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ORIGINAL ARTICLE

Investigation on the influence of different types of dielectrics in electrical discharge machining

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Abstract EDM is a special type of non-traditional machining technique in which material removal takes place due to repeated electrical discharges at short intervals in the presence of a dielectric medium. It is used in high precision machining of all types of conductive materials such as metals, metallic alloys, graphite and even some ceramic materials. In EDM, the main output parameters are the material removal rate (MRR), electrode wear rate (EWR), and surface roughness (R_a). It is generally desirable to obtain the maximum MRR with minimum EWR with good surface finish. The dielectrics play a vital role in machining. Even though EDM process has been traditionally used in die sinking industry mostly for machining hard materials, lighter materials like Ti alloy are machined more recently. In some cases, components made out of soft metals like Aluminium alloys are machined in EDM due to the intricacy of profiles, blind prismatic holes and inaccessible areas by other machining methods. This paper aims to investigate the effect of using different dielectrics, viz., biodiesel, transformer oil and kerosene on the material removal rate, electrode wear and surface roughness in EDM. Based on Taguchi's design of experiments, machining were carried out on Aluminium Alloy 6063 specimens using a die-sinking EDM machine fitted with a copper electrode. The results show that the biodiesel as a dielectric has better performance in MRR, EWR and surface finish in comparison with kerosene and transformer oil. However, performance sustainability and the environmental effect of biodiesel have to be studied.

Keywords Electrical discharge machine · Aluminium alloy · Biodiesel · Transformer oil · Kerosene · Material removal rate · Electrode wear rate · Surface finish (R_a) · Signal-to-noise ratio S/N response factors

Abbreviations

EDM	Electrical discharge machining
MRR	Material removal rate
EWR	Electrode wear rate
TWR	Tool wear ratio
CMC	Ceramic matrix composite

1 Introduction

Electrical discharge machining (EDM) is a thermoelectric process that erodes workpiece material by a series of discrete electrical sparks between the workpiece and electrode immersed in or flushed by a dielectric fluid. The thermal energy of the sparks leads to intense heat generations on workpiece causing melting and vaporizing of workpiece material. It is a non-traditional concept of machining, which has been widely used to produce dies and moulds. It is also used for finishing parts in aerospace, automotive and medical industry in addition to a variety of applications. It is a good machining option for manufacturing geometrically complex or hard material parts that are extremely difficult-to-machine by conventional machining processes.

Even though the phenomena of electric discharges was established in 1694 by Sir Robert Boyle, it was only in the early 1940s that EDM started to become a well-known manufacturing process when Boris and Natalie I. Lazarenko discovered the decisive role of the dielectric fluid [1]. Since then, EDM has experienced a dramatic evolution. Recent

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developments show that EDM can be used to machine conductive, semi conductive, metal matrix and ceramic composites. In EDM, sparks generated melts and expels the molten metal from the surface of materials thereby causing small craters [2]. The material is removed with the erosive effect of the electrical discharges from tool and workpiece [3]. M. Kiyak and O. Cakir [4] observed that surface roughness of workpiece and electrode were influenced by pulsed current and pulsed time, higher values of these parameters increased surface roughness. Lower current, lower pulse time and relatively higher pulse pause time produced a better surface finish.

2 Dielectric fluid

The dielectric fluid fulfils an extremely important function regarding productivity, costs and quality of the machined parts. In addition to health, safety and environment aspects are also to be considered. The physical and chemical properties of dielectric have significant influence on EDM performance. Most of the research in EDM were carried out with kerosene, water and gaseous dielectrics with or without suspended powders. Krar et al. [2] in their work used electric oil as a dielectric. Abbas et al. [3] reviewed the research trends in EDM using water-based dielectrics and gaseous dielectrics. Investigation carried out by Zhang et al. [5] revealed that both productivity and quality are significantly affected by dielectrics. TWR and MRR are affected by the type of dielectric and the method of flushing [6]. Koenig and Joerres [7] indicated that the performance of water-based dielectrics was unfavourable and dissatisfied compared with the hydrocarbon oil-based dielectrics. They also studied the feasibility of adding organic compounds with large molecular structures to improve the removal of the molten metal out from the craters thereby increasing the MRR. The discharge location was affected predominantly by the insulation of dielectric, distance between electrodes and distribution of debris [8].

Leão and Pashby [9] in their review reported that water or gaseous-based dielectrics are more environment-friendly. Investigations carried out by Sivapirakasam et al. [10] showed that aerosol and some hazardous gases were generated in oil-based dielectrics. A recent investigation carried out by Liu et al. [11] in die-sinking EDM indicate that oil water emulsion performance is better than that of kerosene, Kibria [12] made a study on kerosene, boron carbide powder-suspended kerosene and deionized water as dielectrics and investigated their influences on MRR and TWR. Chenjun Wei et al. [13] presented that the material removal mechanism by EDM in the case of ceramic matrix composite (CMC) material is due to crack caused by thermal expansion of matrix. They also reported that high machining rate was achieved by high gap voltage or low duty ratio in CMC machining. Tönshoff et al. [14] reported that when using a dielectric such as mineral oil or an organic fluid, hazardous fumes like polycyclic aromatic hydrocarbons, benzene, the vapour of mineral oil, mineral aerosols and various byproducts were generated by the dissociation of oil and its additives. One of the important research issues in the field of green manufacture is how to minimize the environmental impact of dielectrics in sinking EDM [15]. Use of high velocity air flow causes almost zero electrode wear [16]. Currently, the deionized water-based dielectric is used in the case of micro EDM due to higher MRR and lower tool wear [17]. Mehmet Altug et al. [18] analysed that the transformation in the microstructure is the most important parameter specifying material specifications. Mechanical features are enhanced by checking the texture of alloy and microstructure change with the help of heat and thermo-mechanical procedures. In the literature, there have been studies determining mechanical features of the Ti6Al4V alloy with microstructure changed as a result of heat treatment.

Table 1 Typical mechanical properties of Al alloy 6063

Density	2700 kg/m^3
Melting point	660 °C
Elastic modulus	70–79 GPa
Poisson's ratio	0.33
Tensile strength	230–570 MPa
Yield strength	215–505 MPa
Percent elongation	10–25%
Specific heat capacity	0.9 J/g °C

Kibria et al. [12] introduced boron carbide in deionized water for a better performance in micro machining of the Ti-6Al-4V alloy. Many researchers [19, 20] tried to measure the energy distribution between the anode, cathode and dielectric fluid. Yanzhee Zhang et al. [21] made a comparative study using water in oil emulsion with kerosene and reported that water in oil emulsion has lower carbon adhered to the electrode and more economical and environment-friendly. Ming and He LY [22] demonstrated that an increase of MRR and a reduction of

Fig. 1 Copper electrode

Table 2 The physical properties of copper electrode

Physical properties	Value
Electrical resistivity (μΩ/cm)	1.96
Electrical conductivity (%)	92
Thermal conductivity (W/mK)	268–389
Melting point (°C)	1083
Specific heat (cal/g °C)	0.092
Specific gravity at 20 °C (g/cm^3)	8.9
Coefficient of thermal expansion (×10 °C^{-1})	6.6

TWR with improved surface quality by adding additives to kerosene. Certain alloying elements in the form of fine powders may be introduced through electrode or mixed with dielectric for specific surface modifications. It has been reported that the presence of powder particles in dielectric fluid and the concentration of powder creates conditions suitable for achieving a better surface quality in the machined area [23]. Al (aluminium) powder suspended distilled water dielectric was found to have high MRR, good surface finish and minimum white layer thickness while machining W 300 die steel [24]. The combination of a copper electrode with Al powder mixed with dielectric maximizes the MRR [25]. Yi Jiang et al. [26] reported that using wavelet transform method, the machining efficiency and stability are significantly improved. To alleviate the environmental impact, other dielectrics such as deionized water, water mixed with organic compounds, and oil-in-water emulsions have been studied by many researchers [8, 27–29]. Yan et al. [30] investigated machining of pure Titanium using urea solution in water and reported the formation of Tin hard layer resulting in good wear resistance.

Nowadays, the use of gaseous dielectrics attracts more and more attentions. Compared with the liquid dielectrics, the gaseous dielectrics are much more environmental friendly and more economical. Investigations carried out by Tao et al. [31] showed that there are still some technical problems need to be completely resolved before the industry application of the gaseous dielectrics, and he has experimented machining with the dry and near dry conditions electrical discharge machining of milling operations. As of today, commercial EDM machine tools using gaseous dielectric are still at large. Many researchers reported that the machining performance, while using gaseous dielectric with some special conditions, could be comparable or better than by using liquid dielectrics [16]. Zhang et al. reported that MRR of EDM with a gas can be improved using ultrasonic vibrations of the workpiece as it helps in the flushing of the molten metal from the craters [32]. Janak B et al. [33] investigated with waste vegetable oil bio dielectric fluid and reported that the fluid can be an alternate to hydrocarbon, water and synthetic-based dielectric fluid. Pandey et al. [34] conducted a study on machining of HSS using water and compressed air as dielectric medium and reported that MRR was 62% higher than conventional EDM. Renjie et al. [35] in their study of electric discharge milling of SiC ceramic, developed three emulsions using different concentrations of additives ACE(anionic compound emulsifier),OP-10 (non-ionic surfactant) and rosin. They found that higher MRR and lower SR can be obtained by using optimal concentration of ACE-25 wt%, OP-10, 1 wt% and rosin 2 wt% in emulsified oil. Wang et al [39] made a comparative study on the performance of compound dielectric, kerosene and distilled water and reported better performance of MRR,SR and lower relative electrode wear ratio in machining Titanium alloy with compound dielectric.

Table 4 Level values of input factors

S. no.	Factors	Unit	Levels 1	2	3
1	Peak current (I_P)	A	6	7	8
2	Pulse on time (T_{ON})	μs	30	35	40
3	Pulse off time (T_{OFF})	μs	7	8	9

From the literature survey, it is found that no studies have been reported on EDM using biodiesel as a dielectric for machining Al alloy. In this paper, an attempt is made to machine Al alloy 6063 using kerosene, transformer oil and biodiesel as dielectric and the results are discussed.

3 Experimentation

3.1 Machine, materials and electrodes

The machine used for this present study is Electronica- EMS 5535-R50 ZNC series 2000 machine with NC control in Z-

Table 3 Properties of dielectrics

Dielectrics	Density @30 °C	Kinematic viscosity	Flash point	Dielectric constant	Oxygen wt%
Biodiesel	0.88 g/cm^3	4–6cst	100–170 °C	2.1	11
Transformer oil	0.89 g/cm^3	27cst	140 °C	2.1	0
Kerosene	0.81 g/cm^3	2.71cst	38 °C	1.8	0

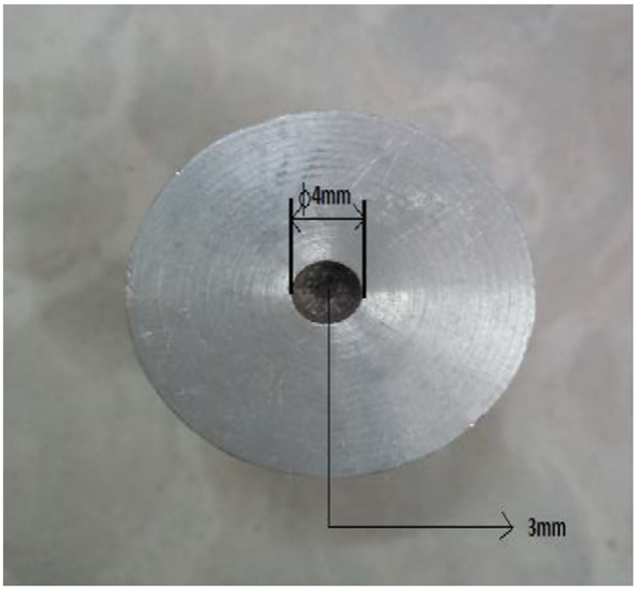


Fig. 2 Al 6063 specimen spark eroded in biodiesel

direction. EDM does not make direct contact with the workpiece and the tool. There are a various combination of material used for EDM research recently. In this study, the workpiece material selected is Al 6063 alloy with a cylindrical rod of 28 mm and length15 mm which is made as anode. The mechanical properties of Al alloy used in this work are shown in Table 1.

The electrode material used is electrolytic copper which is cathode. These electrodes are cylindrical in shape with a nominal diameter of 4 mm as shown in Fig. 1 and its material properties are shown in Table 2.

3.2 Dielectrics

The dielectric fluids used in this study are biodiesel, transformer oil and kerosene. Biodiesel is derived from palm styrene with lower viscosity and higher flash point. Transformer oil is the one that is used for insulation and cooling of a transformer and finally commercially available kerosene.

Table 5 Experimental results for MRR, EWR and R_a with biodiesel as dielectric

Expt. no.	MRR (gm/min)	EWR (gm/min)	R_a (μm)
1	0.0297	0.00094	2.39
2	0.0300	0.00111	2.42
3	0.0506	0.00150	3.15
4	0.0505	0.00135	3.00
5	0.0584	0.00151	3.10
6	0.0514	0.00155	3.36
7	0.0601	0.00170	4.00
8	0.0600	0.00169	4.20
9	0.0721	0.00177	4.62

Table 6 Experimental results for MRR, EWR and *R*a with transformer oil as dielectric

Expt. no.	MRR (gm/min)	EWR (gm/min)	R_a (μm)
1	0.0171	0.00110	5.40
2	0.0200	0.00131	5.71
3	0.0240	0.00147	6.34
4	0.0210	0.00125	6.01
5	0.0276	0.00151	6.11
6	0.0250	0.00159	6.85
7	0.0349	0.00175	6.98
8	0.0310	0.00173	7.10
9	0.0386	0.00195	7.12

The typical properties of dielectrics are shown in Table 3.

The viscosity of dielectrics has greater influence on MRR. Use of high viscosity dielectric increases MRR. This is attributed due to high energy density and the reduction in the expansion of discharge channel (plasma channel and gas bubble) causing concentration of pulse energy onto a smaller area thereby higher MRR is achieved [40]. However, increase in viscosity leads to poor flushing.

3.3 Design of experiment

A pilot study was carried to find the effect of different process variables of input factors and their interactions and well-fitted factors for the dielectrics were chosen for the experiment. Since this is an initiation of a trail experiments using biodiesel as dielectric, only limited parameters are used. Also, machine conditions should support the experiments and therefore the basic conditions of input factors were chosen. Further experiments will be carried out by using the parameters like gap voltage, flushing pressure, duty cycle. The machining conditions for Aluminium 6063 alloy and the number of levels of the parameters that were selected are given in Table 4.

Table 7 Experimental results for MRR, EWR and R_a with kerosene as dielectric

Expt. no.	MRR (gm/min)	EWR (gm/min)	R_a (μm)
1	0.0135	0.00120	5.70
2	0.0140	0.00145	6.08
3	0.0167	0.00173	6.41
4	0.0159	0.00163	6.13
5	0.0186	0.00175	6.35
6	0.0197	0.00183	6.90
7	0.0230	0.00191	7.01
8	0.0221	0.00184	7.48
9	0.0296	0.00200	7.54

Table 8 Response values for S/N ratio for MRR-biodiesel dielectric

Levels	Peak current (I_P)	Pulse on time (T_{ON})	Pulse off time (T_{OFF})
1	−28.97	−26.97	−26.92
2	−25.46	−26.52	−26.41
3	−23.90	−24.85	−25.00
Delta	5.07	2.12	1.92
Rank	1	2	3

Table 9 Analysis of variance for S/N ratios for MRR-biodiesel dielectric

Source	DF	Seq SS	Adj SS	Adj MS	F	P
I_P	2	40.500	40.500	20.250	12.56	0.074
T_{ON}	2	7.504	7.504	3.752	2.33	0.301
T_{OFF}	2	5.916	5.916	2.958	1.83	0.353
Residual error	2	3.225	3.225	1.613		
Total	8	57.146				

3.4 Experimental procedure

Based on the range values that can be used for testing, Taguchi-based designs of experiments were performed using commercial software with an L9 orthogonal array. The spark eroded Al 6063 specimen using biodiesel as dielectric is shown in Fig. 2.

The hole machined is a blind hole of 4 mm diameter, and the depth of machining is set at 3 mm for all the specimens and for all the three variant dielectrics, viz., biodiesel, transformer oil and kerosene throughout the experiment. The metal removal rate MRR, electrode wear rate EWR were found by measuring the weight difference using a balance with a precision of 0.0001 g. For each experiment, a separate electrode was used. The machining time was noted using a stopwatch. The diameters of the electrode, before machining and after machining, were measured. The surface roughness (R_a) measurements were performed by using Mitutoyo Surftest (SJ 201). The R_a is used as the roughness parameter. The surface roughness (R_a) measurements were taken at five different regions on the machined surface, and the mean of these five measurements was taken as the final value for the surface finish. The electrode and hole diameters were represented by the average value of their respective measured diameters. The experimental results for MRR, EWR and R_a based on the L9 orthogonal array are shown in Tables 5, 6 and 7 for biodiesel, transformer oil and kerosene respectively.

4 Results and discussion

From the experimental results, different response factors like MRR, EWR and R_a of the machined holes were calculated. Then statistical analyses were performed on the calculated values, and the signal-to-noise ratio values of three response factors was plotted for comparison. ANOVA table was generated using the commercial software and regression analysis

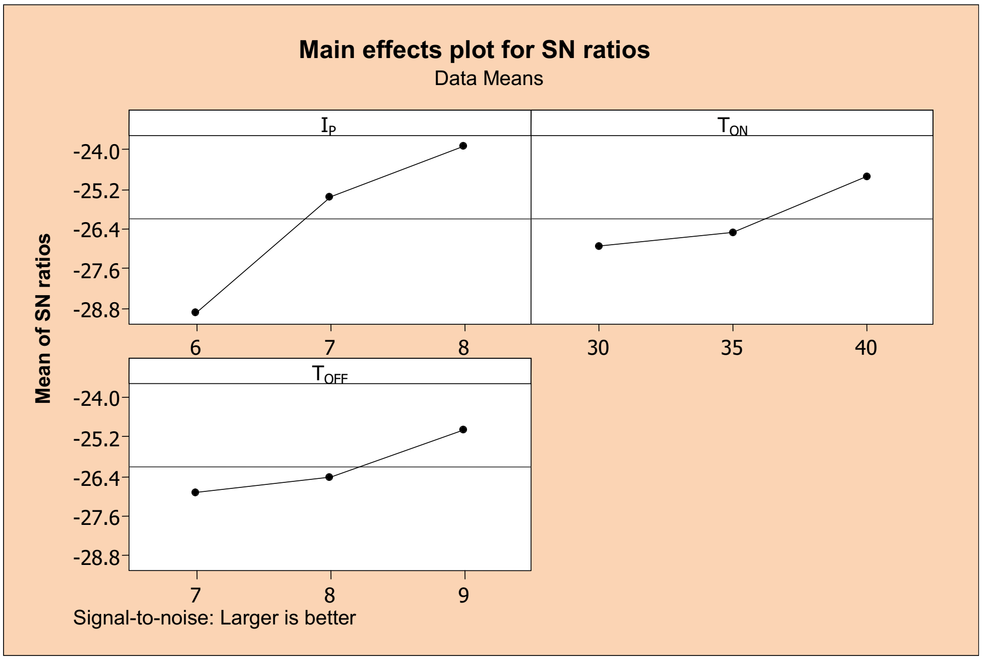


Fig. 3 S/N ratio curve for MRR with I_P, T_{ON} and T_{OFF}-biodiesel dielectric

Table 10 Response values for S/N ratio for EWR-biodiesel dielectric

Levels	Peak current (I_P)	Pulse on time (T_{ON})	Pulse off time (T_{OFF})
1	58.70	57.77	57.39
2	56.67	56.99	57.18
3	55.29	55.90	56.10
Delta	3.41	1.87	1.29
Rank	1	2	3

Table 11 Analysis of variance for S/N ratios for EWR-biodiesel dielectric

Source	DF	Seq SS	Adj SS	Adj MS	F	P
I_P	2	17.676	17.676	8.8378	14.71	0.64
T_{ON}	2	5.288	5.288	2.6439	4.40	0.185
T_{OFF}	2	2.887	2.887	1.4434	2.40	0.294
Residual error	2	1.201	1.201	0.6007		
Total	8	27.501				

was carried, and the corresponding regression equation was generated for each dielectric.

4.1 Dielectric biodiesel

4.1.1 Effect of input parameters on MRR

MRR response values for biodiesel are shown in Table 8. The calculation of S/N ratio is based on “Larger is better quality characteristic”. It is observed from the Table 8 that the current “I_P” ranks first which means that it has the maximum effect on MRR, pulse on time “T_{ON}” have a considerable effect and pulse off time “T_{OFF}” has the least influential effect on MRR.

The signal-to-noise ratio of MRR in the case of biodiesel is plotted and shown in Fig. 3. In these plots, the levels are plotted in the X-axis and S/N ratio for the respective levels are plotted in Y-axis. From the plot, it is observed that material removal rate increases with the increase in current as well as increase in pulse on time that leads to higher energy density in the plasma channel since discharge energy is the product of discharge voltage, current and pulse duration. However, increase in pulse off time at a lower level has less influence on MRR but at higher level MRR increases. These phenomena may be attributed to insufficient time for flushing away the debris leaving unexpelled molten aluminium to solidify as recast layer. This is in agreement with various research outcomes [37]. Y.H. Liu et al. [36] in their study used insulating Al_2O_3 ceramic blank as workpiece, steel as electrode and copper strip as assisting electrode material. They reported that using a suitable chemical additive and its dosage for water-based emulsion, dielectric strength, washing capability and viscosity of the machining fluid can be modified in order to increase MRR of the ED milling. Using high flow velocity of the machining fluid, the author reported that MRR of ED milling increases and its surface roughness changes was found less. Table 9 presents the analysis of variance for S/N ratios for MRR-biodiesel dielectric.

The regression analysis was conducted to see the difference between the main effects of levels 1, 2 and 3 of the variables on the MRR, EWR and R_a.

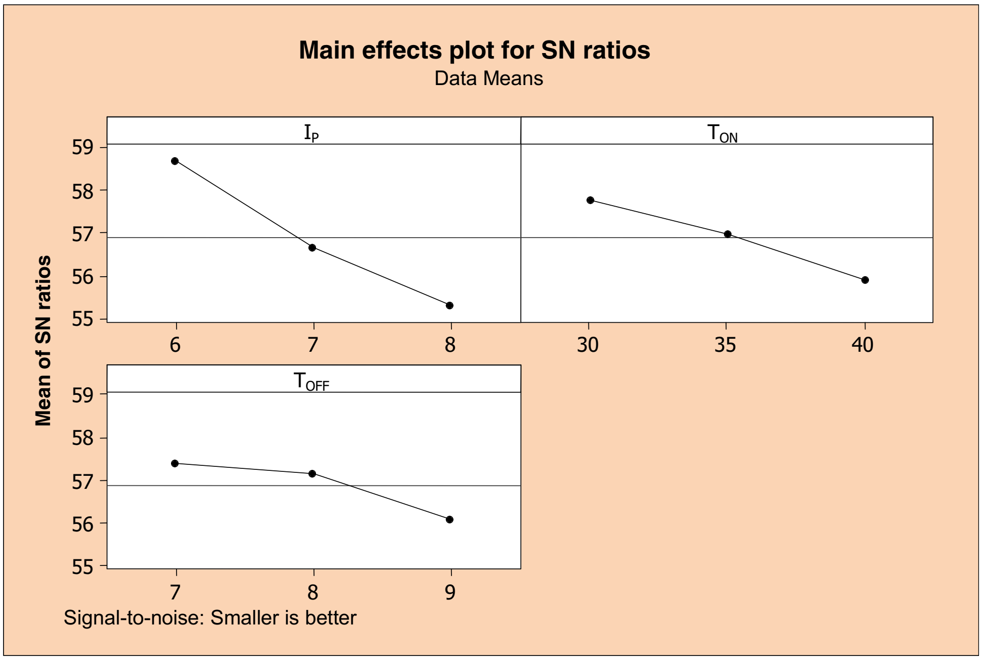


Fig. 4 S/N ratio curve for EWR with I_P, T_{ON} and T_{OFF}-biodiesel dielectric

Table 12 Response values for S/N ratio for R_a-biodiesel dielectric

Levels	Peak current (I_P)	Pulse on time (T_{ON})	Pulse off time (T_{OFF})
1	−8.403	−9.717	−10.187
2	−9.965	−9.990	−10.171
3	−12.600	−11.262	−10.612
Delta	4.196	1.545	0.441
Rank	1	2	3

Table 13 Analysis of variance for S/N ratios for R_a-biodiesel dielectric

Source	DF	Seq SS	Adj SS	Adj MS	F	P
I_P	2	26.9867	26.9867	13.4934	50.18	0.020
T_{ON}	2	4.0795	4.0795	2.0398	7.59	0.116
T_{OFF}	2	0.3754	0.3754	0.1877	0.70	0.589
Residual error	2	0.5378	0.5378	0.2689		
Total	8	31.9794				

1. Statistical regression analysis for MRR vs I_P, T_{ON} and T_{OFF}

$$S = 0.00486677 \ \text{R−Sq} = 92.4\% \text{R−Sq(adj)} = 87.8\%$$

The regression equation is

$$\text{MRR} = -0.121 + 0.0136\, I_P + 0.00113\, T_{ON} + 0.00467\, T_{OFF}$$

4.1.2 Effect of input parameters on EWR

EWR response for biodiesel is shown in Table 10. The calculation of S/N ratio is based on “Smaller is better quality characteristic”.

From the Table 10, it is observed that I_p ranks first which means that it has a maximum effect on EWR, T_{ON} has a considerable effect and “T_{OFF}” has the least effect. The signal-to-noise ratio for EWR in the case of biodiesel is plotted and shown in Fig. 4. In these plots, the levels are plotted in the X-axis and S/N ratio for the respective levels are plotted in Y-axis. From the plot, it is observed that the electrode wear rate increases with increase in current. In addition, increase in pulse on time increases EWR in both levels one and two, and the wear rate slope is less in comparison with the effect of current. EWR generally decreases due to increased pulse duration as reported in many works of literature. However, in the present study wear rate is found to increase marginally for a small pulse duration of 2 μs which may be too low to make any justification in comparison with large pulse duration of the order from 10 to 200 μs as reported in the literature. Change in pulse off time at lower level has no much influence in the wear of electrode. Table 11 shows the analysis of variance for S/N ratios for EWR-biodiesel dielectric.

The regression analysis was done to see the difference between the main effects of levels 1, 2 and 3 of the variables on the MRR, EWR and R_a.

2. Statistical regression analysis for EWR vs I_P, T_{ON}, and T_{OFF}

$$S = 0.0000775958 \ \text{R−Sq} = 95.2\% \ \text{R−Sq(adj)} = 92.3\%$$

The regression equation is

$$\text{EWR} = -0.00210 + 0.000268\, I_{P+}0.000028\, T_{ON} + 0.000088\, T_{OFF}$$

4.1.3 Effect of input parameters on R_a

Surface finish R_a, the response for biodiesel is shown in Table 12. The calculation of S/N ratio is based on “Smaller is better quality characteristic”.

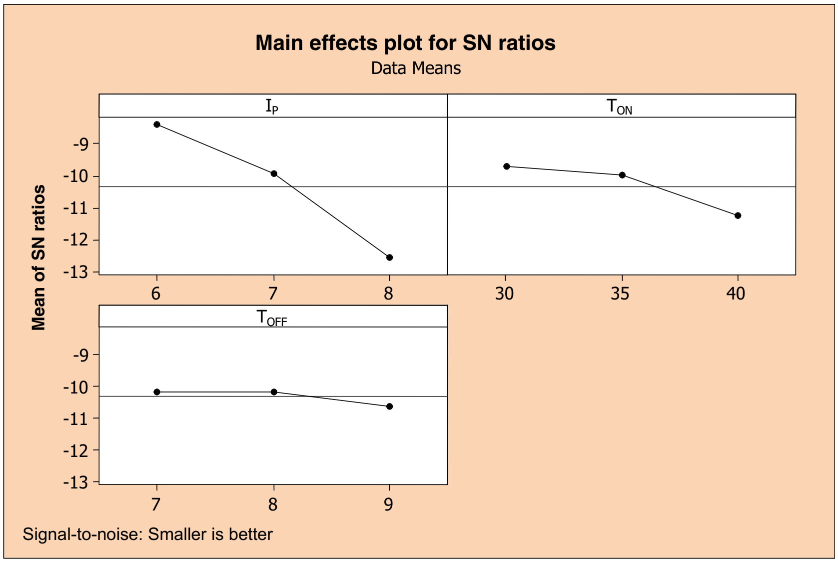
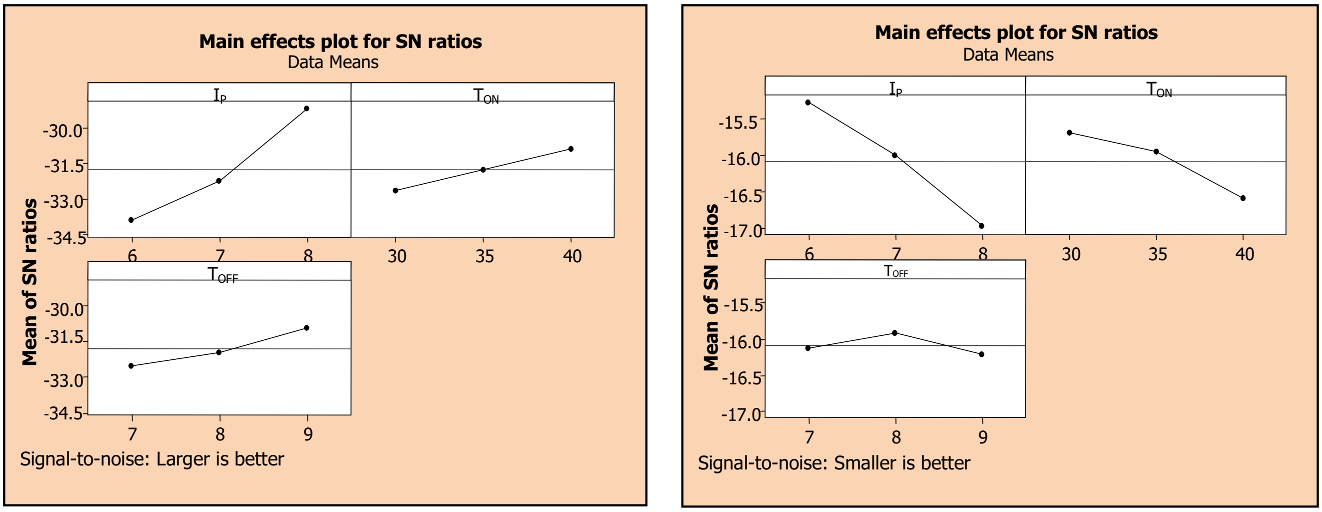
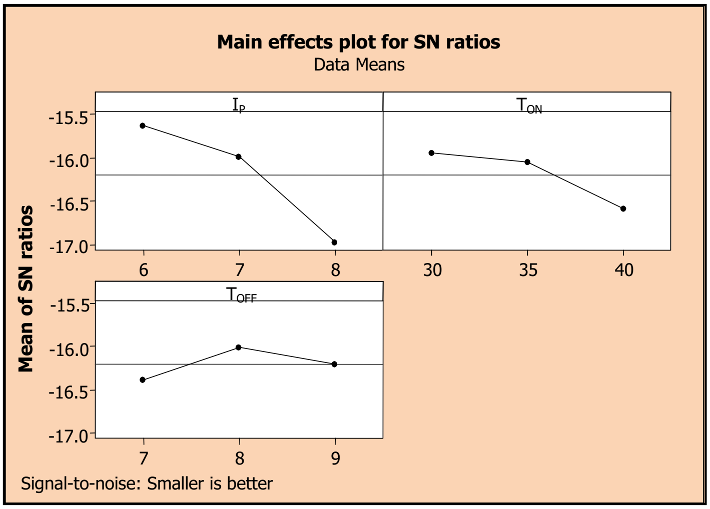


Fig. 5 S/N ratio curve for R_a with I_P, T_{ON} and T_{OFF}-biodiesel dielectric



(a) Material removal rate (b) Electrode wear rate



(c) Surface roughness

Fig. 6 S/N ratio curves for transformer oil. **a** Material removal rate. **b** Electrode wear rate. **c** Surface roughness

Referring to Table 12, it is observed that I_p ranks first which means that it has a maximum effect on R_a, T_{ON} have a considerable effect and T_{OFF} has the least effect on R_a. The signal-to-noise ratio for EWR in the case of biodiesel is plotted and shown in Fig. 5. In these plots, the levels are plotted in the X-axis and S/N ratio for the respective levels are plotted in Y-axis. From the plot, it is observed that surface roughness increases with increase in current. This can be attributed to the fact that the surface roughness obtained is proportional to current and pulse on time. In addition, increase in pulse on time increases roughness values

Table 14 Analysis of variance for S/N ratios for MRR-transformer oil

Source	DF	Seq SS	Adj SS	Adj MS	F	P
I_P	2	34.2867	34.2867	17.1433	108.61	0.009
T_{ON}	2	4.7422	4.7422	2.3711	15.02	0.062
T_{OFF}	2	3.9914	3.9914	1.9957	12.64	0.073
Residual error	2	0.3157	0.3157	0.1578		
Total	8	43.3359				

Table 15 Analysis of variance for S/N ratios for EWR-transformer oil

Source	DF	Seq SS	Adj SS	Adj MS	F	P
I_P	2	13.6613	13.6613	6.8306	49.34	0.020
T_{ON}	2	5.1484	5.1484	2.5742	18.59	0.051
T_{OFF}	2	0.8695	0.8695	0.4347	3.14	0.242
Residual error	2	0.2769	0.2769	0.1385		
Total	8	19.9560				

Table 16 Analysis of variance for S/N ratios for R_a-transformer oil

Source	DF	Seq SS	Adj SS	Adj MS	F	P
I_P	2	4.4165	4.4165	2.20827	12.37	0.075
T_{ON}	2	1.2910	1.2910	0.64548	3.62	0.217
T_{OFF}	2	0.1368	0.1368	0.06841	0.38	0.723
Residual error	2	0.3571	0.3571	0.17853		
Total	8	6.2014				

Table 17 Analysis of variance for S/N ratios for MRR-kerosene

Source	DF	Seq SS	Adj SS	Adj MS	F	P
I_P	2	31.1394	31.1394	15.5697	42.69	0.023
T_{ON}	2	6.3845	6.3845	3.1923	8.75	0.103
T_{OFF}	2	0.4837	0.4837	0.2418	0.66	0.601
Residual error	2	0.7295	0.7295	0.3647		
Total	8	38.7370				

whereas increase on pulse off time has no appreciable effect on surface roughness. Table 13 indicates the analysis of variance for S/N ratios for R_a-biodiesel dielectric.

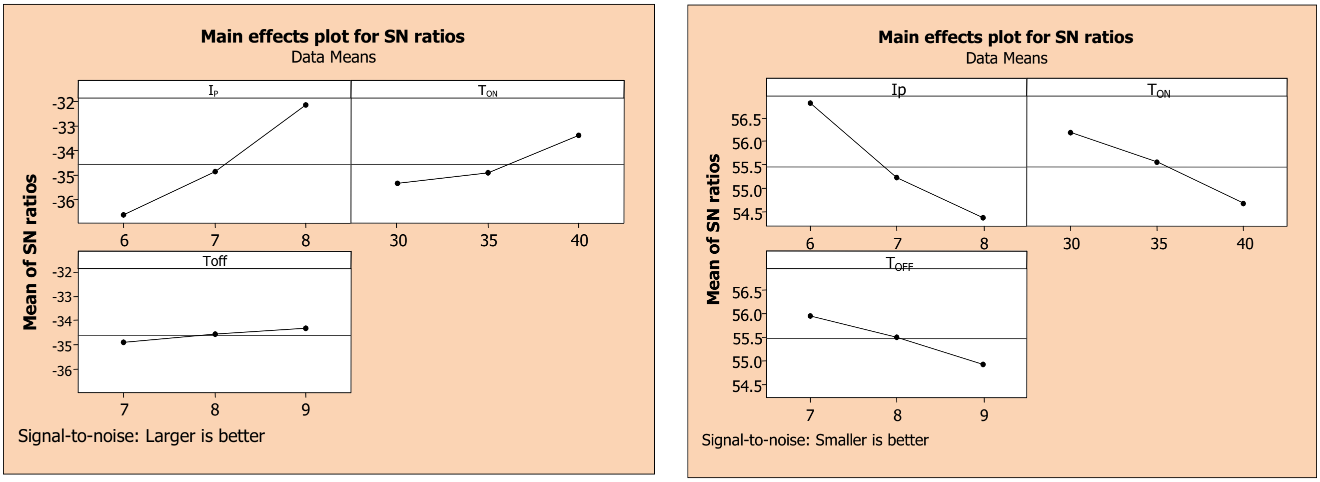
The regression analysis was made to see the difference between the main effects of levels 1, 2 and 3 of the variables on the MRR, EWR and R_a.

3. Statistical regression analysis for R_a vs I_P, T_{ON} and T_{OFF}

$$S = 0.249960 \ \ \text{R-Sq} = 93.4\% \ \ \text{R-Sq(adj)} = 89.5\%$$

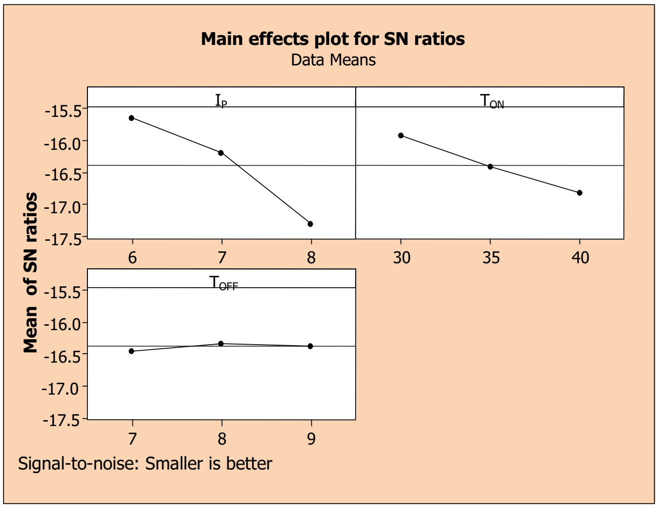
The regression equation is

$$R_a = -4.74 + 0.810\, I_P + 0.0580\, T_{ON} + 0.050\, T_{OFF}$$



(a) Material removal rate

(b) Electrode wear rate



(c) Surface roughness

Fig. 7 S/N ratio curves for kerosene. **a** Material removal rate. **b** Electrode wear rate. **c** Surface roughness

4.2 Dielectric transformer oil

The material removal rate, electrode wear rate and surface roughness plots for transformer oil as working fluid are shown in Fig. 6a–c, respectively, while machining Al 6063 material. The plot trends are almost similar to that of the trends obtained in the case of biodiesel dielectric. Tables 14, 15 and 16 provide the analysis of variance for S/N ratios for MRR, EWR and R_{a} for transformer oil dielectric.

The regression analysis was conducted to see the difference between the main effects of levels 1, 2 and 3 of the variables on the MRR, EWR and R_{a}

1. Statistical regression analysis for MRR vs I_{P}, T_{ON} and T_{OFF}

$$S = 0.00238141 \quad \mathrm{R{-}Sq} = 93.0\% \quad \mathrm{R{-}Sq(adj)} = 88.9\%$$

The regression equation is

$$\mathrm{MRR} = -0.0590 + 0.000723\, I_{\mathrm{P}} + 0.00487\, T_{\mathrm{ON}} + 0.00223\, T_{\mathrm{OFF}}$$

2. Statistical regression analysis for EWR vs I_{P}, T_{ON}, and T_{OFF}

$$S = 0.0000752404 \quad \mathrm{R{-}Sq} = 95.1\% \quad \mathrm{R{-}Sq(adj)} = 92.2\%$$

The regression equation is

$$\mathrm{EWR} = -0.00177 + 0.000258\, I_{\mathrm{P+}}0.00030\, T_{\mathrm{ON}} + 0.000052\, T_{\mathrm{OFF}}$$

3. Statistical regression analysis for R_{a} vs $\mathrm{I_P}$, $\mathrm{T_{ON}}$ and $\mathrm{T_{OFF}}$

$$S = 0.246552 \quad \mathrm{R{-}Sq} = 90.7\% \quad \mathrm{R{-}Sq(adj)} = 85.1\%$$

The regression equation is

$$R_{\mathrm{a}} = -0.32 + 0.625\, I_{\mathrm{P}} + 0.0640\, T_{\mathrm{ON}} + 0.013\, T_{\mathrm{OFF}}$$

4.3 Dielectric kerosene

The material removal rate, electrode wear rate and surface roughness plots are shown in Fig. 7a–c, respectively while machining Al 6063 material using kerosene as dielectric. The plot trends are almost similar to that of the trends obtained as in the case of biodiesel dielectric. Tables 17, 18 and 19 show the analysis of variance for S/N ratios for MRR,EWR and R_{a} for kerosene dielectric. The flash point of kerosene is low and hence its working range is short. This short working temperature range necessitates frequent and strict temperature control of dielectric fluid.

Table 18 Analysis of variance for S/N ratios for EWR-kerosene

Source	DF	Seq SS	Adj SS	Adj MS	F	P
I_{P}	2	9.3106	9.3106	4.6553	13.79	0.068
T_{ON}	2	3.5279	3.5279	1.7639	5.23	0.161
T_{OFF}	2	1.6238	1.6238	0.8119	2.41	0.294
Residual error	2	0.6751	0.6751	0.3376		
Total	8	15.1374				

The regression analysis has been conducted to see the difference between the main effects of levels 1, 2 and 3 of the variables on the MRR, EWR and R_{a}.

1. Statistical regression analysis for MRR vs I_{P}, T_{ON} and T_{OFF}

$$S = 0.00204508\ \mathrm{R{-}Sq} = 90.0\%\mathrm{R{-}Sq(adj)} = 83.9\%$$

The regression equation is

$$\mathrm{MRR} = -0.0362 + 0.00508\, I_{\mathrm{P+}}0.000453\, T_{\mathrm{ON}} + 0.000500\, T_{\mathrm{OFF}}$$

2. Statistical regression analysis for EWR vs I_{P} T_{ON} and T_{OFF}

$$S = 0.0000652261 \quad \mathrm{R{-}Sq} = 95.7\%\mathrm{R{-}Sq(adj)} = 93.1\%$$

The regression equation is

$$\mathrm{EWR} = -0.00154 + 0.000228\, I_{\mathrm{P}} + 0.000027\, T_{\mathrm{ON}} + 0.000087\, T_{\mathrm{OFF}}$$

3. Statistical regression analysis for R_{a} vs I_{P}, T_{ON} and T_{OFF}

$$S = 0.181433\ \mathrm{R{-}Sq} = 95.0\%\mathrm{R{-}Sq(adj)} = 92.0\%$$

The regression equation is

$$R_{\mathrm{a}} = 0.211 + 0.640\, I_{\mathrm{P}} + 0.0670\ \ T_{\mathrm{ON-}}0.0517\, T_{\mathrm{OFF}}$$

Table 19 Analysis of variance for S/N ratios for R_{a}-kerosene

Source	DF	Seq SS	Adj SS	Adj MS	F	P
I_{P}	2	4.34079	4.34079	2.17040	46.73	0.021
T_{ON}	2	1.19933	1.19933	0.59966	12.91	0.072
T_{OFF}	2	0.02736	0.02736	0.01368	0.29	0.772
Residual error	2	0.09289	0.09289	0.04644		
Total	8	5.66037				

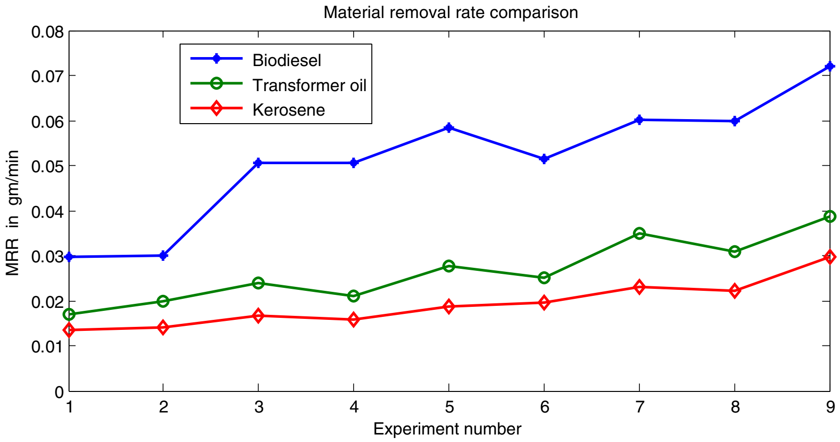


Fig. 8 Material removal rate comparison between biodiesel, transformer oil and kerosene

The material removal rate comparison for biodiesel, transformer oil and kerosene is shown in Fig. 8. It is observed that in the case of biodiesel as dielectric, the material removal rate is much higher compared to transformer oil and kerosene. However, it is noted that material removal rate in the case of transformer oil is slightly better than that of kerosene. The viscosity of EDM dielectric affects its ability to flush away debris and dissipate heat. A relatively low viscosity results in better flushing and more effective heat dissipation. For dielectric with high viscosity, which can restrict the expansion of the discharge channel, the impulsive force is concentrated within a very small area; therefore, the removal effect is enhanced and more debris can be repelled from the crater. Since the viscosity of biodiesel is much larger than that of kerosene, the craters obtained in biodiesel should be bigger and deeper than those obtained in kerosene. In addition, biodiesel has a higher dielectric strength that contributes for higher discharge energy density [37] due to higher breakdown voltage, which leads to higher molten volume of workpiece. Moreover, intense oxidation taking place due to the presence higher oxygen content in biodiesel [38].

In the case of transformer oil even though its dielectric constant is same as that of biodiesel, its viscosity is very high almost 4 to 5 times that of biodiesel. Hence, proper flushing of molten debris would not have taken place and the cooling effect would be very less. This would have caused molten Al to solidify as recast layer. Hence, MRR is less compared with biodiesel dielectric.

Renjie Ji [40] et al. explained that the positive ions in the discharge channel have enough time to be accelerated with long pulse duration. Since the mass of the positive ions is much larger than that of the electrons, the bombardment effect by the positive ions is stronger than that by the electrons; therefore, the MRR is high in positive tool polarity. The surface roughness in negative tool polarity is higher than that in positive tool polarity. The mass and energy of the positive ions are large; the electrical discharges are stable, and the surface quality is good in positive tool polarity.

In kerosene, even though viscosity is less, which is essential for flushing the debris, high discharge temperature

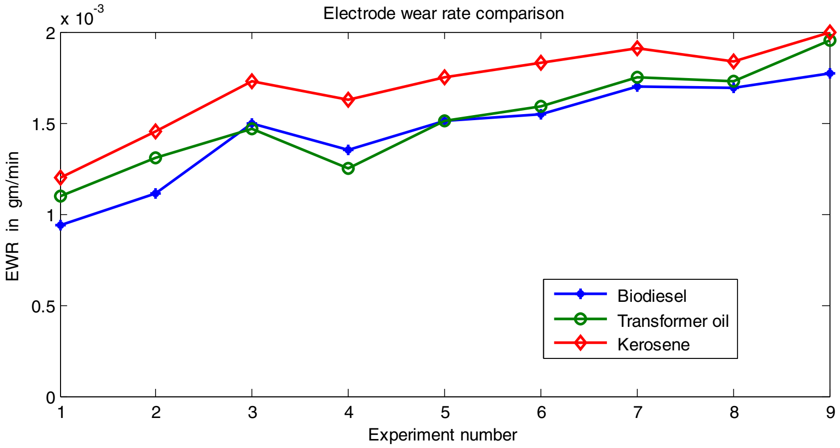
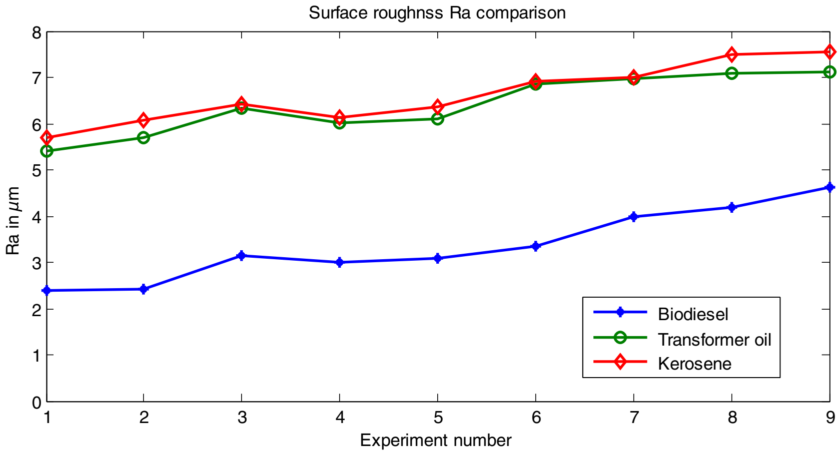


Fig. 9 Electrode wear rate comparison between biodiesel, transformer oil and kerosene

Fig. 10 Surface roughness value (R_a) comparison for biodiesel, transformer oil and kerosene



decomposes the kerosene, causing carbon elements to adhere to the electrode surface, thereby causing lower MRR. Hence, MRR becomes less in comparison with biodiesel and transformer oil. Yonghong Liu et al. [41] used three types of emulsions and kerosene as dielectric and the authors found that the craters on the workpiece surface machined by EDM with kerosene are deep; there are some micro cracks on the workpiece surface. The craters on the workpiece surface machined by EDM in emulsions-1 and -2 are large and shallow, the edges of the craters are smooth, and there are no micro cracks on the workpiece surface.

The electrode wear rates are plotted as shown in Fig. 9. It is observed that the electrode wear is less in the case of biodiesel compared to kerosene and transformer oil as dielectric.

The electrode wear rate (EWR) is mainly affected by peak current (I_P) followed by pulse on time (T_{ON}). The effect of pulse off time (T_{OFF}) is negligible. The electrode wear rate with biodiesel as a dielectric is slightly less in comparison with transformer oil and kerosene dielectric.

The surface roughness values obtained for all the three dielectrics are plotted and shown in Fig. 10. It is observed that the surface roughness value is much less in the case of biodiesel compared to kerosene and transformer oil. Moreover, it is found that there is no significant difference between kerosene and transformer oil in the surface roughness value. Surface microstructure of the materials should be considered as these play a vital role in surface roughness and it will be carried in further studies.

5 Response graph for each mean level of input values

The response values were calculated based upon the input levels. The means of average levels were taken for each $I_{P,}$ $T_{ON,}$ T_{OFF} to calculate the mean MRR, EWR, R_a and are plotted as shown in Figs 11–13. These response graphs were taken to the study of difference between the means of S/N ratio of levels and the means of average levels.

The mean MRR for each average level of input parameter $I_{P,}$ $T_{ON,}$ T_{OFF} is shown in Fig. 11. From the figure, it is evident that there is a higher MRR for biodiesel for each input level of $I_{P,}$ $T_{ON,}$ T_{OFF}. It also predicts higher

Fig. 11 MRR response graph for each mean level of the input

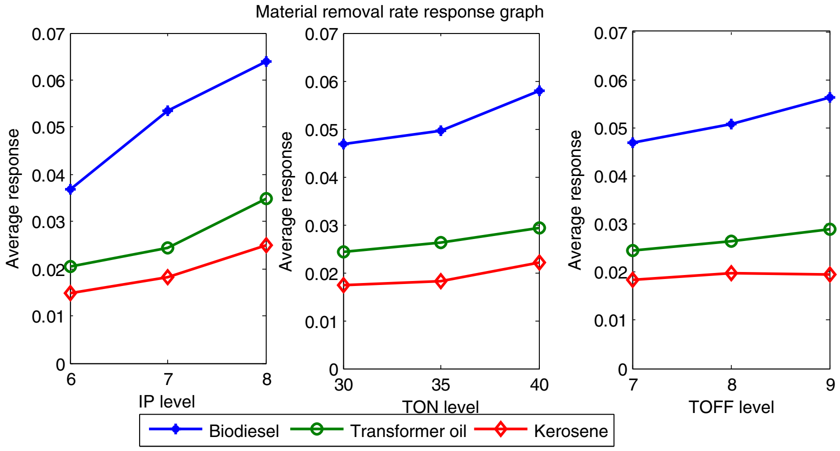
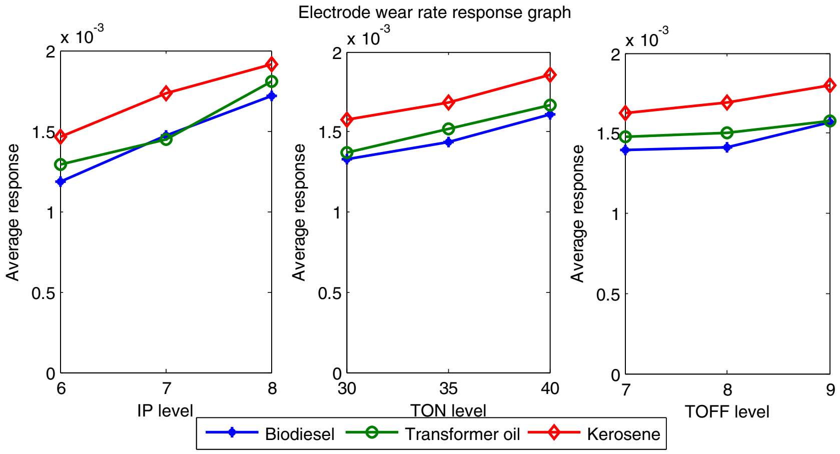


Fig. 12 EWR response graph for each mean level of the input



MRR as the input parameter increases at each levels. By doing these, the differences in the setting parameter level and their influence in their response values for MRR can be calculated, and parameter optimization for the best level for higher MRR can also be done for each setting.

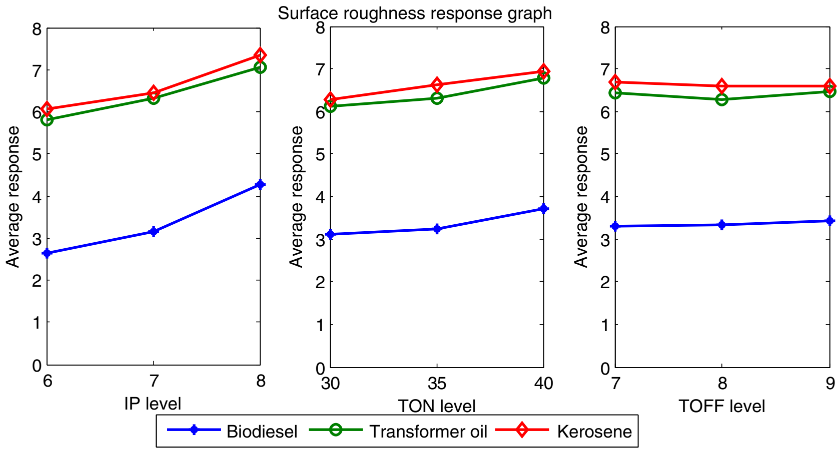
The mean EWR for each average level of input parameters $I_{P,}$ $T_{ON,}$ T_{OFF} is shown in Fig. 12. From the figure,it is evident that EWR for biodiesel is less for each input level of $I_{P,}$ $T_{ON,}$ T_{OFF} . It also predicts EWR at each levels of input. By doing these, the difference in the setting parameter levels and their influence in their response values for EWR can be calculated and parameter optimization for the best level for lower EWR can also be done for each setting.

The mean R_a for each average level of input parameters $I_{P,}$ $T_{ON,}$ T_{OFF} is shown in Fig. 13. From the figure, it is evident that the surface roughness is low in the case of biodiesel at each input level $I_{P,}$ $T_{ON,}$ T_{OFF} . It also predicts a smaller variation of R_a irrespective of change in levels of input of T_{OFF}. By doing these, the difference in the setting parameter levels and their influence in their response values for R_a can be calculated, and parameter optimization for the best level for better R_a can also be done for each setting.

6 Conclusions

- From this research work, it is found that biodiesel can be used as a dielectric in EDM. It gives high MRR and less EWR when compared to the widely used kerosene dielectric.
- Biodiesel and transformer oil emanate lesser smoke and fewer odours.
- The dielectric with lower viscosity and higher flash point are expensive and need to be imported but, biodiesel is economically viable (import substitute) and commercially feasible.
- Use of biodiesel as dielectric increases productivity.
- The material removal rate (MRR) is mainly affected by peak current (I_P) followed by the pulse on time (T_{ON}). Moreover, the effect of pulse off time (T_{OFF}) is negligible.

Fig. 13 Surface roughness R_a response graph for each mean level of the input



- The electrode wear rate (EWR) is mainly affected by peak current (I_P) followed by pulse on time (T_{ON}). The effect of pulse off time (T_{OFF}) is negligible.
- Peak current and pulse on time are the most influential parameters for reducing surface quality. Better surface finish is possible at lower current.
- Various types of biodiesels (edible and non-edible oil) are available with lower viscosity and higher flash point, and their usage as dielectric on commercial basis may be studied in future.
- However, the environmental hazard of biodiesel has to be studied in detail.

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