors, particularly for mold manufacturing and the production of complex parts [2]. In the past decade, research on EDM has shifted from focusing solely on improving material removal rate (MRR) to comprehensively optimizing machining performance, surface quality, and surface integrity [3]. Several studies have investigated the effects of machining parameters, including current intensity, pulse duration, voltage, and pulse-off time, on surface roughness [2,4]. Researchers have also applied advanced optimization methods, such as the Taguchi method and Response Surface Methodology (RSM), to determine optimal parameters for various materials [5]. Additionally, the choice of electrode material remains a significant area of research. While copper electrodes are still widely used, recent studies have explored composite materials. Comparisons between copper, graphite, and copper-tungsten (Cu-W) electrodes have been conducted. These studies indicate that Cu-W electrodes offer lower wear and improved surface quality [6]. However, copper electrodes often provide higher material removal rates in specific applications [7]. More recently, artificial intelligence (AI) and machine learning (ML) techniques have been employed to model and predict machining outcomes. These approaches can accurately forecast removal rates and surface roughness, reducing experimental time and improving process optimization [8]. In Vietnam, where EDM is extensively applied for the production of nut stamping dies and other complex components, it is important to study the effect of copper electrodes on the surface quality of heat-treated C45 steel. Although numerous studies have examined EDM of other steels [9,10], research specifically targeting C45 steel is limited. The primary objective of this work is to experimentally investigate the impact of copper electrodes on surface roughness and surface integrity during the EDM drilling of heat-treated C45 steel. Controlled experiments were designed to explore the relationship between machining parameters and resulting surface characteristics. The findings provide valuable experimental data for selecting optimal machining conditions, helping manufacturers enhance productivity, improve product quality, and reduce production costs. Copper electrodes play a central role in EDM, and this study quantifies their influence on surface quality. The results were also compared with those obtained using Cu-W electrodes, which can provide lower wear and improved surface finish. In recent years, scientists have conducted extensive research on the effects of factors such as temperature, pressure, etc. on the phase transition and crystallization of Cu [11], Ni [12] metals and highlighted the applications and potential of alloy materials [13] and 2D materials [14].

This study confirms that copper electrodes represent an optimal choice when prioritizing high productivity, provided that surface roughness and electrode wear are properly controlled. The findings demonstrate high reliability and accuracy and are directly applicable to precision mechanical engineering industries.

2. Theoretical basis of electrical discharge machining

2.1. Nature and classification of electrical discharge machining

2.1.1. Physical nature of electrical discharge machining

Electrical Discharge Machining (EDM) operates on the principle of using the thermal energy of electrical pulses to remove material. The process takes place in a specialized liquid medium called a dielectric. Machining begins when a voltage is applied between the electrode and the workpiece, which are separated by a small gap, typically 10–100 μm. The electrode, acting as the cutting tool, is usually made of materials with high thermal resistance and electrical conductivity, such as copper, graphite, copper-tungsten, or silver-tungsten. Although the electrode is generally softer than the workpiece, it remains effective due to the nature of the EDM process. The workpiece is usually a hard, heat-treated metal or alloy, all of which must be electrically conductive for sparking to occur.

Under normal conditions, the dielectric medium (e.g., distilled water, transformer oil, or kerosene) acts as an insulator. When the voltage between the electrode and workpiece exceeds a threshold, the dielectric becomes ionized, forming a conductive channel. A localized spark is generated, releasing extremely high energy in a very short time (typically microseconds). This energy melts and vaporizes a small amount of material from both the electrode and workpiece surfaces. The pressure of the expanding hot gas pushes the molten material out of the workpiece in the form of small particles or chips. After the pulse ends, the dielectric cools the workpiece and flushes away the debris, restoring its insulating properties in preparation for the next pulse.

This cycle repeats thousands or even millions of times per second, with each pulse removing only a tiny amount of material. EDM thus enables the creation of complex and highly accurate shapes on hard materials that are difficult or impossible to machine with conventional methods. The choice of dielectric fluid plays a critical role in controlling process efficiency, affecting both the material removal rate and the resulting surface quality.

2.1.2. Classification of EDM

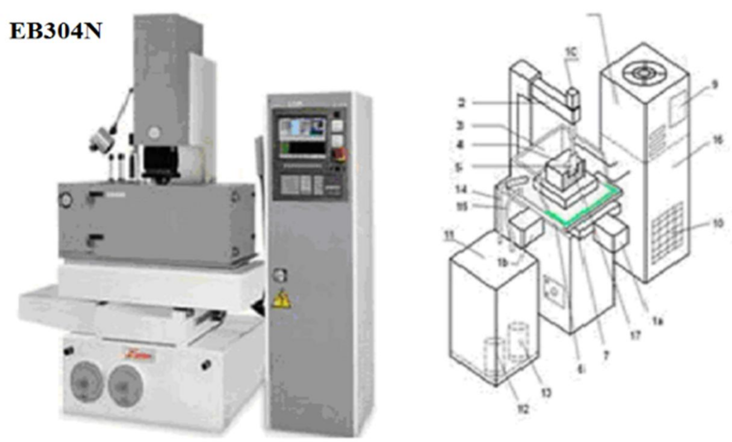


Figure 1. Schematic diagram of shaping pulse [15]

EDM technology has developed into a variety of specialized machine systems, each designed for specific applications. Broadly, EDM can be classified into two main types based on the operating principle and the type of electrode used:

Die-sinking EDM: This is the most common EDM method, often referred to as “pulse shaping.” In this approach, the electrode can have any geometric shape and is designed to replicate that shape onto the workpiece. The electrode gradually erodes the material, precisely “copying” its geometry to produce cavities, holes, or complex surfaces. Die-sinking EDM is particularly effective for manufacturing stamping dies, plastic injection molds, and components with deep cavities. Its ability to create intricate shapes makes it a critical technology in the mold-making industry (Figure 1).

Wire EDM: In contrast to die-sinking, wire EDM uses a thin, continuous metal wire as the electrode, typically with a diameter ranging from 0.1 to 0.3 mm. The wire is guided along a pre-programmed contour by a Computer Numerical Control (CNC) system. Electrical pulses from the wire erode the workpiece, enabling the production of complex shapes, through-holes, or highly precise cylindrical parts. Wire EDM is especially suitable for punching and stamping components, gears, and other precision parts that require tight tolerances. The continuous motion of the wire facilitates effective chip removal and ensures consistent surface quality throughout the cutting path (Figure 2).

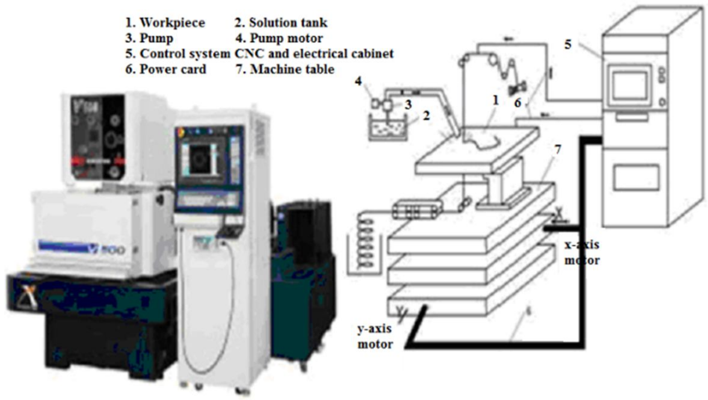


Figure 2. Schematic diagram of wire cutting machine [15]

2.2. Principle of EDM

The schematic diagram of EDM is shown in Figure 3.

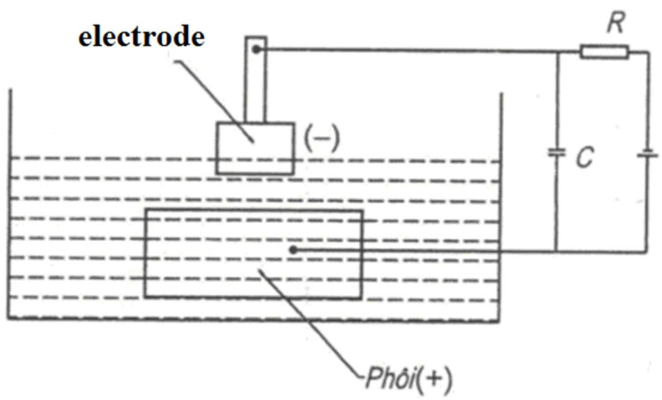


Figure 3. Schematic diagram of electrical discharge machining

A Direct Current (DC) voltage, typically ranging from 80 V to 200 V, is applied between the electrode and the workpiece, both of which are fully immersed in an insulating solution known as the dielectric. When the control system brings the electrode and workpiece within a very small gap (approximately 10–100 μm), the dielectric in the gap begins to ionize. This ionization forms an electrically conductive channel, allowing current to flow and generating an electric spark discharge. The temperature in this localized region can rise to extremely high levels, up to 10,000 °C, releasing intense thermal energy that instantly melts and vaporizes a small amount of material on both the electrode and workpiece surfaces.

To better understand the mechanism, the EDM process can be analyzed in two main steps:

Step 1: Dielectric Breakdown Stage

The process begins with the dielectric breakdown stage. When the electrode and workpiece are placed in the dielectric, an extremely strong electric field is generated in the gap, with an intensity reaching approximately 10^4 V/mm. At this high field strength, dielectric molecules begin to ionize, transforming the insulating medium into a conductive channel. This conductive path allows current to flow, which is essential for the subsequent spark formation. This stage occurs very rapidly, lasting only a few microseconds, and sets the stage for the material removal process (Figure 4).

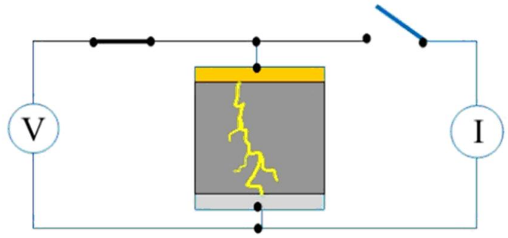


Figure 4. Dielectric Ionization Process

Step 2: Discharge and Material Removal Stage

After the conductive channel is established in Step 1, a strong current flows due to the rapid movement of ions and electrons within the dielectric medium. The energy from this current is concentrated at a very small point, generating a high-intensity electric spark. The temperature at this location rises rapidly, melting and vaporizing a small amount of material from both the workpiece and the electrode. Once the electric pulse ends, the plasma channel collapses, and the surrounding cold dielectric fluid rushes into the gap due to the resulting pressure difference. This sudden influx causes localized cooling and a micro-explosion, which solidifies and removes the vaporized material.

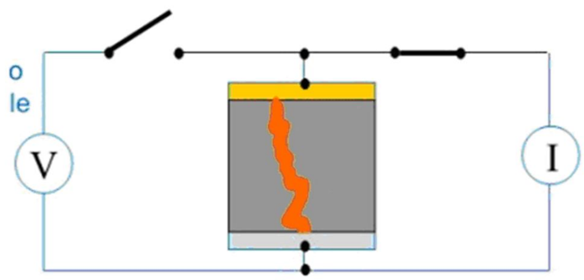


Figure 5. Spark discharge process

Table 1. Technical specifications of cutting machine

1	Machine size (W x D x H)	mm	1200 x 1350 x 2250
2	Magnetic table size (W x D)	mm	500 x 350
3	Working stroke (X, Y)	mm	300 x 200
4	Working stroke Z	mm	300
5	Maximum electrode weight	kg	60
6	Maximum workpiece weight	kg	500
7	Machine weight	kg	1000
8	Maximum machine speed	mm/h	350
9	Achievable arithmetic mean surface roughness R_a	µm	0.25

This process produces extremely small metal particles, often in the form of oxides, which are ejected from the gap. After the area is flushed and cleaned by the dielectric, power is reapplied, initiating a new cycle of sparking and material removal. Thousands of such cycles occur every second, allowing EDM to machine the workpiece continuously and with high precision (Figure 5). The characteristics of the pulse generator used in this process are summarized in Table 1.

2.3. Materials and method

This study aims to identify the most suitable electrode material for EDM machining of hexagonal nut molds, thereby ensuring optimal machining quality.

Processing equipment: The experiments were conducted using a CM 323C electric pulse machine, located at the Mechanical Center, Hanoi University of Industry, Vietnam (Figure 6).

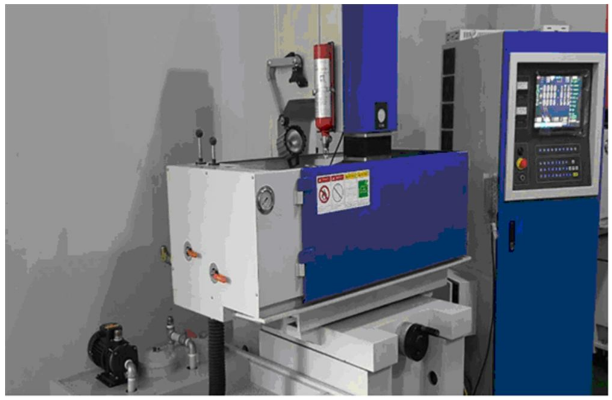


Figure 6. CM 32C Pulse Generator [15]

Machine specifications: CM 323C Pulse.

Material: C45 steel, heat-treated to a hardness of 52 ÷ 54 HRC.

The chemical composition of C45 steel is shown in Table 2.

Table 2. C45 steel chemical composition

Steel grade	Element content (%)						
C45	C	Si	Mn	P (max)	S (max)	Cr (max)	N (max)
	0.42÷0.50	0.17÷0.37	0.50÷0.80	0.040	0.040	0.25	0.25

Processing electrode: A red copper electrode with a diameter of 20 mm (Φ20 mm) was used, as shown in Figure 7.

Measuring device: Surface roughness was measured using a Mitutoyo SJ-301 tester, as shown in Figure 8.

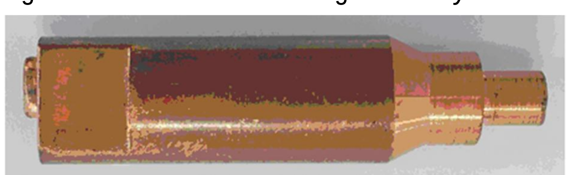


Figure 7. Machined electrode

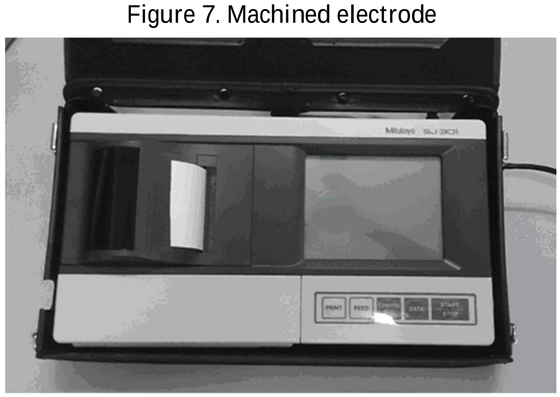


Figure 8. SJ-301 Roughness Gauge [15]

This study investigates the effect of red copper electrodes on surface roughness (R_a) during EDM machining of holes in C45 steel billets. Due to the complexity of the EDM process, theoretical analysis is challenging;

therefore, an experimental approach was adopted. The methodology involves designing experiments to identify key process parameters, optimizing these parameters, conducting practical machining tests, and analyzing the data using experimental design techniques. Finally, conclusions and recommendations are drawn based on the results of the analysis.

3. Results and discussion

The experiments were designed based on the following assumptions to ensure accuracy and repeatability: the stability of the dielectric fluid is maintained consistently across all experiments, disturbances affecting dimensional accuracy remain constant, and the temperature of the machining environment is kept stable.

This study focuses on the parameters with the greatest influence on surface roughness and machining productivity: electrode material, current intensity (I_e), and discharge voltage (U).

Based on preliminary trials on the cutting machine (CM) 323C Electrical discharge machining (EDM) machine, the machining mode was set to S36, and two variables, U and I_e, were selected for investigation.

The input variables were chosen at two levels:

Current intensity (I_e): minimum (I_{min}) = 4 A, maximum (I_{max}) = 8 A.

Discharge voltage (U): minimum (U_{min}) = 40 V, maximum (U_{max}) = 50 V.

According to the experimental design, with two input variables (k = 2), the total number of required experiments is $N = 2^k = 2^2 = 4$.

3.1. Effect of discharge voltage (U) and current intensity (I_e) on surface roughness

To evaluate the effects of these parameters, Minitab software was used to design the experimental plan and analyze the data. Four experiments were conducted, corresponding to four test samples. The measured results illustrating the influence of discharge voltage (U) and current intensity (I_e) on the arithmetic mean surface roughness (R_a) are shown in detail in Table 3.

Table 3. Electrode dimensions before and after machining on the same coordinates

No	I_e	Electrode Cu		
		φ_{dc}	φ_{dc} after pulse	Δ_{dc}
1	4	7.02	7.014	0.004
2	5	7.05	7.023	0,007
3	6	7.03	7.019	0.009
4	7	7.06	7.028	0.012

The results indicate that the surface roughness and corrosion behavior of the electrode are primarily influenced by current intensity and discharge voltage, as these parameters determine the total pulse energy, which directly affects the size of the discharge crater and the resulting surface finish.

Variations in current intensity also influence the voltage distribution along the electrode, impacting both surface roughness and electrode wear. In this study, only current intensity and discharge voltage were considered in order to specifically investigate their effects on surface roughness and electrode wear. Including additional parameters, such as pulse on/off time, could further influence surface roughness and electrode degradation, providing a more comprehensive understanding of these phenomena.

For the purposes of this work, the CM 323C machine was operated in its rough/medium machining mode, maintaining fixed pulse on/off times to ensure that the experiments were conducted under stable and consistent conditions.

3.2. Electrode Wear in EDM

During EDM, the electrode material gradually wears due to repeated sparking. This phenomenon is commonly quantified using the tool wear rate (TWR). One method to evaluate electrode wear is by measuring the change in electrode dimensions (Δd_e), which can be calculated using the following formula:

$$\Delta_{\text{đc}} = \Phi_{\text{đc after pulse}} - \Phi_{\text{đc before pulse}} \quad (1)$$

where: $\Delta_{\text{đc}}$ is the increase in electrode size (unit: mm), $\Phi_{\text{đc before pulse}}$ is the electrode diameter before machining (mm), $\Phi_{\text{đc after pulse}}$ is the electrode diameter after machining (mm).

These results indicate that the electrode undergoes dimensional changes during machining. Controlling and minimizing electrode wear is critical for maintaining machining accuracy and reducing production costs. By effectively managing electrode wear, manufacturers can optimize the use of materials and technological processes, thereby enhancing overall productivity.

Figure 9 illustrates the change in electrode size more clearly. Analysis of the relationship between arithmetic mean surface roughness (R_a) and machining parameters, such as discharge voltage (U) and current intensity (I_e), indicates that these two variables have the most significant impact on surface quality when machining C45 steel with copper electrodes. In contrast, other parameters, such as pulse on time and pulse off time, exert a considerably smaller influence.

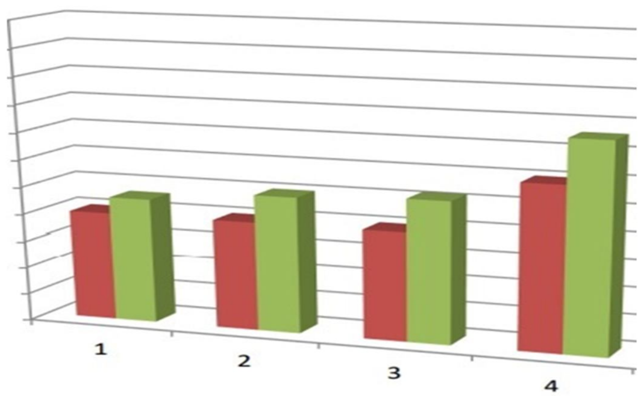
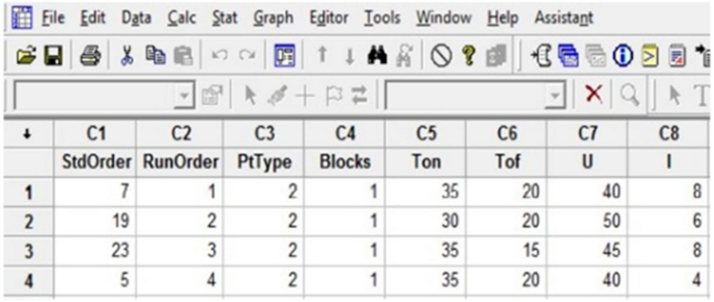


Figure 9. Electrode dimensions before and after pulse

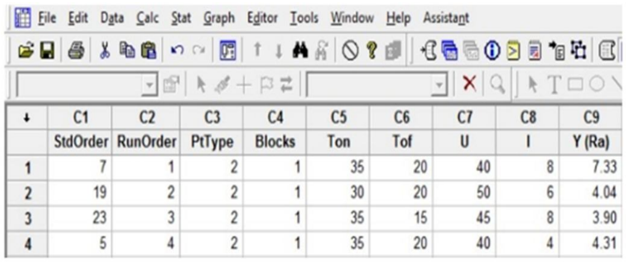
To visualize the results, this relationship was presented using a characteristic graph (Figure 10), illustrating how Ra varies with changes in U and I_e. Figure 11 shows the actual measured surface roughness values, confirming that Ra increases with both current intensity and voltage. This observation is consistent with the theoretical principle that higher thermal energy from the electric pulses enlarges the discharge crater, resulting in a rougher surface [16]. These findings provide a valuable basis for selecting optimal machining parameters to achieve the desired surface finish. From the analyzed data, the minimum arithmetic mean surface roughness (R_a) obtained was 2.2943 μm.

This value represents the optimal surface quality achievable with the investigated machining parameters. As the current intensity (I_e) increases, the wear on the copper (Cu) electrode increases significantly. This observation aligns with the theoretical principles of EDM: higher current intensity produces stronger electric pulses, releasing more thermal energy and increasing the material removal rate. However, it also accelerates electrode wear, resulting in greater degradation of the Cu electrode compared to other materials such as graphite or copper-tungsten. While increasing current intensity enhances machining productivity, it simultanesously leads to higher electrode wear and can reduce the dimensional accuracy of the machined part.



↓	C1	C2	C3	C4	C5	C6	C7	C8
	StdOrder	RunOrder	PtType	Blocks	Ton	Tof	U	I
1	7	1	2	1	35	20	40	8
2	19	2	2	1	30	20	50	6
3	23	3	2	1	35	15	45	8
4	5	4	2	1	35	20	40	4

Figure 10. Input variables



↓	C1	C2	C3	C4	C5	C6	C7	C8	C9
	StdOrder	RunOrder	PtType	Blocks	Ton	Tof	U	I	Y (Ra)
1	7	1	2	1	35	20	40	8	7.33
2	19	2	2	1	30	20	50	6	4.04
3	23	3	2	1	35	15	45	8	3.90
4	5	4	2	1	35	20	40	4	4.31

Figure 11. Arithmetic mean surface roughness (R_a) results obtained using a copper (Cu) electrode

4. Conclusion

This study presents an in-depth experimental investigation into the influence of machining parameters on surface quality during hole machining of heat-treated C45 steel using copper electrodes. The results indicate that current intensity (I_e) and discharge voltage (U) are the most critical factors affecting surface roughness. A key contribution of this work is the quantitative determination of the optimal arithmetic mean surface roughness, (R_a) = 2.2943 μm, for this specific material and process combination. This finding is both direct and practically applicable, providing manufacturers with a reliable reference for process optimization. The study also highlights the trade-off between machining productivity and electrode wear: higher current intensities increase the material removal rate but simultaneously cause significant wear of the copper electrode. These insights offer a valuable dataset for industry, enabling manufacturers to balance productivity and material costs. Beyond reinforcing the broader understanding of electrical discharge machining, this work delivers practical value to the mechanical industry, particularly in the production of commonly used components such as nuts and bolts, by providing experimentally validated process parameters and optimization guidelines for heat-treated C45 steel.

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