Assessment of Bio-dielectric *Calophyllum inophyllum* (Polanga) Oil in Electro-discharge Machining: A Step Toward Sustainable Machining

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1 Introduction

The electro-discharge machining (EDM) process is a non-conventional machining process in which electrically conductive material is machined. The mechanism of material removal in EDM is due to the electron bombardment on the workpiece in repeated intervals. In this process, material is machined in the form of tiny debris. This process is mainly used to manufacture forging dies, press tool and molds for injection molding. It is also employed for producing intricate and irregular shaped profiles. Small holes on carbide and hardened steel can be machined by EDM. There are different varieties of EDM processes such as die shrink EDM, micro-EDM and wire EDM [1]. The hydrocarbon-based oils are generally used for the die shrink EDM, but in wire EDM and micro-EDM deionized water is used. These dielectric fluids work as a medium in which controlled electrical discharge occurred. It also helps to carry away debris and heat generated by the discharge. The dielectric fluid significantly affects the productivity, quality and cost of the machining and when hydrocarbon-based dielectric fluid is used health hazards and environmental impact becomes two other important aspects for selecting the dielectric fluid [2].

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The manufacturing industries have been considered as one of the main sources of environmental hazards [3]. The minimization of environmental hazards is the prime focus after implementation of the ISO 14000 environmental management system standard. The main requirements of ISO 14000 standard are identifying the source of pollution in the manufacturing industries. Hence, today's researchers are thinking about eco-friendly manufacturing, i.e., green manufacturing. In EDM process, hydrocarbon-based dielectric fluid is the main source of pollution. The complete replacement of the hydrocarbon-based dielectric fluid has not yet been developed. Zia et al. [4] reported that the environmental concern is due to the emission from and disposal of the hydrocarbon dielectric. However, the main health concern is connected to fire explosion, inhalation of fume and contamination of dielectric on the skin. Kou and Han [5] experimentally investigated the EDM of Ti–6Al–4V using water-based dielectric for their study and reported that the environmental pollution can be minimized by using water-based dielectric. The environmental pollution and health hazards can also be minimized by using vegetable oil as a dielectric fluid. Higher operational safety due to low risk of vegetable-based dielectric catching fire makes it as safer fluids to use. The hydrocarbon-based dielectric like kerosene has higher emission of pollutant into atmosphere making it less environment friendly, but vegetable oil emits less pollutant and hence environment friendly. As discussed, vegetable oil is environment friendly, so they provide better personnel health. The vegetable oils have low manufacturing cost and also have higher breakdown voltage, hence more efficient than conventional oils. Valaki et al. [6] reported the practical viability of jatropha curcas oil-based bio-dielectric for EDM. They suggested that the jatropha curcas oil can be used as an alternative to hydrocarbon-based bio-dielectric. Das et al. [7] experimentally investigated the technical feasibility of jatropha, canola and neem oil as the bio-dielectric and reported that all the bio-dielectrics ensure better MRR and better surface finish. However, jatropha and canola are remarkable. Mishra and Routara [8] have conducted EDM of EN 24. They used polanga bio-dielectric (PBD) and hydrocarbon-based dielectric for their study and reported that the performance of PBD is remarkable in terms of MRR and eco-friendly aspect. Das et al. [9] experimentally studied efficacy of neem oil as a dielectric with EDM of Ti–6Al–4 V. They reported an improvement in material removal rate by 22 % with neem oil as the dielectric. The better surface integrity is also achieved in neem dielectric environment.

Though works have been reported on PBD as dielectric, more investigation is needed to establish PBD as a bio-dielectric. In this study, EDM of P20 steel is examined using PBD and kerosene as dielectric fluids.

2 Preparation of Bio-dielectric

The PBD has been chosen as the bio-dielectric fluid to study the EDM process. Since the dielectric fluids have different properties, their operating efficiency differs from each other. The raw polanga oil might get pre-breakdown during EDM process as it has high viscosity. So, to make the polanga oil suitable for the dielectric fluid, multiple refining stages have been followed to decrease the viscosity and achieve other desirable properties (Fig. 1). In general, three stages have been used to minimize the viscosity of the raw polanga oil. These steps are degumming and esterification which is followed by transesterification. After transesterification water washing, heating and steering have been conducted to convert it to the desired dielectric fluid. The characterization of the dielectric was done based on the ASTM standard. The raw polanga oil and the processed polanga oil, i.e., PBD are shown in Fig. 2. The different fluid properties, viz. viscosity, thermal conductivity, specific heat, etc., have been recorded for this study.

3 Experimental Methods

The experiments have been performed by using a CNC electric discharge machine classified as (die-sinking type) MIC 432CS (Make: ECOWIN, Taiwan) machine whose polarization on the electrode is considered as negative and the workpiece as positive. The schematic diagram of the setup is shown in Fig. 3. The process parameters used for the experiments are given in Table 1. Two types of dielectrics, viz. kerosene and PBD are used to perform the experiments. Different properties of

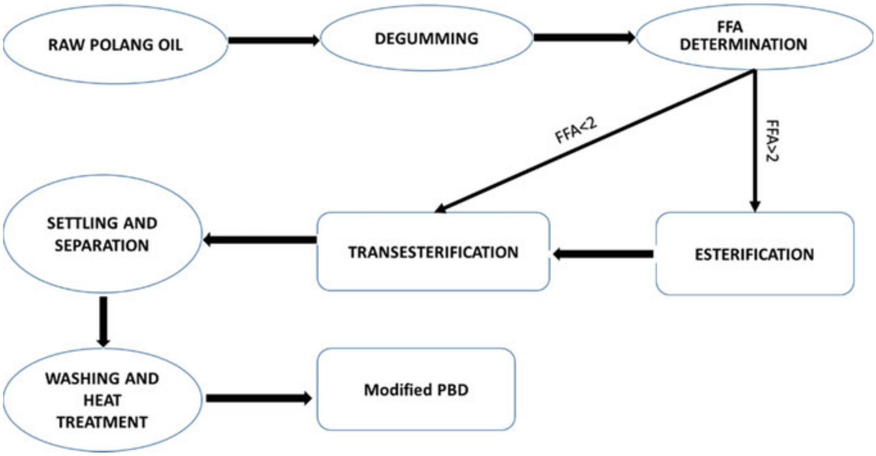

Fig. 1 Various purifying process used to produce suitable dielectric from raw polanga oil (FFA stands for free fatty acid test)

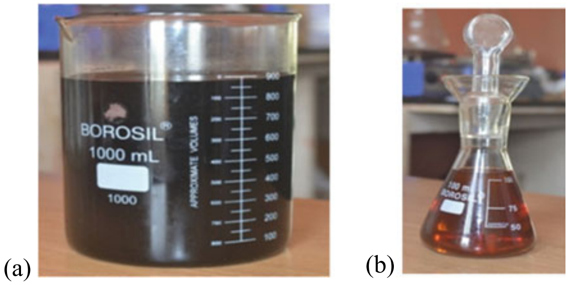

Fig. 2 **a** Raw polanga oil and **b** processed polanga oil

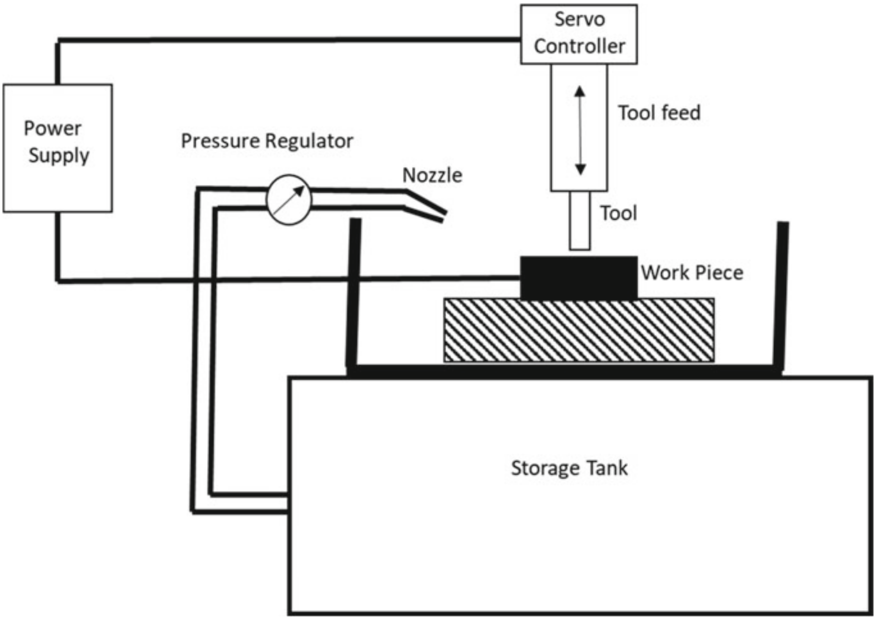

Fig. 3 Line diagram of the experimental setup

these two dielectrics are given in Table 2. The material removal rate (MRR) and surface roughness (R_a) have been recorded to analyze the efficacy of the PBD. In this experiment, P20 plastic mold steel of size 220 mm × 203 mm × 15 mm has been used. The physical properties and chemical composition of the workpiece are presented in Tables 3 and 4, respectively. The workpieces before and after machining are shown in Fig. 4a, b, respectively. The 99% pure copper rod of 20 mm diameter (Fig. 5a) has been chosen to produce the tool of required dimension (60 mm length). Each piece underwent turning and facing operation in a lathe machine, till the required dimensions were obtained. A fresh tool (Fig. 5b) is used for each experiments.

Table 1 Experiment process parameters and their levels

Process parameters	Levels
Pulse current (A)	3, 6, 9, 12, 15, and 18
Pulse ON time (μs)	21, 50, 100, 200, 400, and 600
Pulse OFF/Interval time (μs)	6, 11, 20, 30, 40, and 75
Polarity	Positive (electrode +ve)

Table 2 Fluid properties of dielectrics kerosene and PBD

Properties	Kerosene [6]	Polanga bio-dielectric (PBD)
Density	0.80 g/ml	0.71 g/ml
Viscosity 40 °C	1.2199 cSt	14.5 cSt
Flash point	100–185 °F	421.8 °F
Thermal conductivity	0.145 W/mk	
Specific heat capacity	2.01 J/gk	
Break down voltage	60 kV/2.5 mm	80 kV/2.5 mm
Acid value	0.049 mg KOH	4.0–12 mg KOH
Dielectric strength	60 kV/2.5 mm	80 kV/2.5 mm
Color	Colorless	Greenish yellow

Table 3 Mechanical properties of P20 plastic mold steel [6]

Properties	Hardness (Brinell)	Hardness (Rockwell)	Tensile strength (MPa)	Yield strength (MPa)	Compressive strength (MPa)
Value	300	30	965–1030	827–862	862

Table 4 Chemical composition (wt%) of P20 plastic mold steel [6]

Carbon	0.28–0.40
Silicon	0.10–0.50
Manganese	0.20–0.80
Phosphorous	0.030 max
Sulfur	0.030 max
Chromium	1.40–2.00
Molybdenum	0.30–0.55

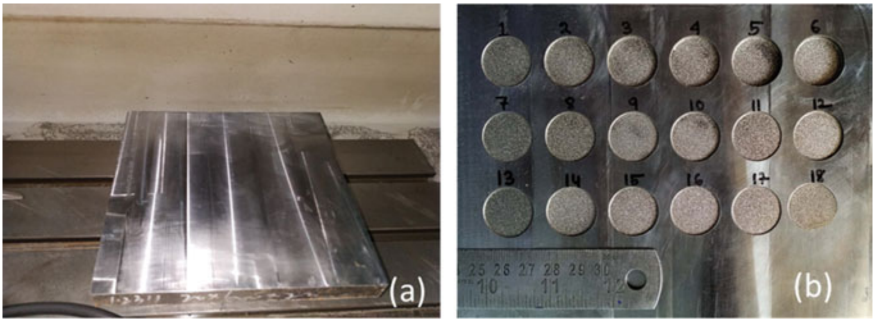

Fig. 4 **a** Workpiece before and **b** workpiece after electro-discharge machining

Fig. 5 **a** Raw copper rod and **b** copper electrode after machining

4 Result and Discussion

4.1 Material Removal Rate

The MRR can be defined as the total volume of material machined and divided by the time required for machining. The mathematical expression of MRR is

$$\mathrm{MRR} = \frac{W_\mathrm{B} - W_\mathrm{A}}{t_\mathrm{m}}$$

where W_B and W_A are the weight of the workpiece before and after machining, respectively, and t_m is the machining time.

Figure 6a illustrates the variation of MRR with peak current. For both the dielectrics, the MRR is increasing with increase in the peak current. The percentage of increment in MRR is 59.81–78.45% when PBD is used as the dielectric. This could be due to the higher average temperature generated at machining zone when PBD is used as a dielectric. The reason of higher average temperature in case of

PBD is due to high amount of oxygen content in PBD fluid [10, 11]. This causes vaporization and melting. Another reason for greater MRR in case of PBD is because of efficient flushing of debris from machining zone. The higher flushing ability of PBD is because of its high viscosity [10]. Figure 6b represents the influence of T_{on} time on MRR. Longer discharge energy cycle and higher discharge channel might be the reason of improvement of MRR with increase in T_{on}[12, 13]. Higher MRR is recorded when used PBD as compared with the kerosene. The percentage of improvements varies from 30 to 51%. This could be owing to greater thermal conductivity of PBD, which causes higher heat transformation toward the machining zone. Lower specific heat of PBD could be another reason for better MRR [11]. Figure 6c shows the influence of T_{off} on MRR. With increase in T_{off} time MRR decreases. Higher T_{off} time causes narrow plasma channels, which further minimizes the striking area of positive ions on workpiece surface. The percentage of improvement is varying from 6 to 40% when PBD is used as the dielectric. Lower specific heat and higher thermal conductivity of PBD are the reason behind it [14].

4.2 Surface Roughness

The surface finish reflects the nature of the machined surface. The tribological connection between the mating parts relies upon the surface finish of individual parts. Better surface finish boosts the service life of the mating parts. In this investigation, arithmetic average surface roughness (R_a) was recorded and presented in Fig. 7a–c. Each machined surface is measured twice, and average values have been recorded for analysis. A Taylor Hobson profilometer (0.8 mm cutoff length) has been used to record the arithmetic average roughness parameter. Figure 7a represents the variation of R_a with the current. The trend indicates that R_a increases with increase in the current. The higher current increases the impingement energy, resulting in deeper and uneven crater on the work surface. The R_a value recorded for the machined surface for machining with PBD as a dielectric is comparatively low (in comparison with machining with kerosene). The percentage of decrement varies between 0.04 and 17.79%. The lower R_a when PBD is used might be because of the good thermal property and lower specific heat of the dielectric, which might have limited the energy density. The efficient heat transfer to the environment, i.e., dielectric media produces shallower cavities. Figure 7b illustrates the variation of R_a with T_{on}. More sparking time drags out vaporization and melting, resulting in an increase in R_a as more profound and extensive cavities. The lower R_a obtained with PBD as a dielectric might be because of the greater thermal conductivity, which ensures improved heat distribution on the workpiece surface. In addition, increased dielectric temperature as an effect of lower specific heat of PBD minimizes the viscosity which enhances the flushing effectiveness. Figure 7c indicates the impact of T_{off} time on R_a. It is clearly seen that T_{off} has marginal effect on R_a. Higher T_{off} ensures maximum gap condition for ensuing

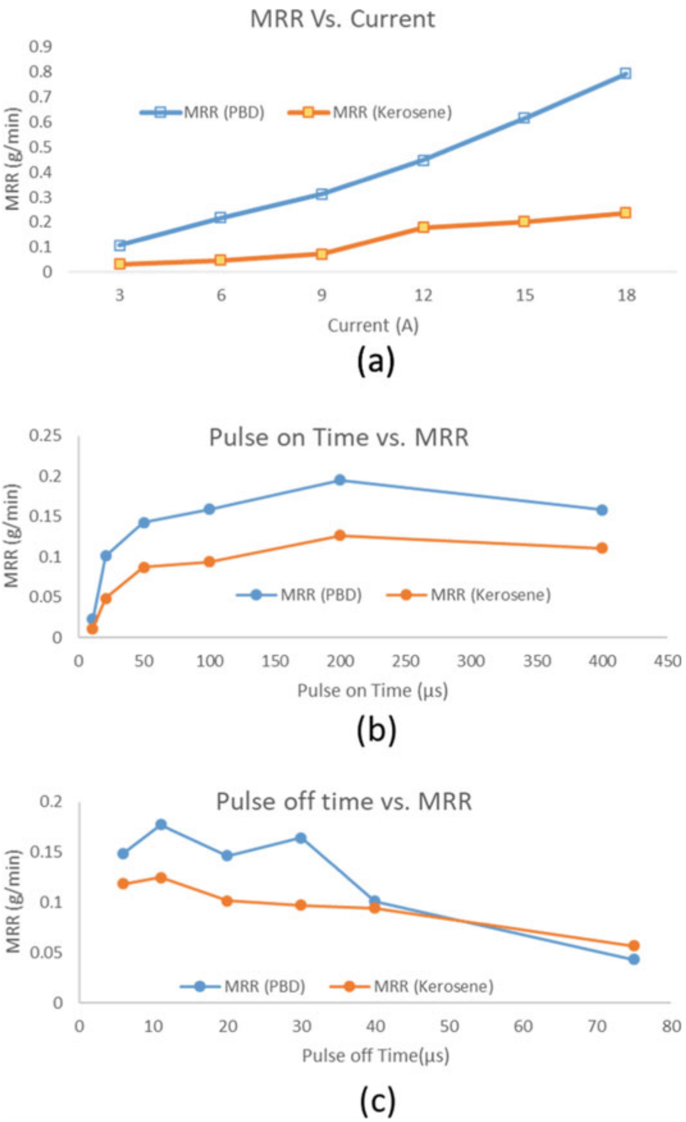

Fig. 6 Variation of material removal rate with **a** current, **b** pulse ON time and **c** pulse OFF time

starting cycles by permitting re-ionization of the ionized gap. Also, smaller and narrower cavities are shaped because of reduced sparking time to diminish R_a. Marginally, lower R_a values recorded with PBD might be because of the good thermal property which could have resulted in well distribution of energy density on the workpiece surface [7].

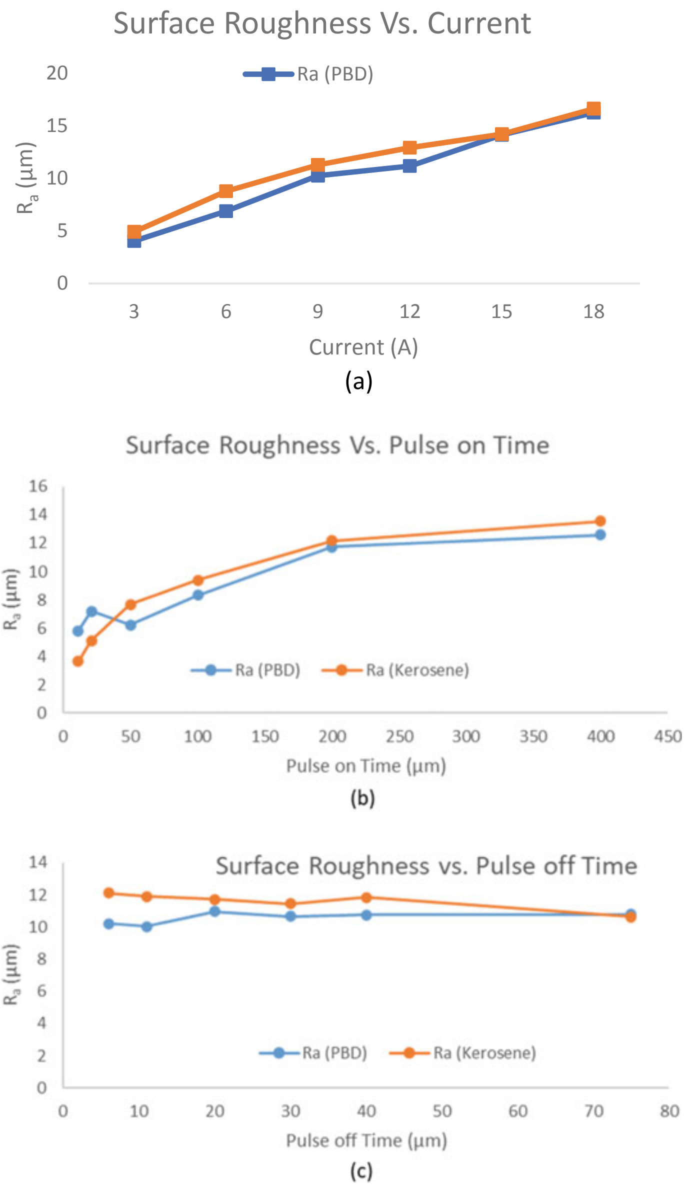

Fig. 7 Variation of surface roughness with **a** current, **b** pulse ON time and **c** pulse OFF time

5 Summary

The above reported experimental study can be outlined as follows:

- Experimentations were conducted, with primary objective of operational and functional feasibility of using transesterification polanga oil as bio-dielectric (PBD) and proved successful.
- Study was conducted, and information is gathered for two predominant output responses such as MRR and R_a.
- Comparative analysis of output responses (MRR and R_a) was done for machining with hydrocarbon-based oil, i.e., kerosene as dielectric and transesterification polanga oil as bio-dielectric.
- 0.08–0.77 times improvement in MRR is observed in case of EDM with PBD.

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