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Surface Integrity Study of AISI D2 Steel Using Powder Mixed RBD Palm Oil-Based Dielectric Fluid in Electrical Discharge Machining Process

Muhammad Aliff Nazmi Nordin[1], Said Ahmad[1]*

[1] *Faculty of Mechanical and Manufacturing Engineering*
Universiti Tun Hussein Onn Malaysia, Parit Raja, 86400 Johor, MALAYSIA

*Corresponding Author: said@uthm.edu.my
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EDM, Nano Alumina, Surface integrity, Surface topography, RBD palm oil

Abstract

A series of regulated electrical discharges between an electrode and a workpiece immersed in a dielectric fluid removes material from the workpiece during Electrical Discharge Machining (EDM). The dielectric fluid plays a crucial role by aiding cooling, stabilizing sparks, and removing debris, all of which influence machining performance. This study examines the surface integrity of AISI D2 steel machined using a copper electrode with biodegradable Refined, Bleached, and Deodorized (RBD) palm oil, both with and without nano aluminum oxide (Al_2O_3) powder, in comparison with conventional kerosene-based dielectric fluids. The experiments varied peak current (10A, 20A, 30A) and pulse durations (50 µs, 100 µs, 150 µs), focusing on surface roughness (Ra), recast layer thickness (RL), and microhardness (MH) as key responses. The findings reveal that adding nano-alumina powder to both kerosene and RBD palm oil significantly improves surface finish and reduces recast layer thickness, with kerosene with powder achieving the thinnest RL and lowest Ra. Although kerosene generally produces a smoother surface, RBD palm oil with powder demonstrates comparable effectiveness while providing a more sustainable alternative. Microhardness near the machined surface increased across all dielectrics due to thermal effects and rapid solidification, with powder-mixed fluids aiding in controlling heat distribution and stabilizing discharges. These results indicate that powder-mixed RBD palm oil is a practical and environmentally friendly substitute for petroleum-based fluids in EDM, maintaining machining quality while aligning with global sustainability goals.

1. Introduction

Here, introduction Electric discharge machining (EDM) is a modern machining process that has become a well-established alternative for machining advanced materials throughout the world, regardless of each country's level of academic or industrial advancement. Several research projects in EDM improved its machining capabilities and extended its application from working with only metallic materials to being able to work with nonconducting materials [1]. The EDM process utilizes thermoelectric energy to erode conductive materials through a series of rapid electrical discharges in the presence of a dielectric fluid. This process is particularly valued for its ability to produce precise shapes without physical contact between the tool and the workpiece, making it ideal for materials like AISI D2 steel, known for its high hardness and wear resistance [2].

EDM methods that employ the same material removal mechanism include die-sinking EDM, wire EDM, micro EDM, powder-mix EDM, and dry EDM. Different technologies make the process more flexible and ideal for machining relatively wide and microscopic. Die-sinking EDM is a method of removing material from a workpiece that includes a series of quickly occurring current discharges along electrodes separated by a dielectric fluid and exposed to an electrical voltage. To produce sparks, both the electrode and the workpiece must have electrical conductivity [3]. Electrical Discharge Machining (EDM) is a non-traditional machining process that utilizes controlled electrical discharges to remove material from a workpiece. The process operates on the principle of thermoelectric energy conversion, where localized melting and vaporization occur due to high temperatures generated by the electrical discharges [4]. EDM is particularly effective for machining hard materials and complex geometries that are often challenging for conventional machining methods. Its applications range from aerospace components to intricate molds used in manufacturing industries [5].

The operational efficiency of EDM is influenced by several factors, including the choice of electrode material, dielectric fluid properties, and various machining parameters. Common electrode materials include copper, graphite, and tungsten, each offering distinct advantages in terms of conductivity and wear resistance. The dielectric fluid serves multiple purposes: it acts as an insulator until breakdown occurs, cools the workpiece and electrode during machining, and flushes away debris generated from the process [6]. Understanding these operational mechanisms is crucial for optimizing EDM performance across different materials. Fig. 1 shows a schematic diagram of EDM.

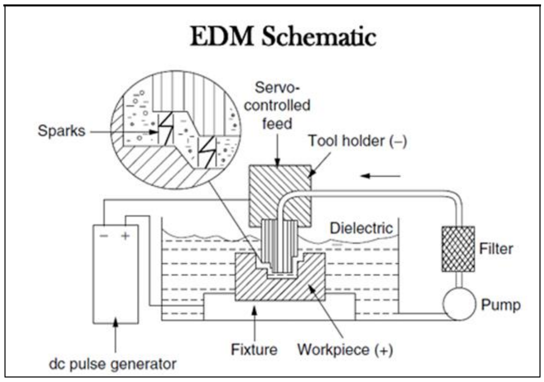


Fig 1: *Schematic diagram of electric discharge machining [7]*

The superior electrical insulating qualities and capacity to promote efficient spark generation during the machining process, kerosene has long been utilized as a dielectric fluid in EDM. Better flow and cooling are made possible by its low viscosity, which is crucial for preserving ideal operating conditions while milling [8]. However, there are serious environmental issues with kerosene use, especially given its toxicity and the poisonous fumes created during the EDM process. According to research, when exposed to high temperatures, kerosene can break down and release harmful gasses, which can pollute the air and endanger the health of operators [9].

Because of its biodegradable nature and advantageous machining properties, RBD (Refined, Bleached, and Deodorized) palm oil has drawn a lot of interest as an environmentally acceptable substitute for conventional petroleum-based dielectric fluids in Electrical Discharge Machining (EDM). According to studies, RBD palm oil offers comparable or even higher material removal rates (MRR) and a much lower environmental impact than traditional dielectrics like kerosene [10]. By reducing toxic waste and harmful emissions, RBD palm oil not only supports sustainability goals but also offers efficient cooling and flushing capabilities during the EDM process. When machining hard materials like AISI D2 steel, where maintaining ideal temperature conditions is essential for attaining high-quality surface integrity, this is especially significant. Additionally, studies show that RBD palm oil can result in lower electrode wear rates than kerosene, extending tool life and lowering operating expenses over time [8]. The use of biodegradable dielectric fluids, such as RBD palm oil, is a promising development in EDM technology that will help preserve the environment and increase machining efficiency as the industry moves more and more toward sustainable practices.

When utilized in Electrical Discharge Machining (EDM), Nano alumina oxide (Al_2O_3) serves as a beneficial powder addition that enhances machining performance, particularly with hard materials such as AISI D2 steel. By increasing thermal conductivity and improving heat dissipation during the machining process, the incorporation of Al_2O_3 into dielectric fluids reduces the risk of thermal damage and enhances cooling efficiency. Furthermore, Al_2O_3 contributes to the erosion process, resulting in higher material removal rates (MRR) and improved surface integrity by minimizing the formation of recast layers and residual stresses [11]. It also lessens electrode wear, which prolongs tool life and lowers operating expenses [8]. When combined with biodegradable fluids, AlO_3 is a more eco-friendly choice that minimizes environmental impact and promotes sustainable manufacturing methods [10].

2. Methodology

The choice of electrode material in Electrical Discharge Machining (EDM) is crucial as it significantly impacts the overall performance and efficiency of the machining process. Commonly used materials include copper, graphite, and tungsten, each offering unique advantages and disadvantages. Copper is renowned for its excellent electrical conductivity and thermal properties, making it a popular choice for applications requiring high precision and fine finishes [4]. Its ability to conduct electricity efficiently allows for effective spark generation, which is essential for achieving optimal material removal rates (MRR).

Table 1: *Specification for electrode*

Parameter	Specification
Electrode Material	Copper
Electrode Type	Cylindrical Electrode
Shape & Size	10 mm diameter, 30 mm height

Due to its high carbon content, which provides remarkable hardness and wear resistance, AISI D2 steel (Table 2) is commonly selected for EDM applications. This makes it a perfect choice for assessing surface integrity during machining operations. AISI D2 is a high-carbon, high-chromium tool steel that performs well under mechanical and thermal stress because of its distinctive microstructure, which contains big, chromium-rich carbides [12]. According to [13], this composition enables thorough testing under various conditions, guaranteeing dependable results across many tests and applications. In EDM, where a lot of heat is produced during the machining process, AISI D2's capacity to retain its hardness at high temperatures is especially useful.

Table 2: *Material Properties of AISI D2 Steel*

Property	Specification
Type	High-carbon, high-chromium tool steel
Density	7695 kg/m^3
Thermal Conductivity	41.5 W/m·K
Size	40mmx30mmx10mm

In Electrical Discharge Machining (EDM), surface roughness is a crucial element that greatly affects the frictional properties of machined parts, which in turn affects wear rates and overall performance. It is described as a surface's texture, which is typified by its imperfections and departures from a perfectly level plane. When components contact, these surface imperfections may increase friction, hastening wear and shortening the life of parts used in demanding applications. Because it gives information about how well the EDM process has produced the intended surface characteristics, measuring surface roughness is crucial for assessing the quality levels attained during machining processes. When it comes to optimizing EDM settings, a smoother surface finish is crucial since it typically correlates with better performance features like decreased friction and increased fatigue resistance [8].

One important element affecting the functionality and durability of machined components is the recast layer created during the Electrical Discharge Machining (EDM) process. This layer is produced when some of the workpiece material melts due to the extreme heat produced by electrical discharges and quickly resolidifies when cooled. Depending on the precise machining parameters used, such as discharge energy, pulse duration, and electrode material, the resulting recast layer can have a thickness that varies, usually ranging from a few micrometers to several hundred micrometers [14]. The recast layer's microstructure and composition frequently diverge greatly from the source materials, changing mechanical characteristics including brittleness and hardness. For example, this layer may become more brittle and break under stress, but it may also show greater hardness as a result of quick solidification.

When assessing the impact of the Electrical Discharge Machining (EDM) process on workpieces, microhardness testing is a crucial analytical method that offers insights into the material properties at the microscopic level. Microhardness testing, which measures the hardness of small-scale regions, can identify variations that correspond with modifications in machining parameters including electrode material, discharge energy, and pulse duration. Because they have a direct impact on overall performance characteristics including fatigue resistance and wear characteristics of the machined components, these microhardness differences are important. Higher microhardness values close to the surface, for example, frequently signify a hardened layer that was created by the EDM process's quick cooling, which can improve the component's resistance to operational stresses and lengthen its service life.

3. Result and discussion

This chapter presents the experimental results and discussion of the EDM process conducted on AISI D2 steel using four types of dielectric conditions: kerosene, kerosene mixed with nano-alumina powder, RBD palm oil, and RBD palm oil mixed with nano-alumina powder. The results focus on three key surface integrity parameters: surface roughness, recast layer thickness, and microhardness. The machining parameters were varied to analyze the impact on the machined surface. Each subsection provides detailed explanations of the methods used, followed by tables and figures representing the observed data and a discussion correlating machining parameters with the resulting surface features.

3.1 Surface roughness

Ra values are lowest when using kerosene, followed by palm oil and PM palm oil. The increase in roughness for palm oil-based fluids is attributed to their viscosity and different flushing efficiency. PMEDM results in more consistent crater distribution and smoother textures.

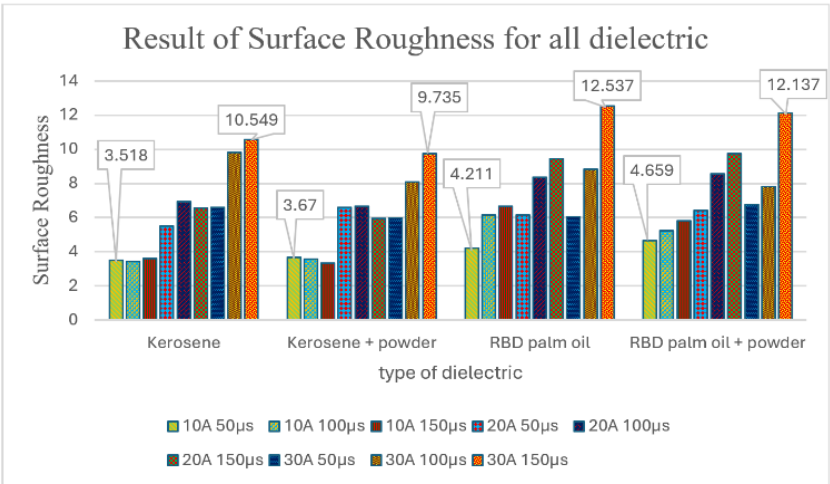


Fig 2: *Result of Surface roughness for all dielectric kerosene, kerosene with nano alumina powder, RBD palm oil, RBD palm oil with nano alumina powder.*

Based on the comparison of all four dielectrics (Fig. 2), it is evident that the surface roughness is lowest when kerosene with alumina powder is used and highest when pure RBD palm oil is used. The nano alumina powder improves discharge uniformity and flushing, resulting in smaller and shallower craters. Among the conditions tested, the highest Ra was 12.537 µm for RBD palm oil at 30A and 150 µs, and the lowest was 3.320 µm for kerosene with alumina at 10A and 150 µs. The results support that peak current has the greatest influence on Ra, followed by pulse duration.

It can be concluded that the inclusion of nano alumina powder enhances surface integrity in both petroleum-based and bio-based dielectrics. The observed trend aligns well with the literature, which states that spark energy regulation and thermal control through powder-mixed dielectric media can significantly reduce surface roughness and promote better machining stability [15]. Therefore, for applications requiring high surface quality, kerosene with alumina is most effective, while RBD palm oil with alumina offers a sustainable alternative with reasonably improved surface properties.

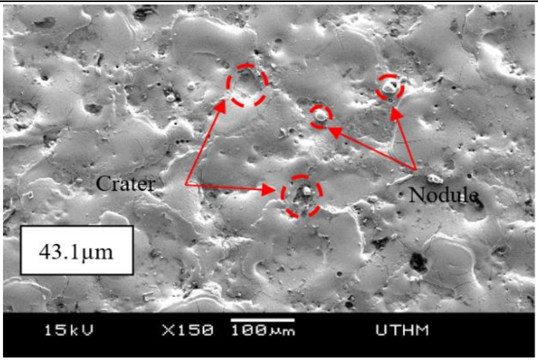
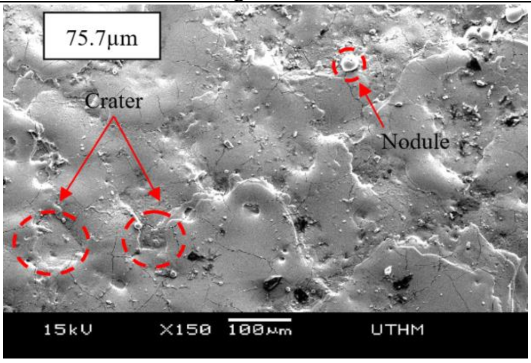
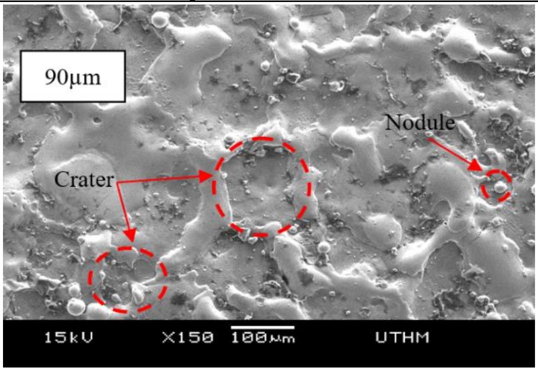
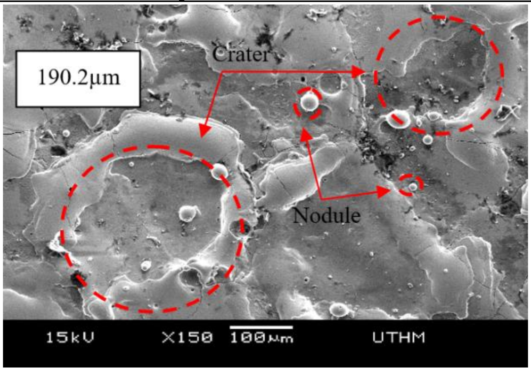
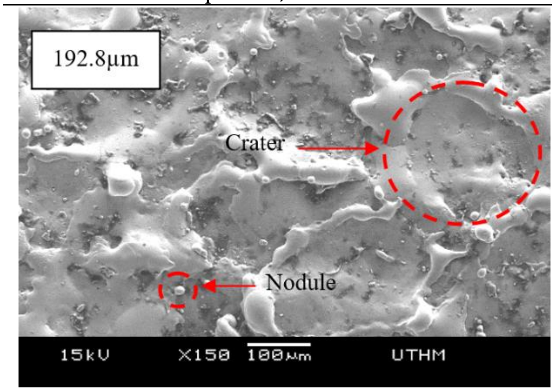
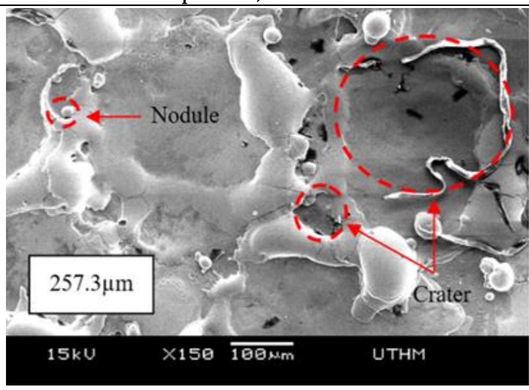
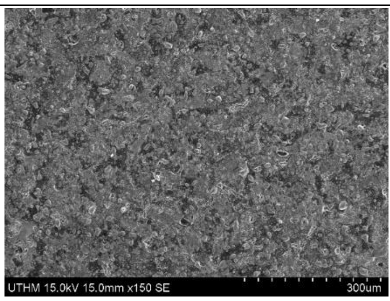
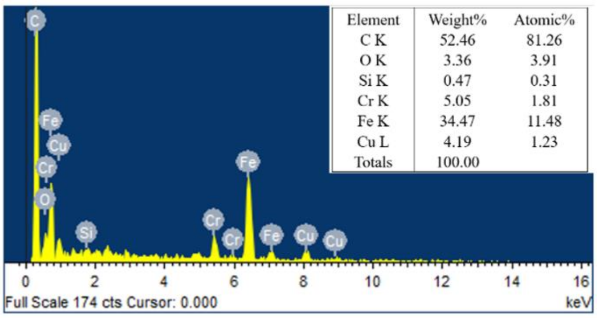
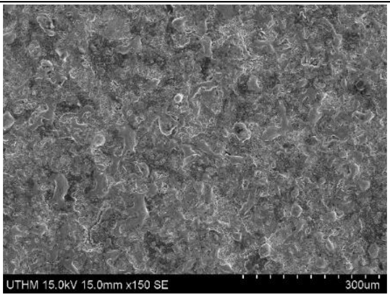
Lowest R_a	Highest R_a
	
Ip=10A, ton=50	Ip=10A, ton=150
	
Ip=20A, ton=50	Ip=20A, ton=150
	
Ip=30A, ton=50	Ip=30A, ton=150

Fig 3: The EDM machined Surface Topography of AISI D2 Steel by using Cu Electrode for Kerosene

Picture	EDX result
	
(a)Ip=10A, ton=50	



(b)Ip=30, ton= 150

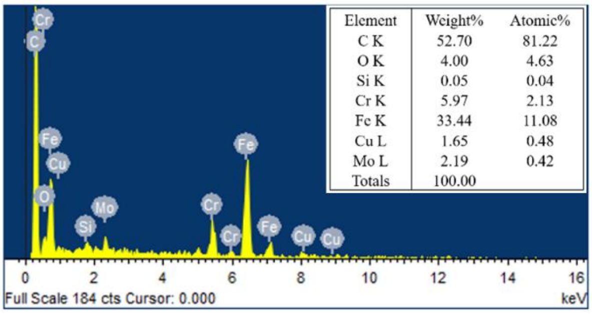
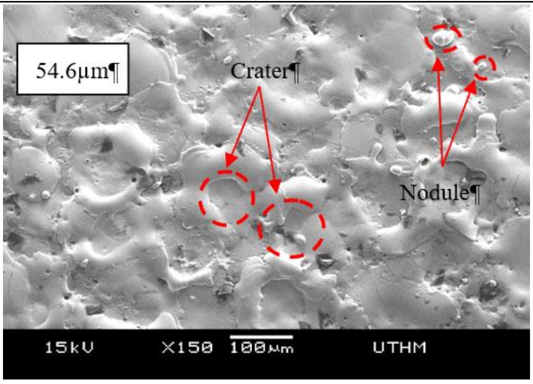
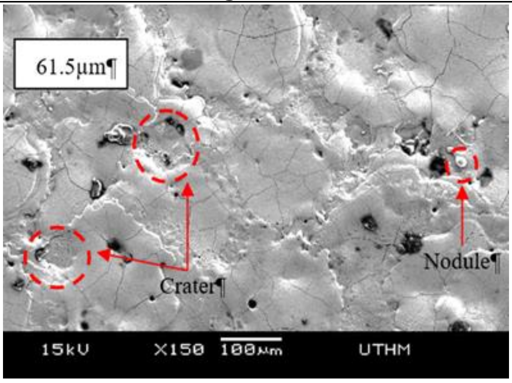


Fig 4: *Surface Morphology and EDX Testing of the Cu Electrode when Kerosene Dielectric was Employed [(a) Lowest EWR and (b) Highest EWR]*

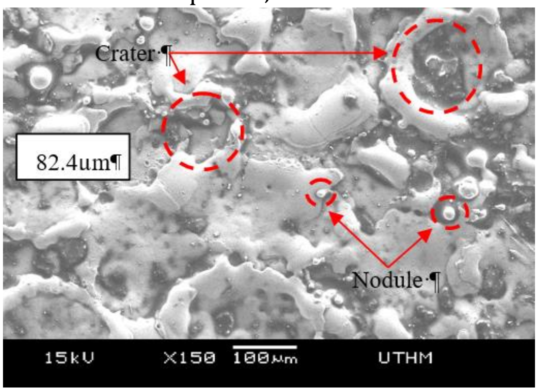
Lowest R_a	Highest R_a



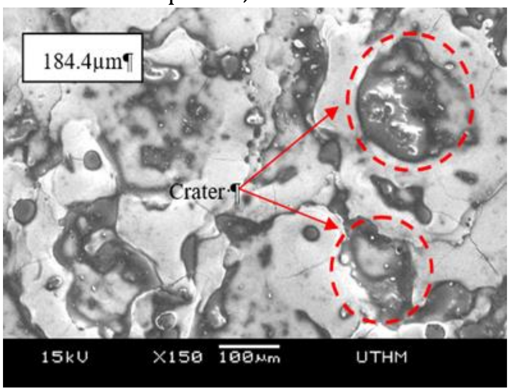
Ip=10A, ton=50



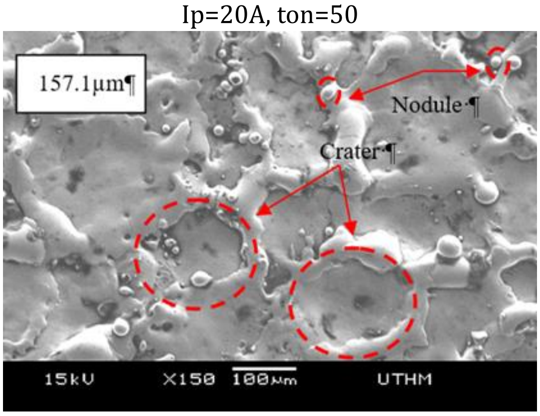
Ip=10A, ton=150



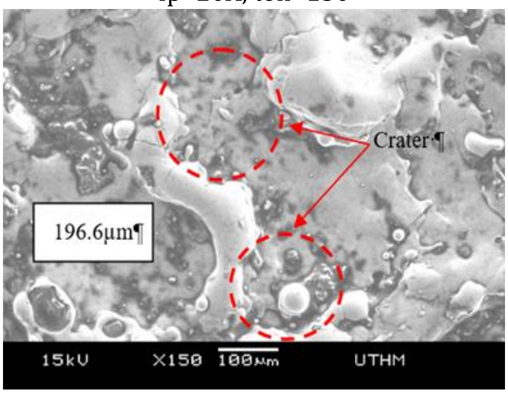
Ip=20A, ton=50



Ip=20A, ton=150



Ip=30A, ton=50



Ip=30A, ton=150

Fig 5: *The EDM Machined Surface Topography of AISI D2 Steel by using Cu Electrode for Kerosene with nano alumina al203 [Ip=10A, Ip=20A and Ip=30A]*

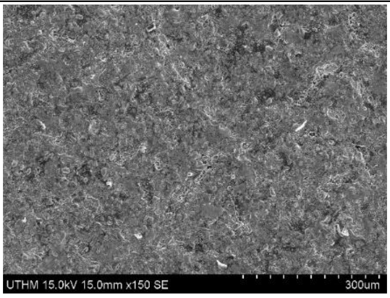
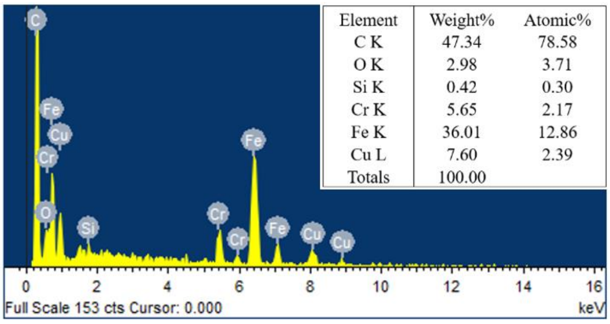
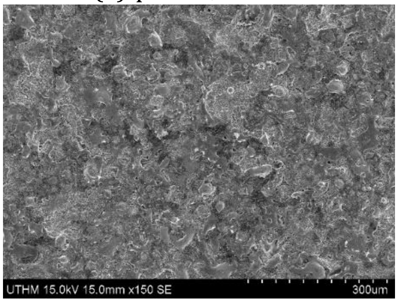
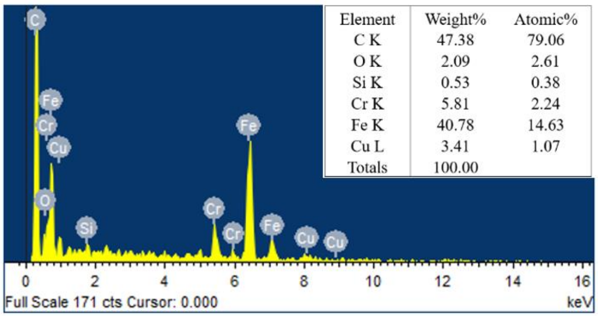
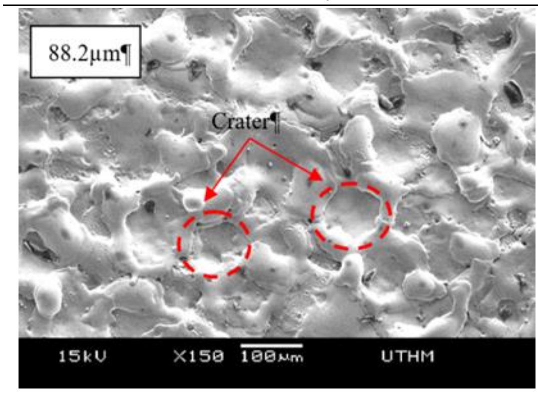
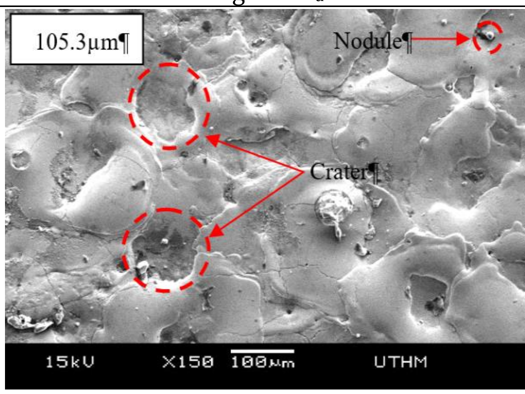
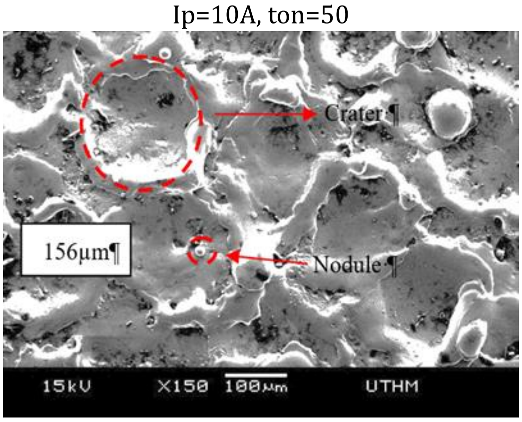
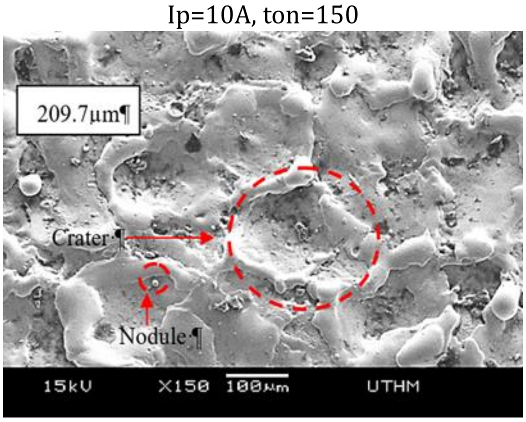
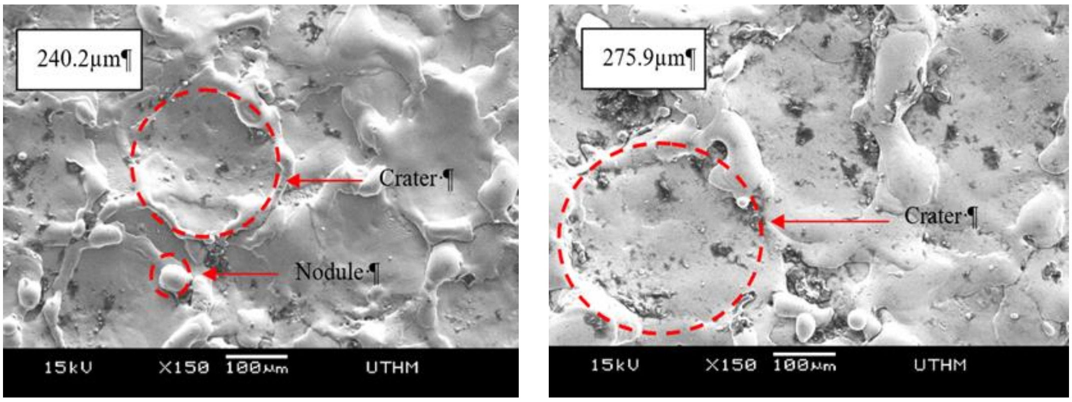
Picture	EDX result
 (a)Ip=10A, ton=50	
 (b)Ip=30A, ton=150	

Fig 6: *Surface Morphology and EDX Testing of the Cu Electrode when Kerosene with nano alumina al203 Dielectric was Employed [(a) Lowest EWR and (b) Highest EWR]*

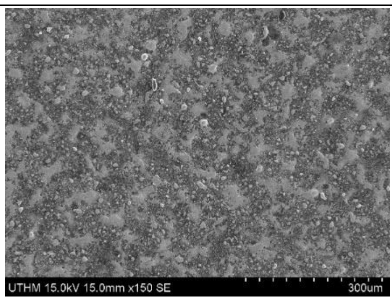
Lowest R_a	Highest R_a
 Ip=10A, ton=50	 Ip=10A, ton=150
 Ip=20A, ton=50	 Ip=20A, ton=150

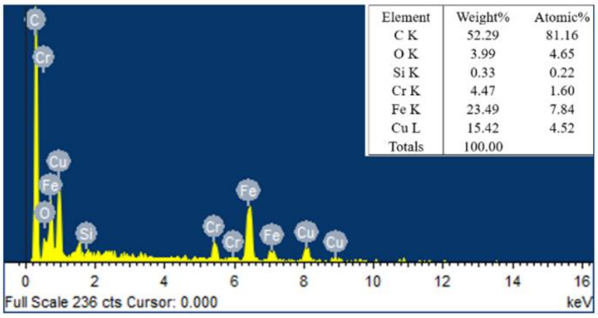


Ip=30A, ton=50 Ip=30A, ton=150

Fig 7: *The EDM Machined Surface Topography of AISI D2 Steel by using Cu Electrode for RBD palm oil [Ip=10A, Ip=20A and Ip=30A]*

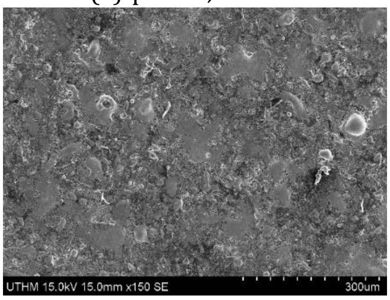
Picture	EDX result

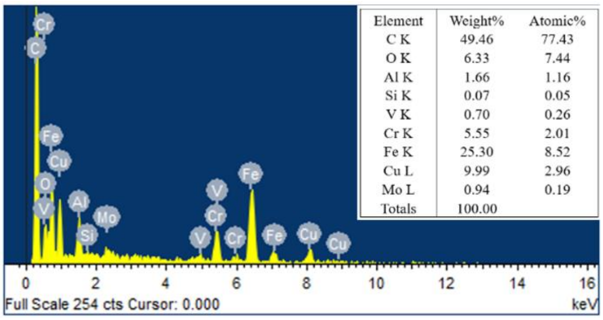




Element	Weight%	Atomic%
C K	52.29	81.16
O K	3.99	4.65
Si K	0.33	0.22
Cr K	4.47	1.60
Fe K	23.49	7.84
Cu L	15.42	4.52
Totals	100.00	

(a)Ip=10A, ton=50



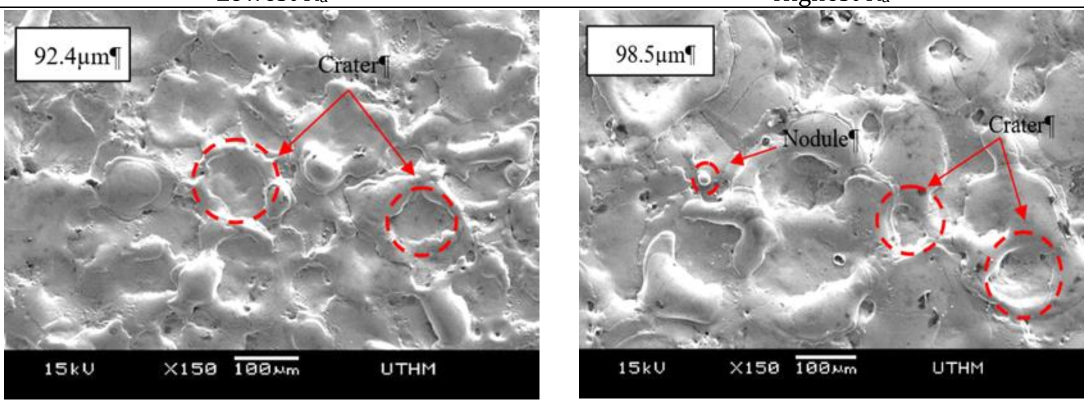


Element	Weight%	Atomic%
C K	49.46	77.43
O K	6.33	7.44
Al K	1.66	1.16
Si K	0.07	0.05
V K	0.70	0.26
Cr K	5.55	2.01
Fe K	25.30	8.52
Cu L	9.99	2.96
Mo L	0.94	0.19
Totals	100.00	

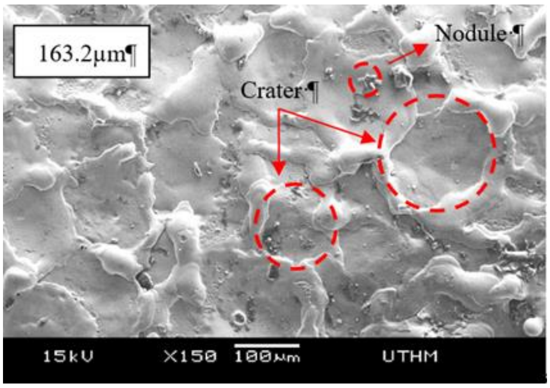
(b)Ip=30A, ton=150

Fig 8: *Surface Morphology and EDX Testing of the Cu Electrode when RBD palm oil Dielectric was Employed [(a) Lowest EWR and (b) Highest EWR]*

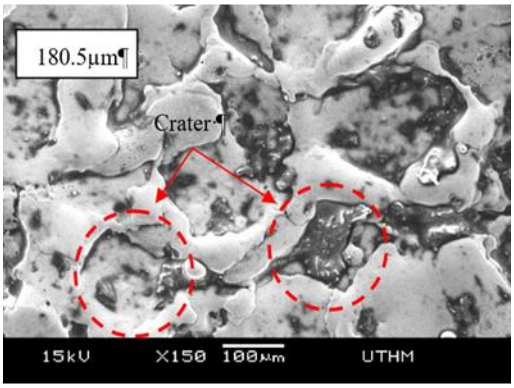
Lowest R_a	Highest R_a



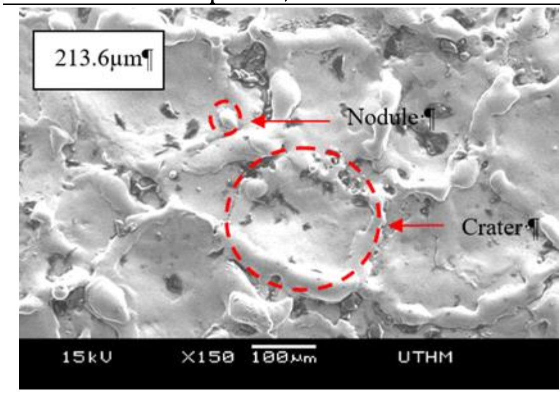
Ip=10A, ton=50 Ip=10A, ton=150



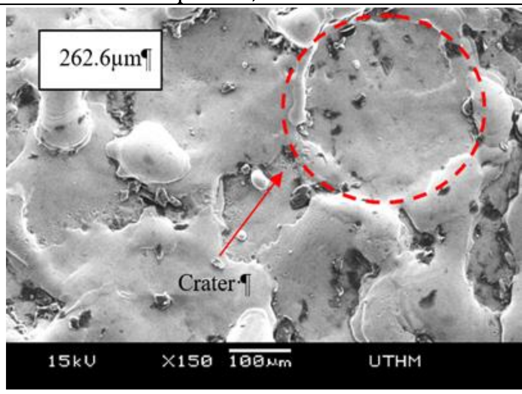
Ip=20A, ton=50



Ip=20A, ton=150



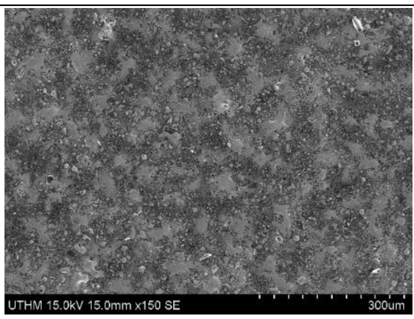
Ip=30A, ton=50

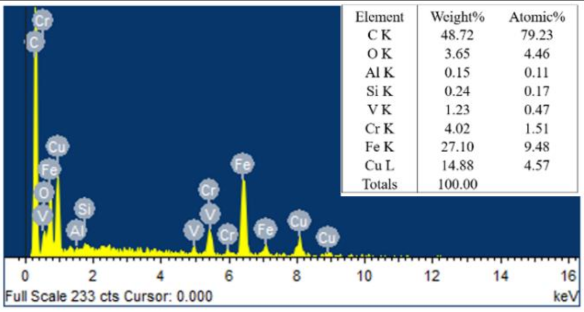


Ip=30A, ton=150

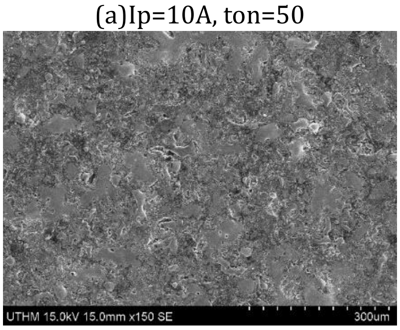
Fig 9: *The EDM Machined Surface Topography of AISI D2 Steel by using Cu Electrode for RBD palm oil includes alumina al203 [(a) Ip=10A, (b) Ip=20A and (c) Ip=30A]*

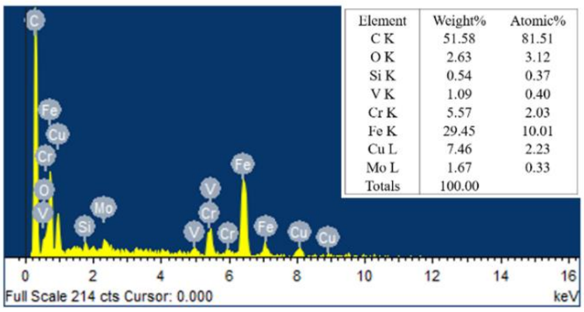
Picture	EDX result





(a)Ip=10A, ton=50





(b)Ip=30A, ton=150

Fig 10: *Surface Morphology and EDX Testing of the Cu Electrode when RBD palm oil includes alumina al203 Dielectric was Employed [(a) Lowest EWR and (b) Highest EWR]*

3.2 Recast layer

Recast layer analysis was performed after the initial surface roughness measurement. The samples were sectioned and then subjected to a sequence of grinding (240cw, 360cw, 800cw, and 1200cw grit) followed by polishing. Finally, the samples were etched with 2% Nital to reveal the recast layer for observation under optical microscopy. Fig. 11 shows the results of the recast layer for all dielectric types.

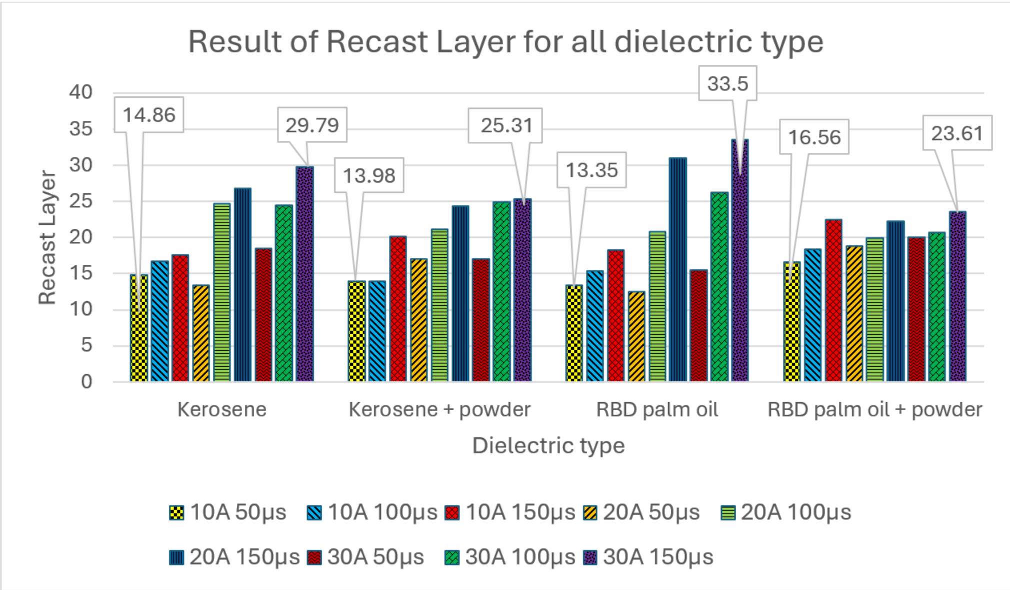


Fig 11: *Result of Recast Layer for all dielectric types*

Recast layer (RL) thickness reduction is essential for improving surface integrity in EDM. Figure 11 shows kerosene with nano alumina powder consistently produced thinner RLs, such as 13.98 µm at 10A, 50 µs, compared to kerosene alone (14.86 µm) and RBD palm oil + powder (16.56 µm). This is due to alumina powder aiding energy dispersion and improving flushing. RBD palm oil without powder had the thickest RL, reaching 33.50 µm at 30A, 150 µs, due to its higher viscosity and lower thermal conductivity, which hinder debris removal and increase heat retention. Generally, RL thickness increased with higher peak current and pulse-on time, but powder-mixed dielectrics reduced this effect. For example, at 30A, 150 µs, kerosene with powder reduced RL to 25.31 µm versus kerosene's 29.79 µm, and RBD palm oil with powder reduced RL to 23.61 µm versus 33.50 µm with pure palm oil. These results indicate that adding nano alumina powder enhances spark stability and thermal management, reducing RL thickness and microcrack formation while improving surface quality. Although kerosene with powder is most effective in reducing RL thickness, RBD palm oil with powder remains a viable, environmentally friendly alternative, consistent with findings from Ekmekci et al. [4].

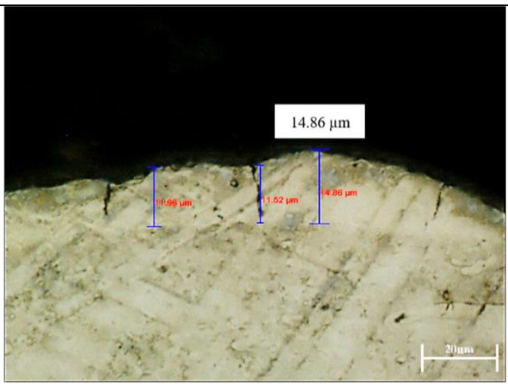
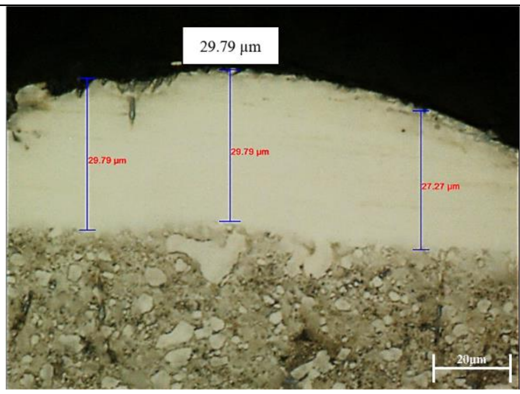
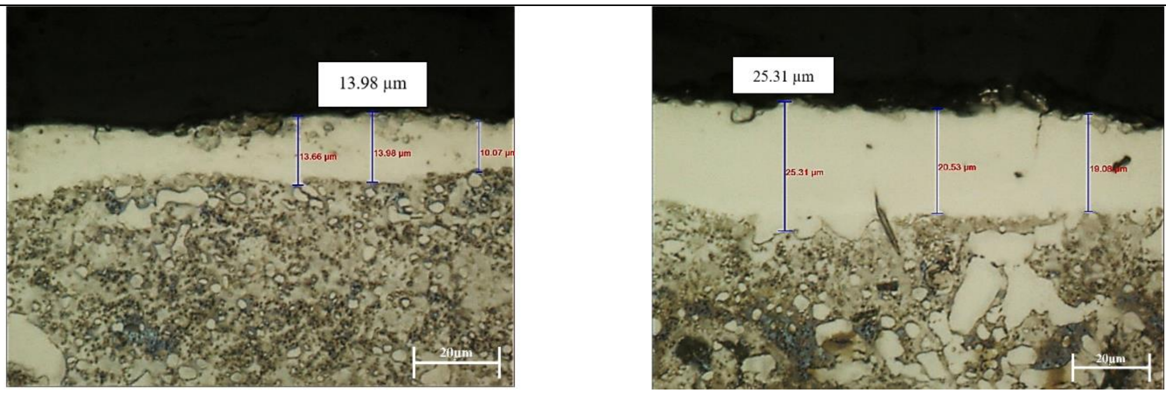
Low parameter	High parameter
 Ip=10A, ton=50µs	 Ip=30A, ton=150µs

Fig 12: *The EDM machined Surface Topography of AISI D2 Steel by using Cu Electrode for Kerosene*

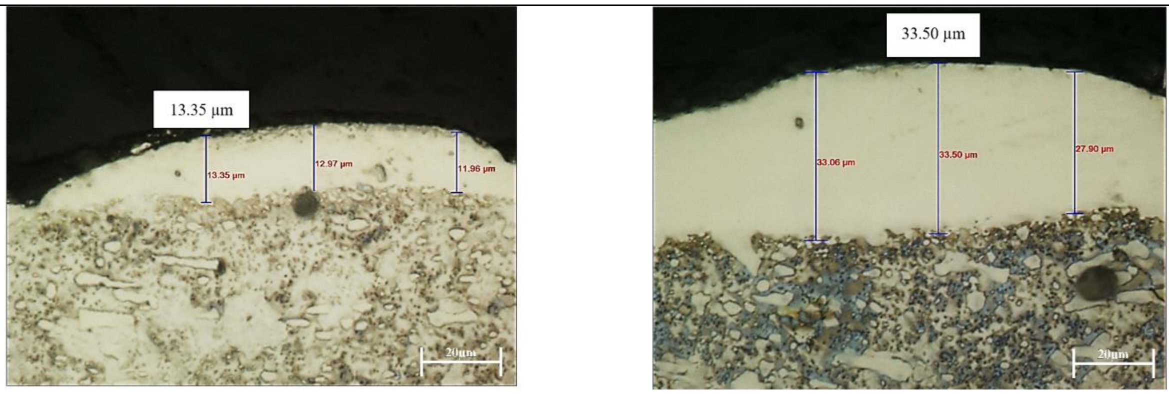
Low parameter	High parameter



Ip=10A, ton=50µs	Ip=30A, ton=150µs

Fig 13: *The EDM Machined Surface Topography of AISI D2 Steel by using Cu Electrode for Kerosene with nano alumina Al_2O_3*

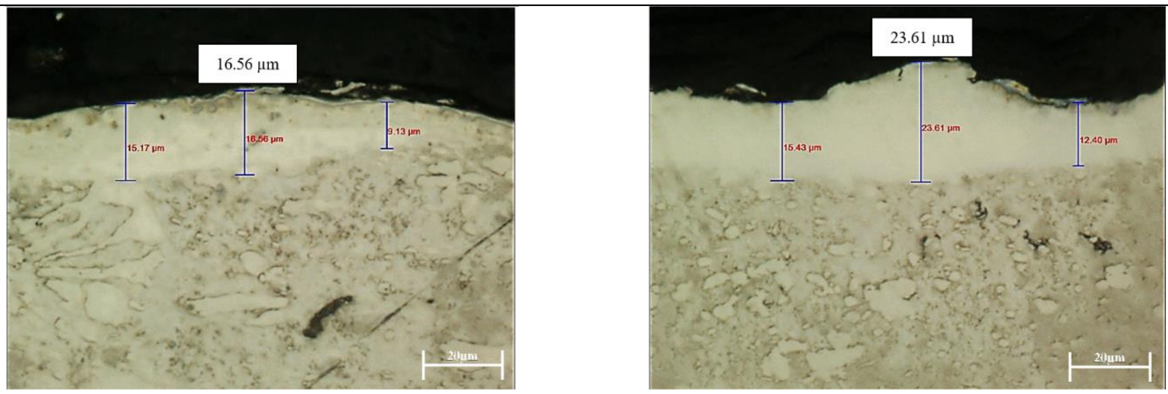
Low parameter	High parameter



Ip=10A, ton=50µs	Ip=30A, ton=150µs

Fig 14: *The EDM Machined Surface Topography of AISI D2 Steel by using Cu Electrode for RBD palm oil*

Low parameter	High parameter



Ip=10A, ton=50µs	Ip=30A, ton=150µs

Fig 15: *The EDM Machined Surface Topography of AISI D2 Steel by using Cu Electrode for RBD palm oil + Nano alumina*

3.3 Microhardness

Microhardness testing was conducted after the recast layer was clearly observed. A Vickers hardness tester was employed with a 980.7 mN (100 gf) load, a 10-second dwell time, and ten indentations spaced 0.05 mm apart. The objective was to evaluate the hardness profile near the EDM surface and assess how it varies with different dielectrics and machining parameters.

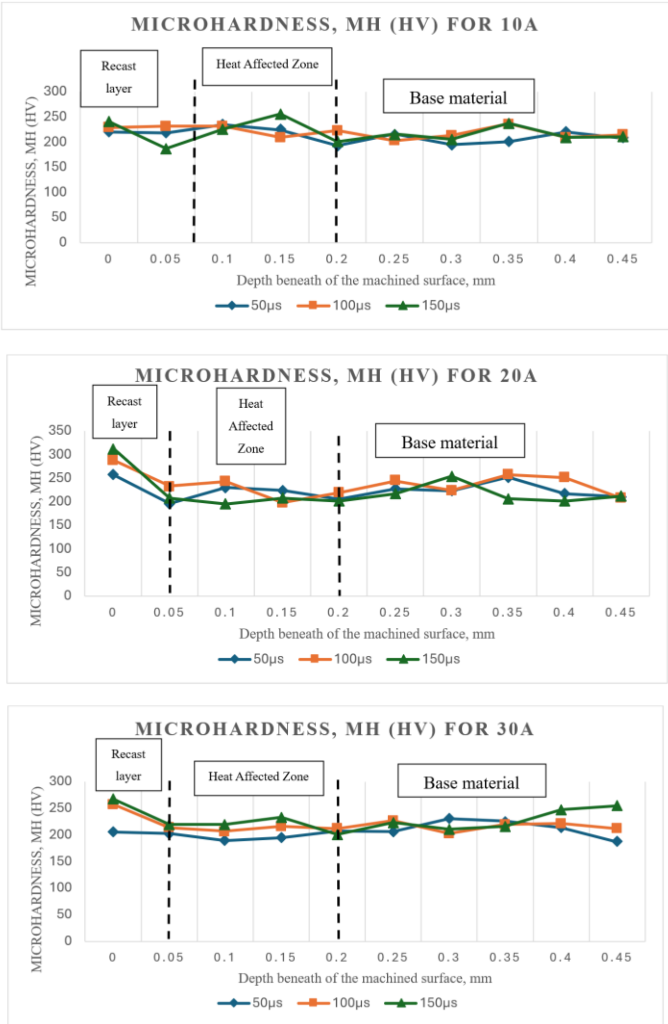
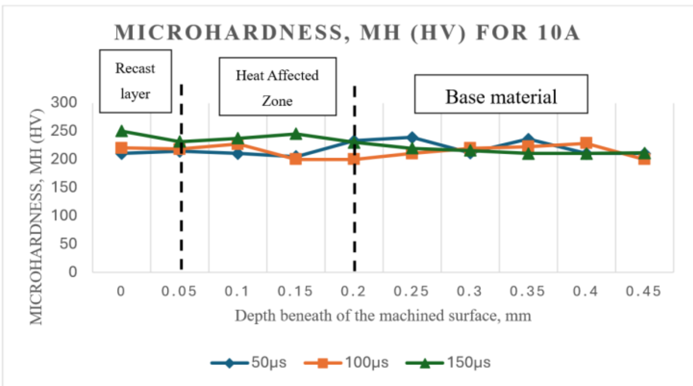


Fig 16: *Result of Microhardness for Kerosene Based Dielectric Fluid with Different Pulse Duration, Ton*



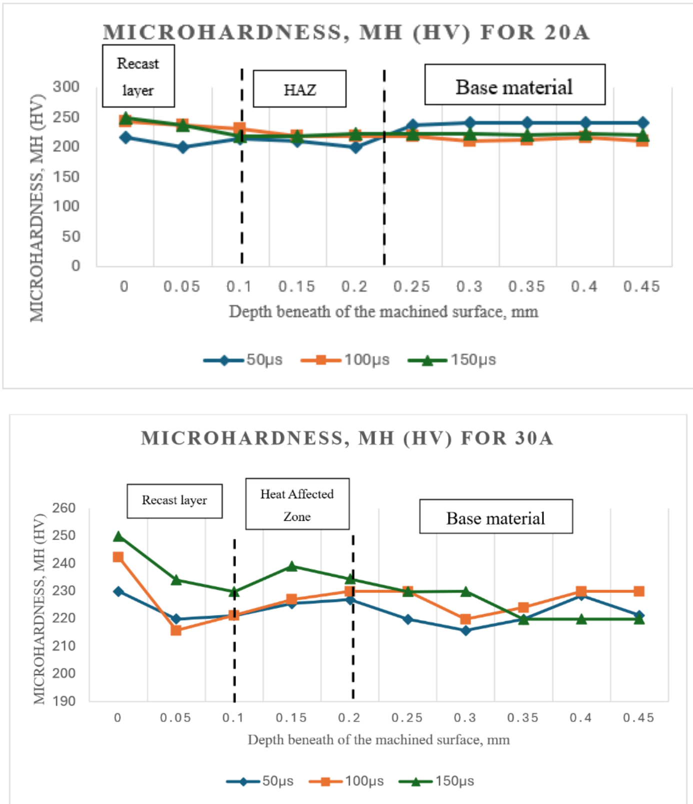
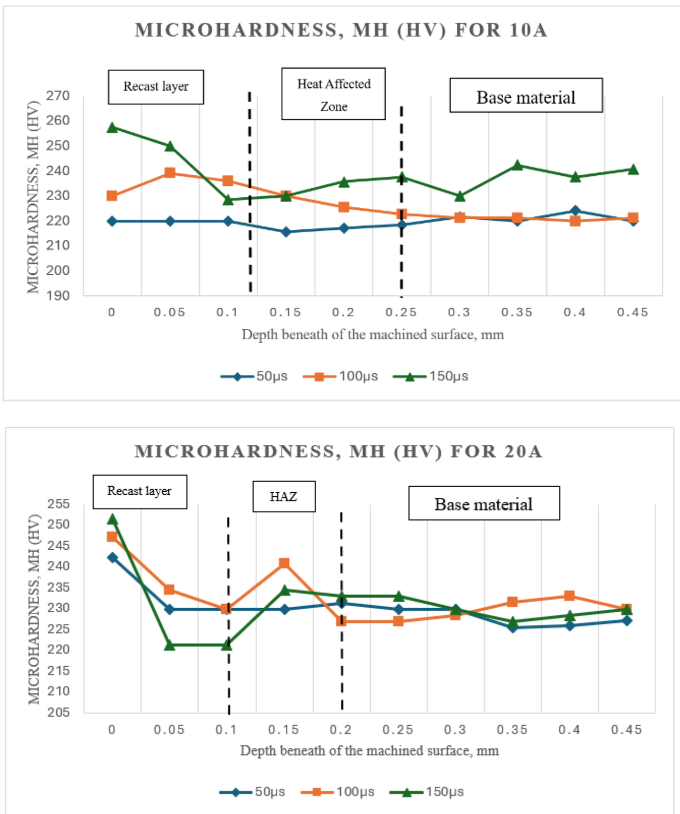


Fig 17: *Result of Microhardness for Kerosene with nano alumina, Al_2O_3 Based Dielectric Fluid with Different Pulse Duration, Ton*



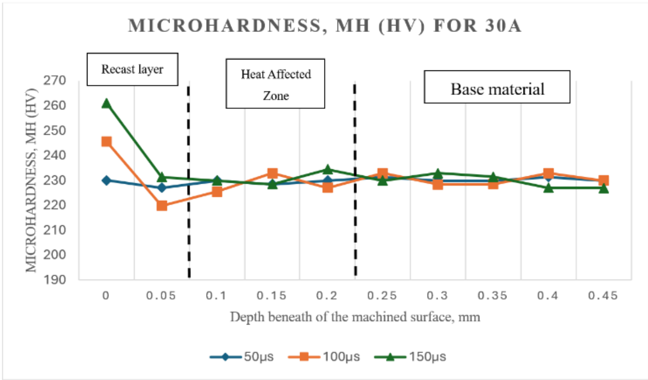


Fig 18: *Result of Microhardness for RBD palm oil Based Dielectric Fluid with Different Pulse Duration, Ton*

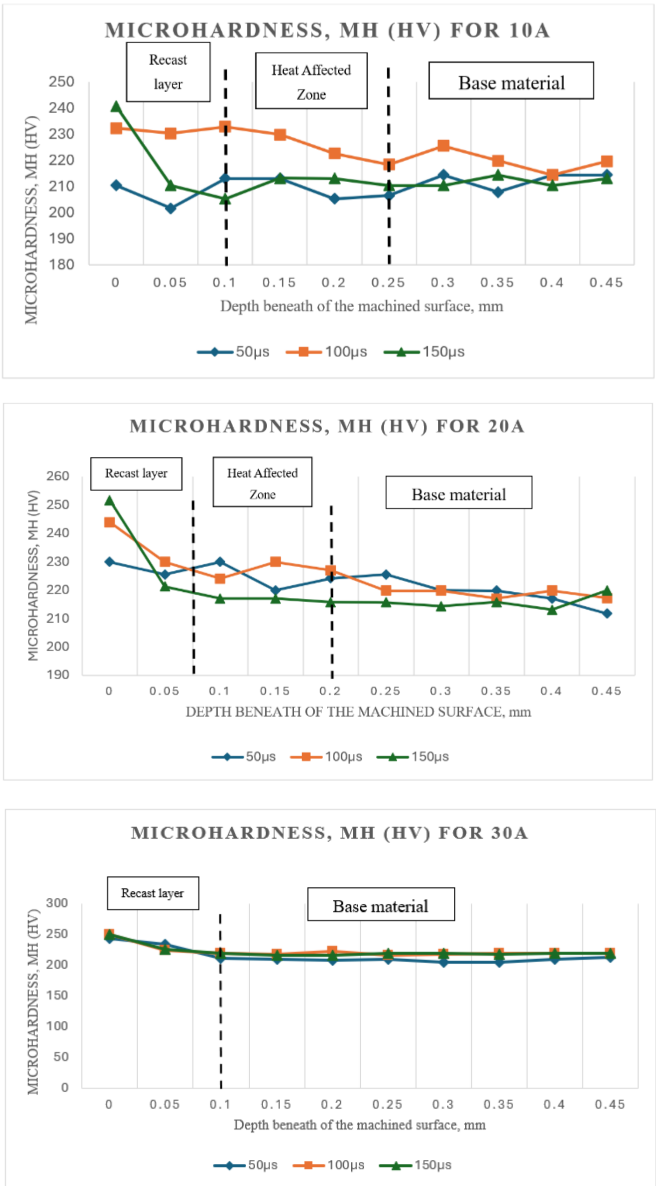


Fig 19: *Result of Microhardness for RBD palm oil with nano alumina, Al_2O_3 Based Dielectric Fluid with Different Pulse Duration, Ton*

The Vickers hardness test was carried out with a stress of 980.7 mN for 10 seconds with ten indentations spaced 0.05 mm apart, in accordance with the microhardness data shown in your seminar paper. With increasing pulse durations, the microhardness of the kerosene-based dielectric fluid increased steadily, maintaining a comparatively modest profile under all test circumstances. In contrast, kerosene combined with nano alumina powder produced better outcomes. Due to improved heat management and spark energy dispersion, the use of alumina increased the microhardness close to the surface, producing a denser and more refined recast layer. This implies a surface that has been toughened and is better suited to endure operational stress.

However, because of its increased viscosity and worse thermal conductivity, RBD palm oil showed somewhat lower microhardness values while being more environmentally friendly. However, RBD palm oil's microhardness greatly increased and, in some instances, exceeded that of pure kerosene when nano alumina powder was added. This suggests that the combination of nanopowder with biodegradable fluid not only improves sustainability but also yields surface qualities that are technically competitive. Moderate peak current and pulse duration settings were associated with the highest microhardness readings for this group, indicating ideal discharge energy management in powder-mixed conditions.

4. Conclusion

The potential of RBD palm oil and its powdered form as sustainable dielectric substitutes in EDM is demonstrated by this work. Variants made of palm oil produce thinner recast layers and superior microhardness, but kerosene preserves the best surface quality. PMEDM offers the best possible balance between environmental friendliness and performance. The findings also demonstrate how PMEDM with RBD palm oil enhances the dielectric medium's thermal characteristics while guaranteeing more consistent material removal, which enhances surface morphology. Because palm oil is a renewable and biodegradable resource, it considerably lessens the ecological impact of EDM operations in terms of environmental sustainability.

Additionally, the thinner recast layer seen with PMEDM suggests improved surface integrity, which is crucial for applications requiring accuracy and fatigue resistance. Better wear resistance is another benefit of increased microhardness, which prolongs the useful life of machined parts. Thus, using RBD palm oil that has been powder-mixed has both technical and environmental benefits. To maximize EDM performance, this study lays the groundwork for future investigations into mixing other kinds of powders with bio-based oils. To increase the range of applications for sustainable EDM technologies, further research on wear rate, thermal damage, and thorough energy efficiency evaluations is also advised.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: study conception and design: Author 1, Author 2; data collection: Author 1; analysis and interpretation of results: Author 1, Author 2; draft manuscript preparation: Author 1, Author 2. All authors reviewed the results and approved the final version of the manuscript.

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