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The Investigation of Material Removal Rate on Electrical Discharge Machining of Titanium Alloys (Ti-6Al-4V) at Different Peak Currents and Pulse Durations by using RBD Palm Oil and Kerosene as Dielectric Fluids

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ABSTRACT

The type of dielectric fluid is the most significant component that might affect the machining performance of EDM such as material removal, tool wear, and electrode surface roughness. However, the most serious of these issues is the inability to comply with health and environmental rules when the conventional dielectric was harmful to the surrounding ecosystem. One approach to ensure the long-term sustainability of EDM is to use vegetable oil as the dielectric fluid as it is environmentally friendly and biodegradable. To satisfy industrial objectives, the machining industry must ensure that the maximum material removal rate (MRR) can be achieved. This paper investigated the effect of kerosene and refined, bleached, and deodorised (RBD) palm oil as dielectric fluids with different peak currents (6, 9, and 12A) and pulse duration (50, 100 and 150µs) settings on MRR of Titanium alloy. Kerosene was used as a benchmark to compare the performance of the EDM process. The implementation of RBD palm oil recorded the lowest MRR at the lowest peak current of 6A with the lowest pulse duration of 50µs, which is 1.1260mm^3/min. In contrast, the highest MRR with a value of 12.1323mm^3/min was recorded at the highest peak current of 12A with a pulse duration of 150µs. Overall, RBD palm oil shows an excellent MRR performance for substituting hydrocarbon or mineral oil as a dielectric fluid in EDM applications, improving cost, time, and production efficiency.

1. Introduction

Industrial technology development has led to the implementation of a wide range of superior materials. These materials have high mechanical properties such as higher toughness, strength, hardness, and melting point by having good mechanical properties and thermal characteristics, as well as sufficient electrical conductivity so that they can readily be machined by spark erosion [1,2]. The machining process allows these excellent materials to be handled to meet a variety of

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requirements. However, to process these superior materials using current manufacturing methods becomes difficult. Therefore, alternative manufacturing techniques such as electrical discharge machining (EDM) must be implemented [3,4]. EDM has been replacing drilling, grinding, milling and other traditional machining operations and is now a well-established machining option in many manufacturing industries around the world [5,6].

EDM is commonly used to process difficult materials and alloys that are resistant to high strength temperatures but are difficult to process using existing approaches. Many researchers have investigated with different machining parameters and analyzed the results. Material removal rate (MRR) is the process of transforming material elements between the work piece and the electrode [6]. Material removal as a result of such a localized extreme when temperature rise. The molten is not completely removed, but only a part of it is. The plasma channel is no longer sustained as the potential difference is reduced. As the plasma channel collapses, pressure or shock waves are generated, causing the molten material to be evacuated, leaving a crater of removed material around the spark location [6,7]. Furthermore, the conversion of electrical energy into heat energy is the mechanism of material removal in the most extensively used EDM technique. The mechanism of material removal rate (MRR) is shown in Figure 1.

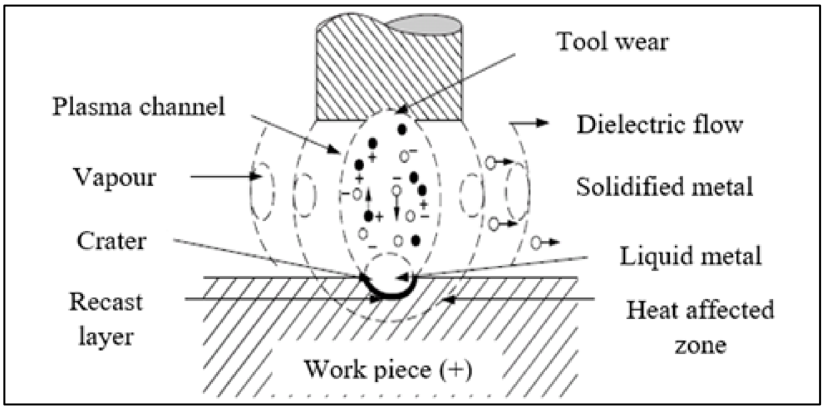


Fig. 1. Mechanism of material removal rate [6]

The peak current, which is measured in amperage, is the most important machining parameter in EDM. In EDM, it refers to the amount of power used. The current increases during each pulse on-time until it reaches a current level, which is expressed as the peak current [8-10]. All of these parameters are even more important in EDM since the machined cavity is a mirror image of the tool electrode, and excessive wear will reduce machining precision [9-12]. Pulse on-time is a term used to describe how long a pulse lasts (time during the discharge phase). More work piece material will be melted away with longer pulse duration. The crater formed will be wider and deeper than one formed by a shorter pulse duration. Extreme pulse duration, on the other hand, can be harmful. Material removal rate begins to decline as the optimum pulse duration for each tool and work piece material combination is exceeded. In this case, increasing the period leads the electrode to grow even more due to plating build-up [12,13].

Electrodes can be categories into two groups which are metallic and graphite. Copper, zinc, tungsten, graphite, and brass are some of the electrode materials often utilized in electro discharge machining [11-14]. Copper electrode is one of the metallic electrodes that can provide a superior outcome in terms of fine surface quality when used in traditional EDM technology. For example, despite its greater melting point, copper is suggested for EDM due to the higher frequencies required. Copper also has a notable edge over graphite when it comes to discharge-dressing performance. In addition, the copper electrode can be reused for a final cut or to make a new part [15,16].

Material is removed in electrical discharge machining (EDM) by a series of electrical discharges between an electrode and a work piece in the presence of a dielectric liquid or gas. The selection of dielectric fluid is a main consideration for EDM performance because dielectric fluid plays such an important part in every electrical discharge machining operation [15-18]. It performs a variety of activities in addition to transporting condensed metal particles from the spark gap region, all of which have a significant impact on the process's effectiveness. EDM dielectric fluid serves two main purposes. First, it works as a semiconductor between the electrode and the work piece, allowing for a more stable and controlled spark gap ionization. It also serves as a flushing agent, washing and removing eroded material from the spark gap area.

Palm oil is economical, easy to use, widely available, and has a higher sustainability impact rating than conventional palm oil. It also has the advantage of being reusable and not causing harm to the environment or human health when in use [17-21]. Because of its biodegradability and lack of pollutants, RBD palm oil has been found to improve the machining process and is clearly the greatest option for kerosene [18,19,22-24]. To increase the sustainability of the electric discharge machining (EDM) process, Valaki *et al.,* [25] carried out an experiment to examine the technical viability of a recently developed Jatropha curcas oil-based bio dielectric (Jatropha BD) fluid. The experiment's findings indicate that the use of bio-dielectric fluid derived from jatropha increased production rates, improved surface finishes, and raised surface hardness. Some of the primary findings of this study include the following: under the effect of process variables such as current, gap voltage, pulse duration, and pulse interval, Jatropha BD produced 38%, 26%, 28%, and 15% higher MRR than kerosene. Additional studies by Valaki and Rathod [26] examined the viability of EDM using recently suggested vegetable oil-based green dielectric fluids, waste vegetable oil (BD2) and jatropha oil (BD1). Research has been done on comparative analyses between BD1, BD2, and kerosene to evaluate the performance in terms of material removal rate (MRR). To investigate the viability of the newly proposed fluids, an experimental plan has been designed using a one variable at a time approach, with the input parameters being current, gap voltage, pulse on-time, and pulse off-time. The outcomes demonstrate that the newly recommended bio dielectrics, BD1 and BD2, perform better for MRR than kerosene dielectrics that are sold commercially. In an experiment, Harlal and Kumar [19] compared the usage of blended used vegetable oil (BUVO), waste vegetable oil (WVO) from Pongamia Pinmata, and conventional hydrocarbon oil (CHO) made from leftover edible vegetable oil in the EDM of Inconel 718. WVO has a 32% greater MRR than CHO, which translates to a cheaper production cost because more material is removed in each amount of time. In contrast, BUVO has a 10% lower MRR, which raises production costs.

In addition, engineers are under constant pressure to create intricate shapes with ever-tinier tolerances for a wide range of industrial applications. This demand is compounded by the continuous introduction of new materials. This makes the machining of exotic materials, such as titanium, extremely important. The most widely used of the several titanium alloys is the grade 5 Ti-6Al-4V $\alpha + \beta$ type two-phase titanium alloy. Titanium is known for its great strength, low weight-to-strength ratio, high-temperature resistance, high corrosion resistance, and high toughness. Therefore, this material is used in power production, chemical plants, pressure vessels, aircraft, and automobiles [27–29]. However, processing titanium and its alloys can be difficult because of several of the material's inherent properties. Almost every material used to make cutting tools interacts with it chemically. Because of its low elastic modulus and low thermal characteristics, it is less machinable [30,31].

To improve EDM efficiency, it is a good idea to use the appropriate dielectric fluid during the process. Based on an investigation of the material removal rate in the EDM machining process by using dielectric fluids, palm oil fluid has a good potential to achieve environmental friendliness and sustainability in the manufacturing process. Therefore, the effect of RBD palm oil-based dielectric fluids and kerosene on the material removal rate and surface topography of Titanium alloy is investigated in this study. Furthermore, a lack of research has been found related to studying the potential of RBD palm oil as a dielectric fluid in the EDM process. Thus, it is indispensable to improve the way of machining approach towards higher productivity by applying RBD Palm oil-based dielectric in sustainable EDM machining. Then, by exploring the application of palm oil as a metalworking fluid in machining, it can be a value-added to the palm oil industry itself.

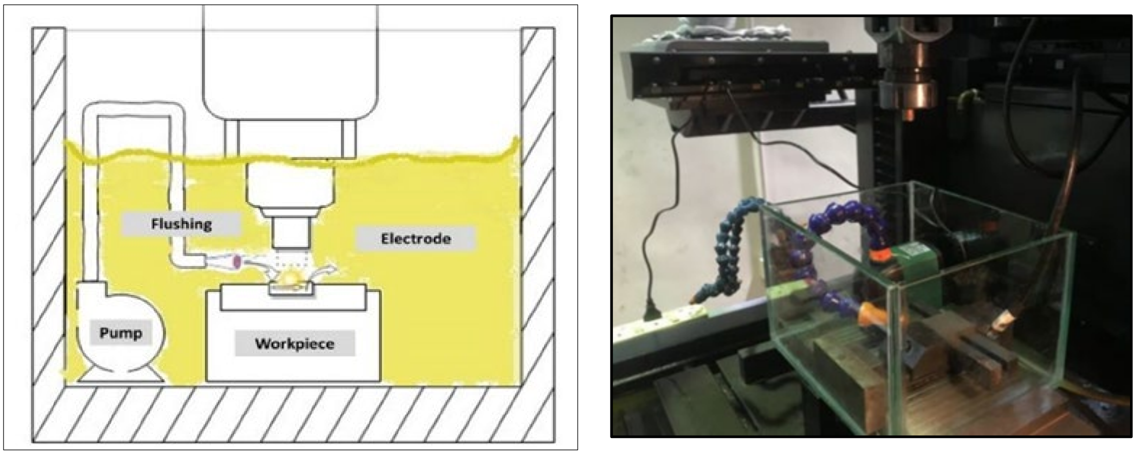
2. Methodology

2.1 Experiment Setup

The experiment was conducted by using Computer Numerical Control (CNC) in 3 Axis linear, Sodick high speed EDM die sink AQ55L by using two types of dielectric fluids. The properties of the dielectric fluid used are shown in Table 1. As shown in Figure 2, the experiment was carried out in a custom-made glass tank of 25x20x15cm when using RBD palm oil fluid.

Table 1
The properties of the dielectric fluids [23]

Properties	Kerosene	RBD Palm Oil
Density, kg/cm3	730	870
Viscosity at 40°C, cSt	5.42	40.27
Breakdown voltage (KV)	6.4-11.4	51-64
Thermal conductivity, W/mK	0.13	0.16
Specific heat, KJ/KgK	2.01	1.87
Flash point, °C	65	154



(a) (b)

Fig. 2. The custom-made glass tank of the machine is set up in (a) Schematic diagram (b) Actual diagram

Titanium alloy (Ti-6Al-4V) grade 5, with a dimension of 40x30x6mm and chemical composition, as shown in Table 2, is used as a workpiece to conduct these experiments. As it has a high compressive strength and is wear-resistant, it is an alloy with a high penetrating hardness and excellent dimensional stability and shape. The EDM experiments were carried out using a commercial electrode constructed of 99.58% pure copper with dimensions of 10x30mm and a dimensional tolerance of ±0.02mm. Copper electrodes have been widely used as electrodes in EDM processes due to their high thermal conductivity. The chemical composition of copper electrodes is shown in Table

3, and Table 4 shows the experimental condition and parameter setting to investigate the material removal rate by using different dielectric fluids.

Table 2
Chemical composition of titanium alloy (Ti-6Al-4V) in mass fraction (wt.%)

Ti	Al	V	Fe	O	C	Others
89.47	6.08	4.02	0.22	0.18	0.02	0.01

Table 3
Chemical composition of copper electrode in mass fraction (wt.%)

Cu	Al	S	P	Zn	Ni	Pb	C	Others
99.58	0.006	0.035	0.052	0.25	0.023	0.02	0.028	0.006

Table 4
Experimental condition and parameter settings of the machining process [23]

Parameters	Levels
Dielectric fluids	Kerosene, RBD palm oil
Workpiece material	Copper (Cu)
Electrode tool	Titanium alloy (Ti-6Al-4V) Grade 5
Peak current (A)	6, 9, 12
Pulse duration (µs)	50, 100, 150
Voltage (V)	120
Depth of cut (mm)	1

2.2 Responses

This study was focused on material removal rate (MRR) by using different dielectric fluids; kerosene and RBD palm oil. The calculation of MRR with the unit mm^3/min is based on the volumes (V) of workpiece losses per time (t) period of machining. The workpiece was dried after each machining procedure was done and before the weight measurement was performed to ensure there was no debris or dielectric on the workpiece. The following equation is used to determine the MRR:

$$MRR = \frac{m_v}{\rho_w t_m} \tag{1}$$

where m_v is the mass of the workpiece, ρ_w is the density of the workpiece, and t_m is the machining time, respectively. The analysis continues with the use of a Scanning Electron Microscope (SEM) to analyse the surface topography.

3. Results

Material Removal Rate (MRR) is defined as the weight of material removed per unit time and is an important process economic parameter. A higher MRR is ideal for more cost-effective manufacturing. The obtained results assist in improving the efficiency of EDM operations, and many factors must be considered. The amount of material that can be removed in a given time is the most important factor in increasing processing speed. The MRR was measured under the control parameters of peak current at 6, 9, and 12A at different pulse durations for two types of dielectric fluids as shown in Figure 3.

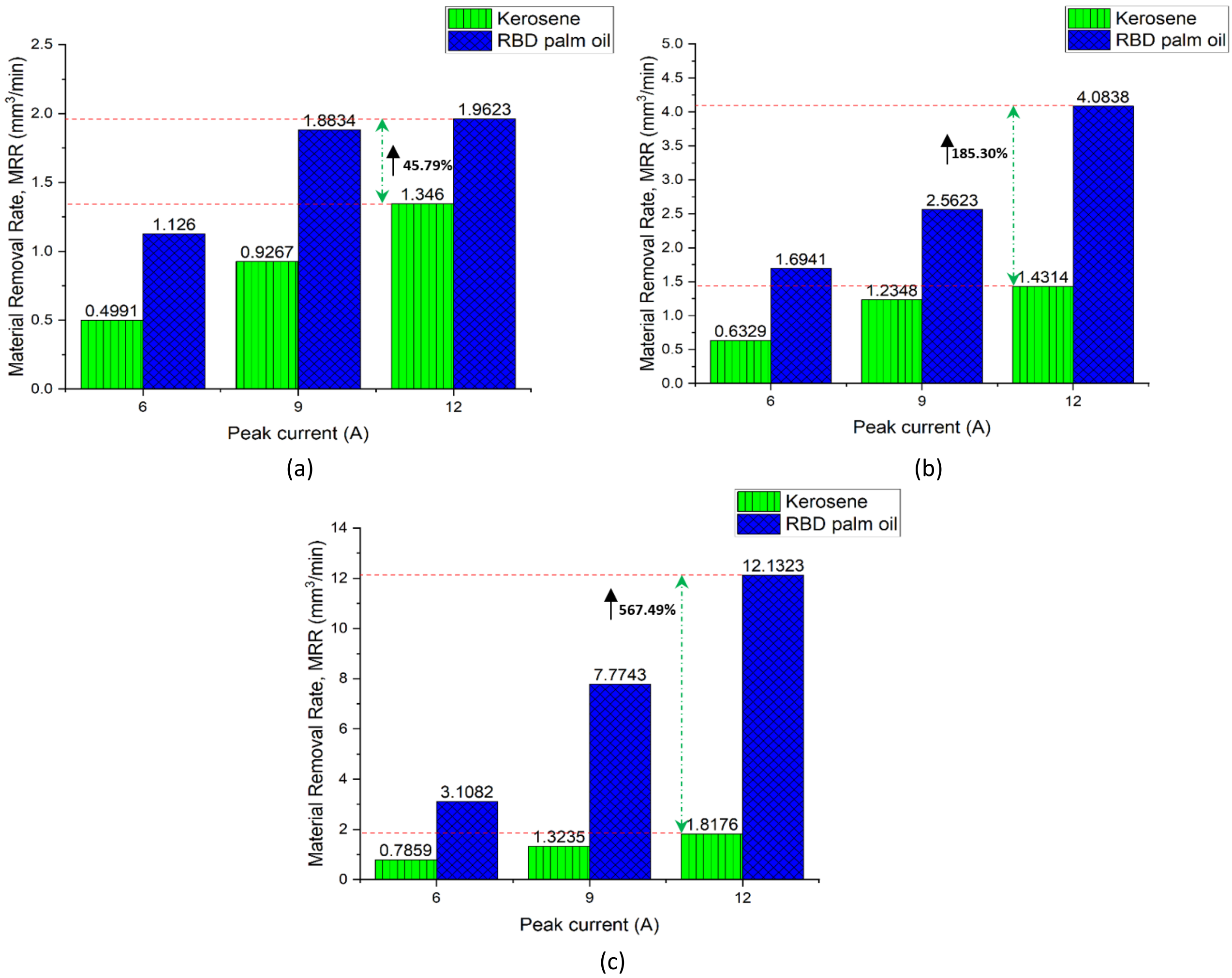


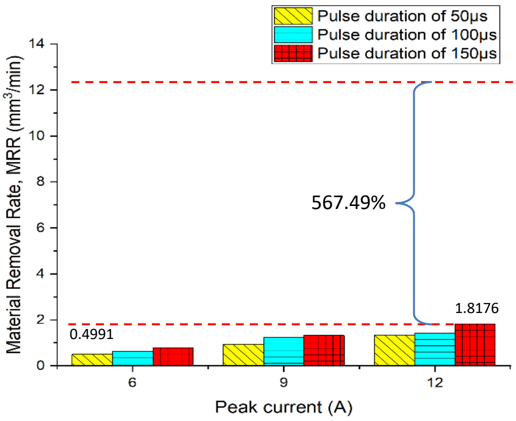
Fig. 3. MRR of kerosene and RBD palm oil at a different pulse duration of (a) Pulse duration of 50µs (b) Pulse duration of 100µs (c) Pulse duration of 150µs

The comparative response of MRR shows that the use of RBD palm oil as dielectric fluid has a better result compared to conventional fluid, kerosene. The higher the peak current (I_p), the higher the MRR results. At a pulse duration of 50µs, the highest MRR was shown at 12A of peak current and the peak current of 6A shows the lowest MRR for both kerosene and RBD palm oil, as shown in Figure 3(a). The MRR recorded the lowest kerosene used at 0.4991mm^3/min compared to 1.1260mm^3/min of RBD palm oil at 6A of peak current setup. The highest MRR was recorded at 1.3460mm^3/min for kerosene, while the MRR of RBD palm oil increased up to 1.9623mm^3/min. The efficiency of EDM operations was increased up to 45.79%.

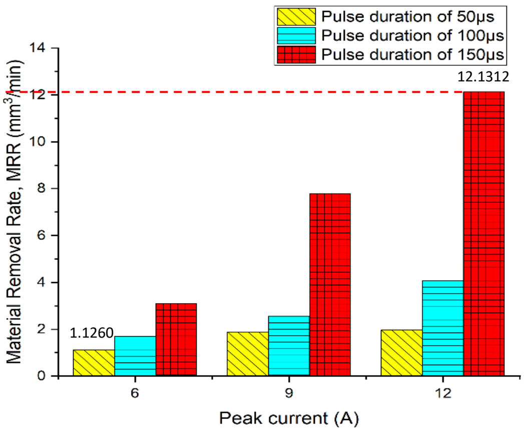
The trends of MRR at a pulse duration of 100µs of RBD palm oil also show the improvement of EDM operations at 185.30% compared to kerosene at higher peak current, as shown in Figure 3(b). The highest MRR by using kerosene was recorded at 1.4314mm^3/min, while the improvement of EDM operations by using RBD palm oil fluid was recorded at 4.0838mm^3/min. The increase of pulse duration from 50µs to 100µs showed a better performance of EDM operations by using RBD palm oil as dielectric fluids. RBD palm oil outperformed kerosene in terms of material removal rate investigation. The amount of energy released during sparking increases proportionally, with higher temperatures melting and removing more materials from the workpiece, as stated in previous work [23,24,31,32]. As a result, it was able to generate more sparks, resulting in an increase in MRR results.

The parameter setting of pulse duration at 150µs is shown in Figure 3(c). The lowest MRR was shown at 6A of peak current with results of 0.7859mm^3/min for kerosene and 3.1082mm3/min for RBD palm oil. The increment of efficiency for EDM operations was up to 295.49%, which is better than using a lower pulse duration, 100µs at a high peak current, 12A for RBD palm oil. The most important factor in increasing machining speed is the amount of material volume that can be extracted per time taken. However, the comparison of MRR showed that the highest peak current at 12A has increased the MRR up to 567.49% when using RBD palm oil with 12.1323mm^3/min compared to kerosene at 1.8176mm^3/min.

Figure 4 shows the effect of peak current, I_p and pulse duration, t_{on} on MRR for kerosene and RBD palm oil. It was observed that the MRR increased as the I_p and t_{on} increased for both dielectric fluids; kerosene and RBD palm oil. RBD palm oil was discovered to be more effective than kerosene. RBD palm oil provides better confinement due to its density and viscosity, resulting in a higher MRR value [19]. The highest and lowest MRR for both dielectrics were found at I_p=12A, t_{on}=150µs and I_p=6A, t_{on}=50µs, respectively. The results showed that the highest and lowest MRR for RBD palm oil was 12.1323mm^3/min and 1.1260mm^3/min, while for kerosene was 1.8176mm^3/min and 0.4991 mm^3/min. In terms of MRR, RBD palm oil performed better than kerosene. As supported by previous research [19], the density and viscosity of the dielectric fluid may affect the MRR. RBD palm oil had a higher viscosity and flash point than kerosene, resulting in more sparking [33-37]. At the same parameter settings of I_p=12A and t_{on}=150µs, the improvement was approximately 567.49%.



(a)

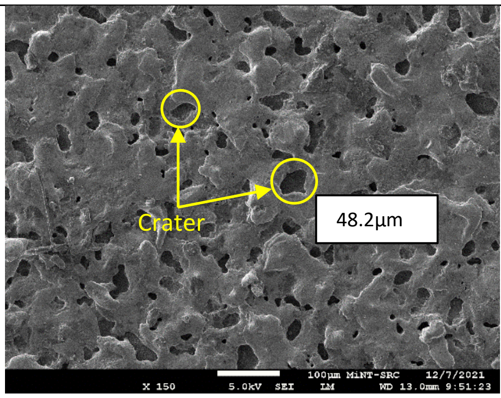
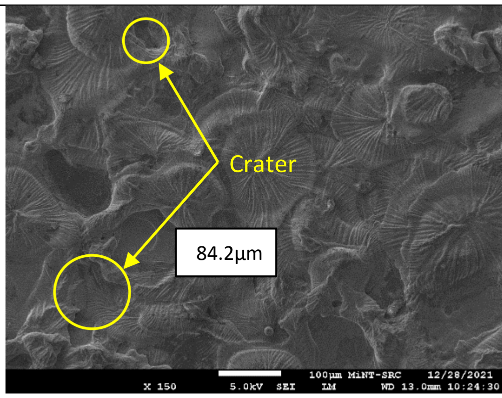
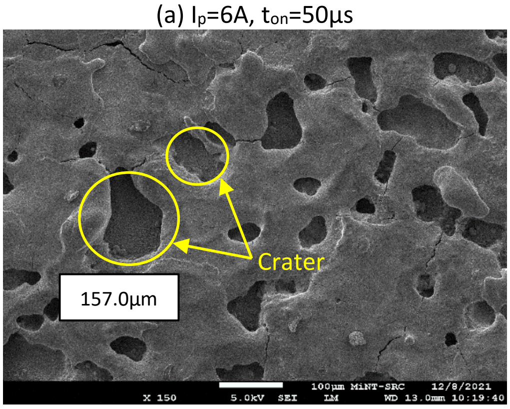
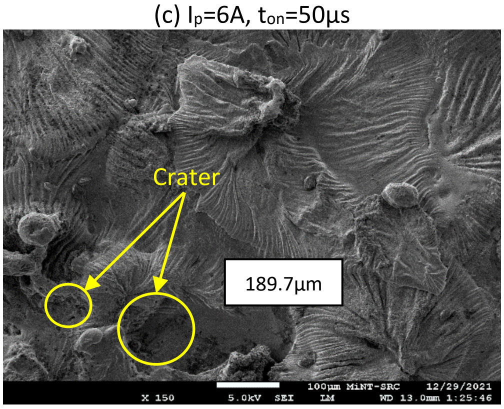


(b)

Fig. 4. The Effect of Peak Current, Ip and Pulse Duration, t_{on} on MRR for (a) Kerosene (b) RBD Palm Oil

Table 5 illustrates the comparison of surface topography of kerosene and RBD palm oil. A high peak current, I_p, improved the MRR but influenced the surface topography after the machining process. During the EDM process, when the setting parameter of high peak current in every spark caused the material to melt and evaporate, leaving a crater on the machined surfaces as stated in a previous study [24]. Table 5(a) shows that at lower MRR for kerosene, I_p=6A and t_{on}=50µs, the conditions of craters are shallow and flattened, whereas, at higher MRR, I_p=12A and t_{on}=150µs, the large crater is formed, as shown in Table 5(b). Higher peak current and pulse duration may enhance the cutting speed, but its effect on the surface finish is inversely proportional. Table 5(c) shows the effect of RBD palm oil on the surface topography, at lower MRR, I_p=6A and t_{on}=50µs, and as a result, the surface looks rougher than kerosene dielectric, and at high MRR, I_p=12A and t_{on}=150µs in Figure 5(d), it is shown that the surface looks rough and bigger compared to the kerosene at high MRR. This was because of the viscosity of the palm oil, which helped in gaining higher sparking intensity during the machining, thus deteriorating the machined surface, as supported by a previous work [19,38].

Table 5
The comparison of surface topography for kerosene and RBD palm oil at low and high MRR

Dielectric Fluids	Kerosene	RBD Palm Oil
Low MRR	 (a) I_p=6A, t_{on}=50µs	 (c) I_p=6A, t_{on}=50µs
High MRR	 (b) I_p=12A, t_{on}=150µs	 (d) Ip=12A, t_{on}=150µs

4. Conclusions

The overall objective of improving EDM performance by employing biodegradable oil as a dielectric fluid was achieved effectively. The conclusions drawn from the present study are as follows. The most important factors contributing to higher material removal rates are peak current and pulse durations in EDM operations. As the peak current and pulse duration increase, the material removal rate also increases. The highest peak current at different pulse durations shows good performance in the material removal rate of Titanium alloy when using RBD palm oil dielectric fluid. Within selected parameters, the difference in MRR when using RBD palm oil dielectric is 567.49% in comparison with kerosene, which shows a significant improvement in machinability. The results also show that palm oil has a high potential to be applied as a dielectric fluid. The use of palm oil as dielectric fluids increases the machining speed compared to kerosene. The efficiency of EDM operations has increased, thus shortening the machining process. However, further fundamental research is required to prove the effect of RBD palm oil viscosity on the EDM machining performance by altering the properties of the palm oil.

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