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INVESTIGATION OF SURFACE CHARACTERISTICS OF INCONEL-625 BY EDM WITH USED COOKING OIL-BASED BIODIESEL AS DIELECTRIC FLUID

In this investigation, the surface characteristics of Nickel based superalloy Inconel-625 were evaluated by the electrical discharge machining with used cooking oil-based biodiesel as a dielectric. Nickel-based superalloys find wide applicability in numerous industries due to their specific properties. The Cu electrodes of various densities prepared by atomic diffusion additive manufacturing process were used for machining. A comparison of the performance was made based on average surface roughness. The Design-expert software was used for experimental design and parametric analysis. The outcome demonstrated that bio-dielectric fluid produced improved surface characteristics. The surface roughness was observed to reduce. The surface micrograph obtained from scanning electron microscopy also confirms a better surface finish of bio-dielectric fluid over EDM oil. The surface roughness was shown to be most significantly influenced by the discharge current, with the other parameters having little or no effect. The results showed that for bio-dielectric, the lowest Ra was 0.643 µm, and for EDM oil, the highest value of 0.844 µm. The slightest difference in roughness value for two dielectric fluids was 0.013 µm, and the highest difference was 0.115 µm.

Keywords: sustainable manufacturing; used vegetable oil-based biodiesel; dielectric fluid; surface roughness; EDM performance

1. Introduction

Electrical discharge machining (EDM) can easily produce intricate shapes, inconsistent dimensions, and complex geometries in difficult-to-machine materials. It finds many applications, such as gear and internal thread cutting, mold and die making, and the automobile industry. The dielectric fluid serves a variety of purposes during spark machining that affects the properties of the machined component. The tasks carried out by dielectric involve insulation, ionization, cooling, and waste removal after the process [1]. Hydrocarbons and synthetic oils are mainly utilized in EDM. Commonly used dielectrics are kerosene, de-ionized water, EDM oil, etc. Using these fluids produces hazardous emissions and by-products, which are bad for the surroundings and the machine operator's health. When dielectric fluid breaks down, it releases a cocktail of cancer-causing gases [2,3]. Hence, efforts should be made to use eco-friendly and sustainable dielectric fluid.

A synopsis of studies on the application of bio-dielectric EDM fluid is presented in TABLE 1. From the available literature, it was noted that there are some drawbacks related with hydrocarbon and synthetic oils. Utilizing plant-based oils as the EDM fluid is one approach. They offer a green means of enhancing the process's sustainability. It was also specified that the output of EDM improved with bio-dielectric fluids. The majority of the bio-dielectric produce superior surface roughness and increased material erosion. Surface hardness with plant oil operation was improved. It is necessary to explore the utility bio-dielectric for diverse materials machining. The concord of the plant-based oils with tool material needs attention. The stability and structural changes of bio-dielectric fluid need to be assessed. The usage of comestible oils as dielectric fluid for EDM operation doesn't seem feasible due to the higher domestic requirements and costliness. Compared with edible oils, the utilization of inedible and used cooking oils is more significant as a substitute dielectric fluid. There are several plant-based oil that can be explored and tested in spark machining. Non-edible oil can be obtained from jatropha, pongamia pinnata, etc. The oil left after cooking or frying is called used cooking oil (UCO), or waste cooking oil (WCO). There is a lot of potential for used oil to be used as the EDM fluid. In the present study, Inconel-625 was machined on EDM with used cooking oil-based biodiesel (UCOB). The surface characteristics of the workpiece were studied after machining.

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TABLE 1

Synopsis of literature review

S. No.	Authors [Ref. No.]	Workpiece material	Tool material	Dielectric fluid	Experimental Conditions	Major Findings
1.	Valaki et al. [4]	P20+ (M238 HH grade) plastic mold steel	Cu	Transesterified jatropha oil	**Pulse current (A):** 3, 6, 9, 12, 15, 18 **Pulse duration (μs):** 21, 50, 100, 200, 400, 600 **Pause duration (μs):** 6, 11, 20, 30, 40, 75 **Gap voltage (kV):** 30, 40, 50, 60, 70, 80	Jatropha bio-dielectric resulted in a higher MRR, lower surface roughness (SR), and improved surface hardness as compared to those obtained with kerosene
2.	Ng et al. [5]	Bulked metallic glass (BMG)	Cu	Hydrocarbon oil, and biodiesel of canola and sunflower oils	**Voltage (V):** 145, 160 **Current (A):** 7, 8 **Pulse duration (μs):** 1 **Duty Factor:** 0.40	Higher MRR and lower TWR was obtained with vegetable oil-based dielectrics while machining BMG. For titanium alloy, a higher TWR was observed.
3.	Sadagopan and Mouliprasanth [6]	Al 6063	Cu	Biodiesel, transformer oil, and kerosene	**Pulse current (A):** 6,7,8 **Pulse duration (μs):** 30,35, 40 **Pause duration (μs):** 7,8,9	Biodiesel was found to give the best result in terms of MRR and TWR.
4.	Triyono et al. [7]	SKD 61 steel	Cu	Mixture of jatropha oil and kerosene	**Current (A):** 15, 21 **Pulse duration (μs):** 20 **Pulse interval (μs):** 20	Impact on tool wear, the material removal was not much affected by the viscosity of the dielectric fluid.
5.	Das et al. [8]	Ti6Al4V	Cu	Biodiesel of neem, jatropha, and canola oils, and kerosene	**Pulse current (A):** 4-12 **Pulse duration (μs):** 50-200 **Pulse interval (μs):** 10-50 **Flushing velocity (m/s):** 0.4	It was found that the bio-dielectrics gave higher MRR and less SR than kerosene.
6.	Dastagiri et al. [9]	EN-31 steel	Cu	Pongamia pinnata oil	**Current (A):** 9,12,15, 18 **Pulse duration (μs):** 100, 200, 500, 900 **Pulse interval (μs):** 100, 200, 500, 900	Better surface quality, similar MRR, less TWR, and reduced dielectric contamination were observed with biodiesel operation.
7.	Mishra and Routara [10]	EN-24 grade alloy steel	Cu	Polanga oil bio-dielectric	**Peak current (A):** 3, 6, 9, 12, 15, 18 **Pulse duration (μs):** 30, 50, 75, 100, 150, 200 **Duty cycle:** 2, 4, 6, 8, 10, 12 **Gap voltage (V):** 30, 40, 50, 60. 70, 80	Bio-dielectric resulted in greater productivity, better surface finish, and lesser aerosol emissions.
8.	Rao et al. [11]	D2 steel	Cu, brass, and W	Canola and EDM oil	**Current (A):** 10, 8, 6 **Pulse duration (μs):** 700, 500, 300 **Pulse interval (μs):** 500, 300, 100 **Gap voltage (V):** 60, 50, 40	Canola-based dielectric gave a higher MRR in contrast to EDM oil. Also, higher TWR and SR values were noticed.
9.	Singaravel et al. [12]	Ti-6Al-4V	Cu, brass, and W	Sunflower oil, canola oil, jatropha oil, and kerosene	**Voltage (V):** 55 **Current (A):** 8 **Pulse duration (μs):** 400, 600, 800 **Pulse interval (μs):** 200, 400, 600	Better SR values were observed with vegetable oil-based dielectric fluids in most of the cases.
10.	Singh et al. [13]	Al-SiC composite	Cu	Pongamia and jatropha oil	**Peak current (A):** 3-15 **Pulse duration (μs):** 50-250 **Gap voltage (V):** 20-60	They found that the machining output (MRR, TWR, and SR) with bio-dielectrics was observed to be better than that obtained with kerosene.

2. Materials used

Inconel-625 was used as the work specimen and copper as the tool. Inconel-625 has excellent strength and toughness. It is extremely temperature and corrosion-resistant. Machining of Inconel 625 is challenging using conventional methods. To machine Inconel alloys, non-conventional machining methods are employed [14]. The workpiece was acquired from M/s Bhagyashali Metals, Mumbai, India. The properties of the workpiece are presented in TABLE 2, while composition, as found by Energy-dispersive X-ray analysis (EDS) is given in TABLE 3. The workpiece dimensions were 12 cm × 5 cm × 0.4 cm. The images of the work specimen prior to and after machining are displayed in Fig. 1.

TABLE 2

Property of Inconel-625

Property	Value
Density	0.00844 g/mm^3
Thermal conductivity	17.5 W/m-K
Melting Point	1290-1350°C
Specific Heat	0.098 Cal/g-°C

TABLE 3

Composition of Inconel 625 using EDS

Elements	Ni	Cr	Mo	Nb	Fe	Si	Al	Co	Ti	Mn	P
Composition (%)	60.2	19.7	7.4	2.2	4.2	3.8	0.4	1.3	0.3	0.08	0.02

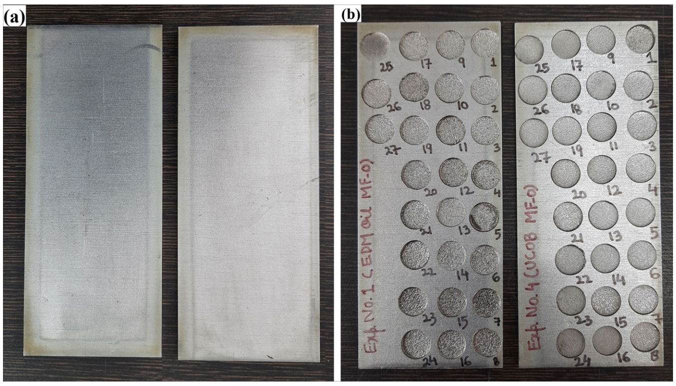

Fig. 1. Image of workpieces prior to and after machining

The two electrodes of copper have different densities, and a solid Cu electrode was used as a tool. A solid Cu rod was purchased from M/s Priyanshu Decor, Delhi, India. Electrodes of two densities were developed using Atomic Diffusion Additive Manufacturing (ADAM) on the Markforged Metal X 3D printer available at 4D Simulations (A Unit of Adroitec Information Systems Private Limited), Noida, India. The densities of electrodes are demonstrated in TABLE 4.

TABLE 4

Densities of electrodes used

Electrode-I	Electrode-II	Electrode-III (solid Cu rod)
0.004795 gm/mm^3	0.007316 gm/mm^3	0.008947 gm/cm^3

A photograph of three electrodes used during experimentation is shown in Fig. 2. Image of three electrodes obtained by the scanning electron microscope (SEM) is shown in Fig. 3. ADAM technique uses a combination of metal and polymer that formed into wire and held in a cartridge. The material mix is deposited like the material extrusion process. The printed part goes to the washing bath, followed by the sintering process. In a washing bath, the green part is immersed in a specialized fluid that removes the primary binding material. A medium-sized furnace converts parts into a final metallic form.

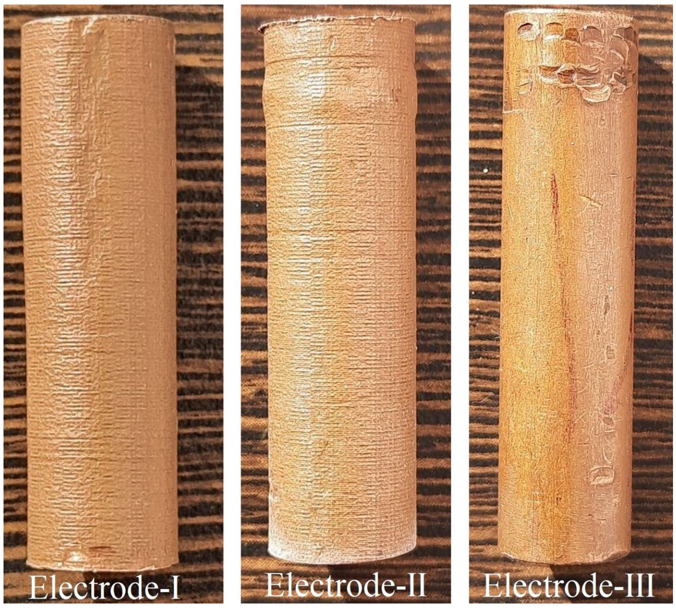

Fig. 2. Image of three electrodes used

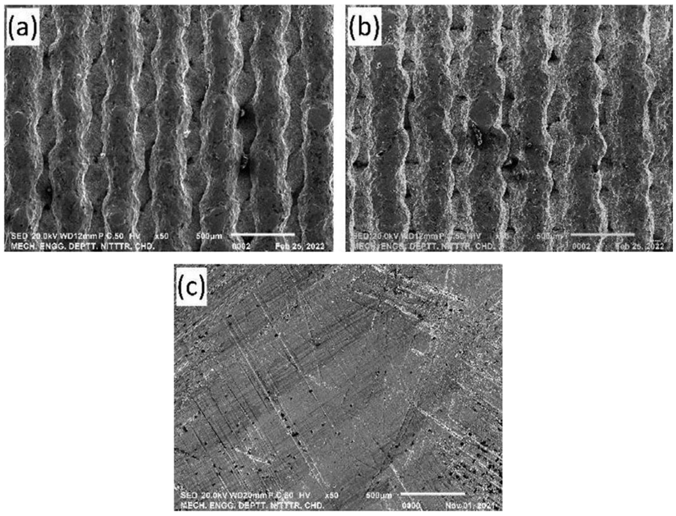

Fig. 3. SEM image of (a) Electrode-I (b) Electrode-II, and (c) Electrode-III

3. Characterization of Dielectric Fluids

Commercial grade EDM oil having market name ST KOOL EDM-250 (M/s See Lube Technologies Private Ltd., Ludhiana, India). Used oil was employed from a nearby restaurant, filtered, and transesterified. The viscosity of UCO at standard temperature is 40.23 cSt, which is very high [15]. The high viscosity is attributed to the colossal molecular mass and chemical structure of plant oil [3] which makes it inappropriate for EDM operation. Viscosity can be reduced by using the transesterification process to turn it into biodiesel. Important properties of UCOB and EDM oil were measured at TRU-FIL Lmt., Mumbai, India. TABLE 5 exhibits the properties of both dielectrics.

UCOB has a little advantage in density over EDM oil. A higher density is useful for enhanced flushing [16]. However, too high density is not desirable as it causes flow problems. The

TABLE 5

Properties of dielectric fluids

Property/ Fuel	ST EDM Oil	UCOB
Density (g/cm^3, at ambient temp.)	0.775	0.842
Viscosity (cSt, at 40°C)	2.33	5.90
Specific heat (J/g°C)	1.95	1.73
Thermal conductivity (W/m-K)	0.139	0.146
Breakdown voltage (kV)	56	36
Dielectric constant	2.02	3.10
Oxygen content (% weight)	0.070	0.225

viscosity of the bio-dielectric fluid is 5.90 cSt as compared to 2.33 for reference dielectric oil. UCOB shows a narrowly lower specific heat than EDM oil. Compared to EDM oil, UCOB has a higher thermal conductivity value. Effective electrode cooling results from high specific heat and thermal conductivity [16-17]. The breakdown voltage for EDM oil is more than that for UCOB. The dielectric constant for UCOB is higher, which displays greater polarity and more potential to stabilize charges [3]. The oxygen content for UCOB is higher, which means fewer harmful emissions [18] and is eco-friendly.

4. Experimental methodology

The experiments were executed on a die-sinker EDM (Toolcraft, Bangalore, India), as shown in Fig. 4(a), accessible at the NITTTR, Chandigarh, India. Specifications of the machine are given in TABLE 6. The experiments were performed with dielectric fluids at the same input variables under positive polarity conditions. To utilize UCOB, the dielectric container was drained, cleaned, and then biodiesel was poured. The input variables picked were discharge current (I_D), pulse on-time (T_{on}), pulse off-time (T_{off}), and density of electrode (ρ_t). It was investigated how these factors affected surface topography and average surface roughness (*Ra*). The levels of input variables were fixed before the experimentation as shown in TABLE 7. Experimentations were organized using the Box-Behnken Design on the Design-expert-13 software. A set of 27 trial runs was carried out for two dielectric fluids. The spark gap value of 0.025 mm was chosen and formulated on the machine manual and literature [14]. The gap voltage was maintained at 60 V throughout the 10-minute machining period. Acetone was used to wash and clean the workpiece after machining to get rid of accumulated debris. A non-contact optical profilometer (RTEC Instruments) as shown in Fig. 4(b) was used to examine the surface roughness. The SEM evaluation was conducted to inspect the topographical appearance of the surfaces at high magnification. A SEM microscope (Joel JSM-IT 100), as displayed in Fig. 4(c) was engaged.

TABLE 6

Specifications of EDM

Model	G30 Integrated type
Supply voltage	415 V, 50 Hz, 3φ, AC
Discharge current	14 A
Gap voltage	60 ± 5 V
Pulse/Pause duration	2 to 3000 µs
Dielectric tank capacity	60 litres

TABLE 7

Input variables and their levels

Input variable	Symbols	Units	Level (-1)	Level (0)	Level (+1)
Discharge current	I_D	A	7.80	9.36	10.92
Pulse on-time	T_{on}	µs	200	300	500
Pulse off-time	T_{off}	µs	150	200	300
Electrode Density	ρ_t	gm/mm^3	0.004795	0.007316	0.008947

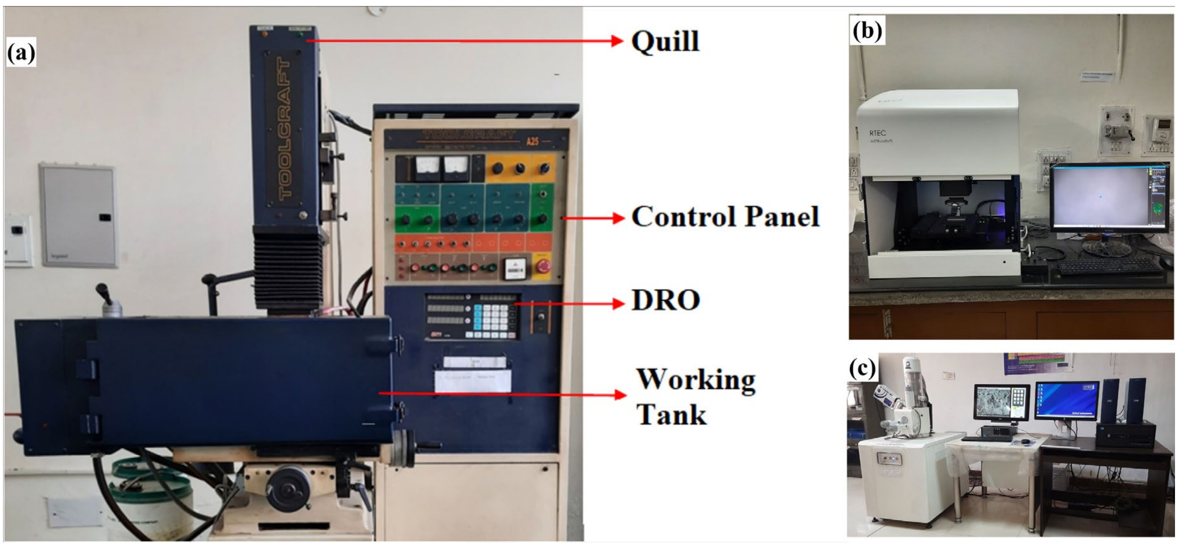

Fig. 4. (a) EDM machine used for experimentation (Courtesy: NITTTR, Chandigarh, India) (b) Optical Profilometer (Courtesy: IIT, Roorkee, India), and (c) Scanning Electron Microscope with EDS (Courtesy: NITTTR, Chandigarh, India)

5. Results and discussions

5.1. Performance Analysis

The performance of EDM while machining Inconel-625 with two different dielectrics was compared based on the average surface roughness. The roughness is a crucial factor influencing the machined component's performance. It depends upon various factors, such as the area of contact, friction, and deformation. The roughness value can be expressed in multiple ways viz arithmetical average roughness, maximum height, ten-point mean roughness, etc. [19]. The most common roughness measurement is the arithmetical average roughness, which is described as the mean surface roughness of the roughness profile deviations from the measurement's center line [20]. The variation of *Ra* related to various input variables is provided in TABLE 8. The optical profilometer image and a corresponding sample of the surface roughness profile (for reading no. 18 with UCOB) are shown in Fig. 5.

Three readings of surface roughness were taken, and the mean value of those readings served as the final measurement of surface roughness. For higher precision, reduced wear, and a longer service life, lower surface roughness values are preferred. It can be noted from TABLE 8 that UCOB generates low surface roughness than EDM oil for almost all experimental trial runs. A clearer picture of the same is represented in Fig. 6. The maximum roughness value of 0.844 µm was observed with EDM oil (for reading no. 11), while the minimum of 0.643 µm was observed for UCOB for reading no. 22. The lower surface roughness with bio-dielectric fluid is because of higher thermal conductance and low specific heat, which might have decreased the energy density due to greater heat transfer to the peripheral fluid [4]. The viscosity directs the energy confinement, and the greater dielectric constant controls the vulnerability of the medium [20]. So, the consolidated impact of these two phenomena resulted in lower surface roughness values with bio-dielectric. Das et al. [20] observed 17% less surface roughness with neem oil than with kerosene. Singh et al. [13] found that bio-dielectrics resulted in 23% and 18% lower surface roughness than conventional dielectric fluid.

5.2. Parametric Analysis

Perturbation curves were utilized to investigate the consequences of control variables on individual output variables.

TABLE 8

Result table

Exp. No.	Input Variables				Output Variable *Ra* (µm)			Percentage reduction in *Ra* when UCOB is used (% Δ*Ra*)
	I_D (A)	T_{on} (µs)	T_{off} (µs)	ρ_t (gm/mm^3)	Before Machining	After Machining		
						EDM oil	UCOB	
1.	10.92	300	150	0.007316	0.873	0.824	0.768	6.76
2.	10.92	300	300	0.007316	0.873	0.829	0.723	12.79
3.	9.36	300	200	0.007316	0.873	0.701	0.664	5.28
4.	10.92	300	200	0.008947	0.873	0.828	0.765	7.61
5.	9.36	300	150	0.004795	0.873	0.703	0.666	5.26
6.	7.80	300	150	0.007316	0.873	0.681	0.643	5.58
7.	9.36	500	200	0.008947	0.873	0.703	0.645	8.25
8.	10.92	300	200	0.004795	0.873	0.802	0.765	4.61
9.	9.36	200	200	0.008947	0.873	0.687	0.653	4.95
10.	7.80	300	200	0.008947	0.873	0.683	0.647	5.27
11.	10.92	500	200	0.007316	0.873	0.844	0.729	13.63
12.	9.36	300	150	0.008947	0.873	0.689	0.676	1.89
13.	7.80	300	300	0.007316	0.873	0.684	0.655	4.24
14.	7.80	300	200	0.004795	0.873	0.704	0.659	6.39
15.	9.36	300	200	0.007316	0.873	0.703	0.676	3.84
16.	9.36	300	300	0.008947	0.873	0.683	0.649	4.98
17.	9.36	200	200	0.004795	0.873	0.679	0.657	3.24
18.	9.36	500	300	0.007316	0.873	0.684	0.657	3.95
19.	9.36	300	300	0.004795	0.873	0.688	0.674	2.03
20.	10.92	200	200	0.007316	0.873	0.802	0.777	3.12
21.	9.36	300	200	0.007316	0.873	0.705	0.644	8.65
22.	7.80	500	200	0.007316	0.873	0.681	0.643	5.58
23.	9.36	500	150	0.007316	0.873	0.699	0.663	5.15
24.	9.36	200	150	0.007316	0.873	0.703	0.663	5.69
25.	7.80	200	200	0.007316	0.873	0.680	0.649	4.56
26.	9.36	500	200	0.004795	0.873	0.698	0.663	5.01
27.	9.36	200	300	0.007316	0.873	0.693	0.656	5.34

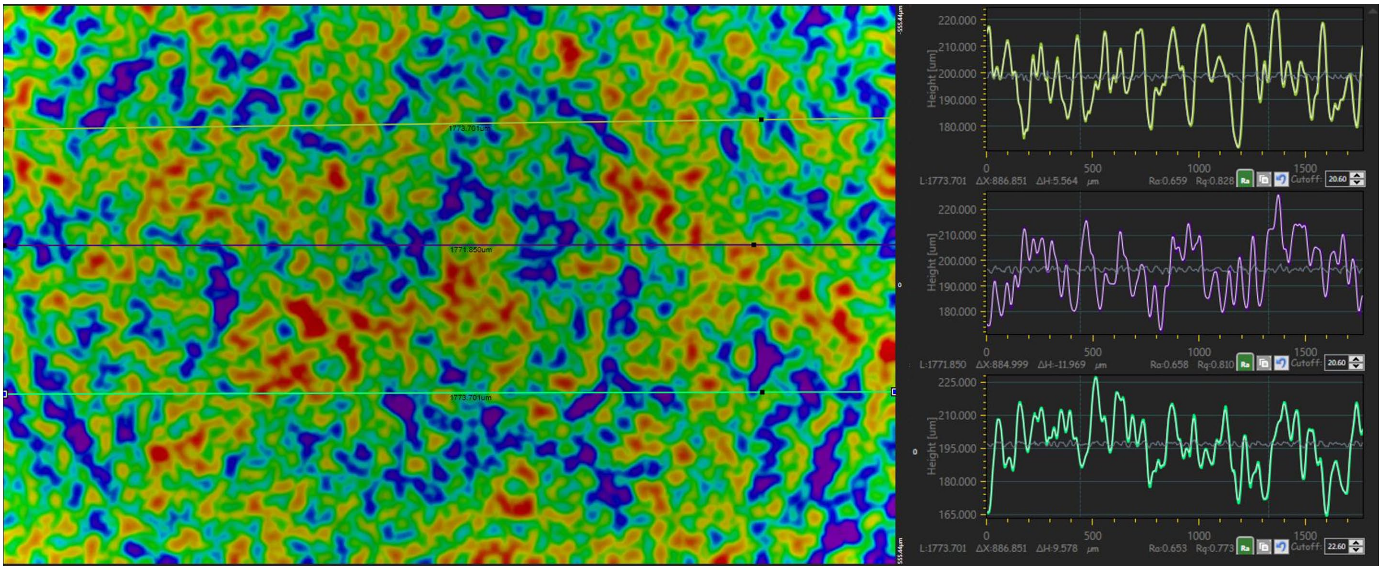

Fig. 5. Optical profilometer image and roughness profile for Reading No. 18 ($I_D = 9.36$ A, $T_{on} = 500$ μs, $T_{off} = 300$ μs, and $\rho_t = 0.007316$ gm/mm^3) of the machined surface with UCOB

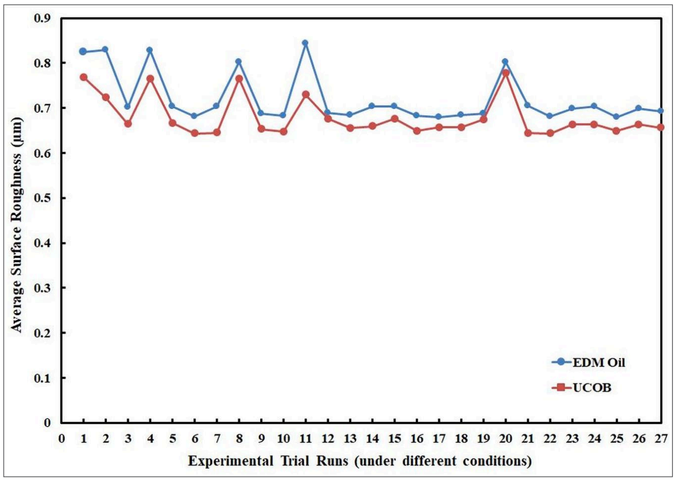

Fig. 6. Comparison of average surface roughness for both dielectrics for all experimental trials

Assessment of Ra for both dielectric fluids under the effect of input variable is shown in Fig. 7(a) and (b). The dimension of craters produced during the material melting and evaporation due to the spark energy, which is dependent on discharge current and pulse duration, has a crucial impact on the Ra. Additionally, the surface roughness produced by the spark machining is significantly impacted by the efficiency of debris evacuation from the sparking gap at the end of the sparking cycle and the quantity of re-solidified debris. The value of surface roughness is low at lower currents. It grew as the discharge current is increased. Thus, a better surface quality is achieved with a discharge current in in the lower range. More discharge energy becomes available with an increment in current, which causes more melting of material and the formation of large craters at high currents, which is responsible for the inferior surface. The effect of other parameters was insignificant compared to the discharge current. Variable

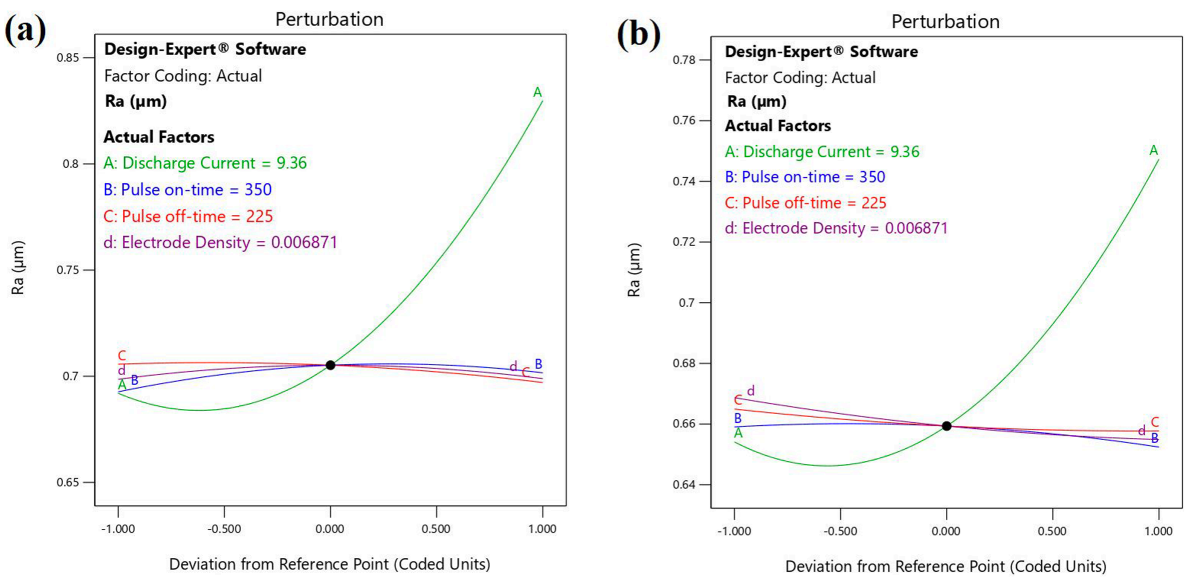

Fig. 7. Effect of input variables on *Ra* with (a) EDM oil and (b) UCOB

density electrode was introduced as a novel idea to study its effect on the surface characteristics of the workpiece. However, it doesn't show any influence on surface roughness. The density is foreseen to play a major part in studying material expulsion and tool wear rates. The working current is the most notable parameter affecting the surface roughness of the workpiece.

5.3. Surface topography

During the EDM process, material erosion occurs as a result of melting and evaporation in the presence of a suitable dielectric medium. The region where the material is expelled from the work material forms a crater, pores, and accumulated debris. The dimension, shape, and type of the crater determine the quality of the machined surface [18]. Assessment of the surface produced using two dielectrics has been done at similar magnifications. Fig. 8(a) and (b) show SEM micrograph (500× Magnification) of the machined workpiece with EDM oil and UCOB, respectively at 10.92 A of current, 500 µs of pulse duration, 200 µs of pulse interval, and 0.007316 gm/mm^3 electrode density (Reading No. 11).

The dark region indicates deep craters, the greyish region indicates shallow craters with heat-affected zones, and the light region indicates the re-solidified mass. The images reveal unevenness, craters, and re-solidified mass on both surfaces, but the relatively less distorted surface is obtained with UCOB. Analysis of these two surfaces shows that the surface processed with UCOB has comparatively better surface integrities than that of the EDM oil at the same input parameters. The experimental results have already shown less surface roughness with UCOB dielectric than EDM oil.

6. Conclusions

The utility of UCOB for spark machining has been experimentally assessed. A comparative examination of UCOB and EDM oil was conducted in terms of the surface quality of the machined component. The characteristics of biodiesel were observed to be in good accord with synthetic oil. The trend of surface roughness for both dielectrics was observed to be the same. However, the values of the parameters were different due to the differences in properties of both dielectrics. Used cooking oil-based biodiesel resulted in better surface roughness in comparison to EDM oil when machining Inconel-625 for all experimental trials.

Analysis showed that the lowest Ra of 0.643 µm was noticed for I_D = 7.80 A, T_{on} = 500 µs, T_{off} = 200 µs, and ρ_t = 0.007316 gm/mm^3 with UCOB for Reading No. 22 while the utmost value of 0.844 µm was attained for I_D = 10.92 A, T_{on} = 500 µs, T_{off} = 200 µs, and ρ_t = 0.007316 gm/mm^3 with EDM oil for Reading No. 11. The lowest difference in Ra of 0.013 µm was noticed for the set I_D = 9.36 A, T_{on} = 300 µs, T_{off} = 150 µs, and ρ_t = 0.008947 gm/mm^3 (Reading No. 12). While the utmost difference was 0.115 µm for Reading No. 11 (I_D = 10.92 A, T_{on} = 500 µs, T_{off} = 200 µs, and ρ_t = 0.007316 gm/mm^3).

The SEM analysis was found to support the results of surface roughness. The SEM images showed relatively less deposition of debris with UCOB dielectric. The effect of various variables on Ra was examined. The most important factor was shown to be the discharge current. Other variables produced a very insignificant effect on surface roughness.

7. Future Scope of Research

The biodiesel derived from different sources (vegetable oils and animal fat) can be tested in EDM to find the best-performing fluid. A combination of hybrid EDM with biodiesel as dielectric fluid can be experimented. Detailed research can be conducted on bio-dielectrics involving more output variables. The research can be extended by optimizing the input variables for the best performance. The consequence of plant based-dielectrics on surface characteristics like recast layer thickness and microhardness can be studied.

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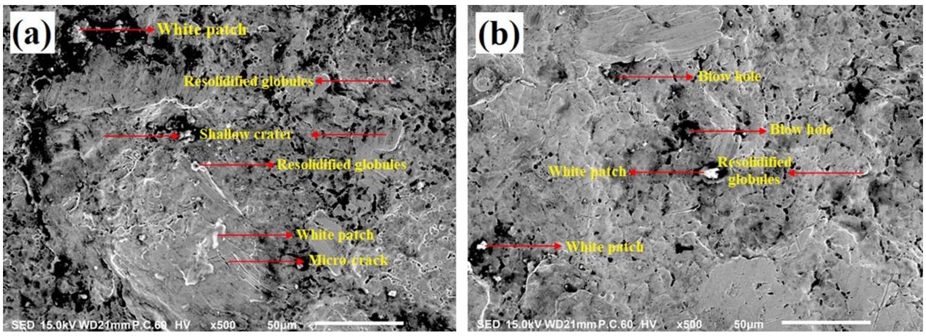

Fig. 8. SEM micrograph at 500X Magnification for Reading No. 11 (I_D = 10.92 A, T_{on} = 500 µs, T_{off} = 200 µs, and ρ_t = 0.007316 gm/mm^3) of the machined surface with (a) EDM oil and (b) UCOB

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