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ORIGINAL ARTICLE

Assessment of operational feasibility of waste vegetable oil based bio-dielectric fluid for sustainable electric discharge machining (EDM)

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Abstract Since the first application of electric sparks for the material removal was demonstrated, the electric discharge machining (EDM) process has gone through considerable changes in terms of technology and application. The process has surpassed the technological barriers by overcoming its then thought limitations like processing speed, material conductivity, dimensional and geometrical accuracies, and surface finish. However, environmental impact due to release of toxic emission products, operator health concerns due to release of toxic fumes, vapours and aerosols during the process, poor operational safety due to fire hazards and electromagnetic radiation, and toxic and non-biodegradable dielectric waste generated are some of the concerns still prevailing in EDM process. Authors, in this paper, have assessed the operational feasibility of waste vegetable oil (WVO) as possible alternative dielectric fluid and compared the response patterns of WVO with hydrocarbon oil, kerosene. Experiments were performed using spark current, gap voltage, pulse on time (pulse duration) and pulse off time (pulse interval) as control parameters to study the response behaviour for material removal rate (MRR), electrode wear rate (EWR) and tool wear ratio (TWR). The results obtained reveal that WVO-based bio-dielectric fluid can be used as an alternate to hydrocarbon-, water- and synthetic-based dielectric fluids for EDM. Besides the successful trials for operational feasibility assessment, application of bio-fluids offers a cleaner, greener and safer solution for dielectric to improve sustainability of EDM process by improving environmental friendliness, operational safety and personnel health issues of the process. Based on the experimental results and observations, the authors have suggested further scope of works to improve sustainability of the EDM process.

Keywords Sustainability · Sustainable manufacturing · Waste vegetable oil (WVO) · Bio-dielectric fluid · Hydrocarbon dielectric · Operational feasibility · Sustainable EDM

Abbreviations

EDM	Electric discharge machining
WVO	Waste vegetable oil
MRR	Material removal rate (mm^3/min)
EWR	Electrode wear rate (mm^3/min)
TWR	Tool wear ratio(%)
BHN	Brinell hardness number
T_{on}	Pulse on time (μs)
T_{off}	Pulse off time (μs)

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1 Introduction to EDM technology

Electric discharge machining (EDM) is one of the most practicing and versatile non-conventional metal removal process with more than 7 % market share amongst all manufacturing processes [1]. Because of its ability for hybridisation with other conventional and non-conventional processes, EDM variants like die sinking, wire cut EDM, electric discharge drilling [2], electro-discharge milling [3], electro-discharge grinding [4, 5], electric discharge coating [6], electric discharge texturing [7] and electric discharge deposition/welding [8] are in practice. In earlier times, application of EDM was limited for processing conductive materials. However, recent developments have shown that it can be used for conductive, for semi-conductive and for insulating materials like glass and ceramics [9], composites [10] and plastics. Moreover, EDM processes have gone through considerable changes in terms of types of dielectric fluids used and modes of dielectric supply. Hydrocarbon oils, water-based solutions, synthetic and mineral oil, and gaseous dielectric fluids have been experimented with wet, powder mixed, dry and near-dry modes of dielectric supply. EDM process has expanded its stems into the manufacture of simple to the most complex geometrical profiles, meso- to micro-manufacturing, processing of low to high melting temperature materials, processing of soft to the hardest materials and generating rough to mirror-finished surface accuracies.

2 Sustainability concerns of EDM process

The US Department of Commerce defined sustainable manufacturing as "the creation of manufactured products that use processes that minimise negative environmental impacts, conserve energy and natural resources, and are economically sound and safe for employees, communities, and consumers" [11]. Sustainability of any manufacturing process can be improved by minimising environmental impact, manufacturing cost and energy consumption while improving of personnel health, operational safety and waste management practices of the process. EDM process is imperative for manufacturing dies, moulds and tools from hard and difficult to cut materials with high dimensional and geometrical accuracies. However, EDM process offers some environmental, economic and social concerns like poor material removal rate, electrode wear, high specific energy consumption, deteriorated surface characteristics, hazardous emissions near operator breathing zone, the possibility of fire explosion and toxic waste and sludge generation.

EDM with liquid dielectric is a well-established process. However, Yeo et al. [12] reported some problems associated with wet EDM, i.e. electrolysis corrosion with water as the dielectric while toxic hydrocarbon disposal when kerosene based dielectric is used. Sivapirakasam et al. [13] have reported in their investigation that large amounts of solid, liquid and gaseous wastes are discharged by kerosene dielectric, which result in serious environmental problems. These toxic substances can enter the body through inhalation and skin contact. Leao and Pashby [14] have reported that hydrocarbon-based oils are one of the main sources of pollution; waste generated from water-based dielectrics are also toxic and needs to follow environmental regulations for its disposal. Kern [15] reported that the sludge, dielectric waste, filter cartridges and deionising resins have serious concerns related to reuse and recycle causing land and water pollution. Powder mixed dielectric increases the machining cost and environmental concern due to disposal of toxic waste. Also, there is a challenge to maintain constant powder concentration and separation of the machined debris from the useful powders as reported by Yeo et al. [12].

Ray [16] has stated that during EDM, various harmful substances are released in solid, liquid and gaseous forms which result in serious occupational health and environmental issues. During the EDM process, toxic fumes, vapours and aerosols are produced. Hydrocarbon-based dielectrics contain aromatic, paraffinic and naphthenic compounds. Goh and Ho [17] investigated that prolonged exposure to these compounds causes carcinogenic, respiratory and occupational dermatitis related diseases. El-Hofy and Youssef [18] reported that EDM has several hazard potentials like hazardous smoke, vapours, aerosols, decomposition products and heavy metals. Hydrocarbon dielectrics affect the skin, and sharp-edge metallic particles damages the skin, with other hazards like possible fire hazard and explosions and electromagnetic radiation. Contamination and long usage of dielectric medium will increase the emission rate and risk of fire. Jose et al. [19] have also observed that higher values of process parameters increase the concentration of aerosol emissions to beyond permissible limit of 5 mg/m^3. Bommeli [20] mentioned that carcinogenic hydrocarbons like benzene and polycyclic aromatic hydrocarbons (PAHs) are expected while using hydrocarbon-based dielectric fluids. Poor surface finish due to debris reattachment, odour of burning and low material removal rate (MRR) are some of the limitations of the dry EDM when using non-oxygen gases reported by Kunieda and Yoshida [21], Kao et al. [22].

Gutowski et al. [23] reported that the EDM process requires high specific energy of the order of 1.E +10 J/cm^3 compared to conventional machining with 1.E +3–4 J/cm^3, which is 30–50 times more energy than its conventional counterparts. It offers slow machining rates of the order of 1.E −06/−07 cm^3/s compared to 1.E −01/+01 in case of conventional machining process, which is 50–60 times slower than conventional processes. Dry EDM technique was developed to decrease the pollution caused by the use of liquid dielectric which leads to production of vapour during machining and the cost to manage the waste [24]. Chen et al. [25] investigated that distilled water as dielectric results in more number of surface cracks. Also, distilled water produces metal oxides on the surface while kerosene produces carbides. Kruth et al. [26] experimented using C35 steel for white layer characteristics and observed that the machined parts in hydrocarbon oil contained about four times more carbon than the base material. On the other hand, in machined parts with deionised water, the white layer contained 50 % less carbon content of the base material. Difference in carbon content, thermal conductivities, maximum temperature rise and other properties of dielectric fluids affects the corrosion resistance, oxidation, pyrolysis, fatigue and endurance strength, hardness, recast and white layer thicknesses. Even though dry and near-dry dielectric systems have been used for certain requirements, liquid dielectric is imperative for stable, consistent and efficient EDM reported by Pandey and Singh [27].

Some researchers have performed process parameter optimisation for achieving green EDM. Sivapirakasam et al. [13] have developed a decision making model for the selection of process parameters to achieve green EDM. Tang and Du [28] have optimised the process using Taguchi and grey relational analysis to obtain green EDM. Ray JA [29] used integrated approach of using entropy and grey relational analysis for selection of optimum process parameters to achieve green EDM.

From the reviewed past works, it can be summarised that hydrocarbon-, water- and gas-based dielectrics have an adverse influence on process performance in terms of environment, social and economic viewpoints. Decomposition products of dielectric causes carburisation or decarburisation which affects surface hardness; different thermal conductivities result in surface cracks and affect endurance and fatigue strengths due to varying cooling rates. Viscosity of dielectric fluid influences the quantity and quality of emission products generated. Density and dielectric strength of the fluid affect debris evacuation efficiency which in turn affects surface roughness and material removal rate. Composition of the dielectric affects corrosion and other surface characteristics of the material.

3 Vegetable oil based bio-fluids as possible dielectric fluid for EDM

Shah et al. [29] reported that vegetable oil based esters have dielectric properties comparable to hydrocarbon and synthetic oils. Martin et al. [30] have used esterified bio-oils for electrical power transformer due to its superior properties and characteristics than hydrocarbon and mineral-based oils. Based on its impact on sustainability, vegetable oils are categorised into edible, non-edible and used oil in terms of highest to lowest severity. Recondition and reuse of used vegetable oils may have enormous positive impact on sustainability. Bio-based fluids have some potentials to replace hydrocarbon-, water- and gas-based dielectric for EDM process.

The potential of the bio-fluids as a dielectric fluid for EDM 221 is identified due to following facts and qualitative assessment given in (Table 1):

- Higher flash point [29, 31]
- Excellent biodegradability [31]
- Higher oxygen content [32]
- Low carbon atom chain [32, 33]
- Nontoxic [30, 34]
- Higher breakdown voltage [29, 35, 36]
- Higher viscosity [36]
- Lower toxic emissions [37]
- Lower volatility and toxic emissions [37]

Bio-fluids have been used as dielectric media for electrical engineering applications and reported to have comparable or even superior performance to hydrocarbon-, silicone- and synthetic-based oils [30, 31, 33–37]. However, application of bio-fluids in EDM has yet not been reported. Due to the abundance and ready availability and ease to esterification, waste vegetable oil (WVO) can be a potential alternate dielectric fluid for EDM. Khan et al. [38] have reported that amongst all bio-oils, WVO has the highest impact index of sustainability. WVO is the cheapest of all vegetable oils, has the highest conversion ratio and has the most economical process [39, 40]. Also, application of WVO saves landfills, rivers, municipal sewage lines and other sources of potable water from polluted waste disposal. Authors have tried this novel alternative bio-fluid to assess operational feasibility through performance analysis to study the response behaviour of MRR, electrode wear rate (EWR) and tool wear ratio (TWR) and compared the results with kerosene.

4 Experimental details for performance analysis

4.1 Work piece, electrode and dielectric

For this study, M238 HH grade (equivalent to P20+ grade) cold worked plastic mould steel workpieces were used as workpiece material. Material used was prehardened and tempered, having Brinell hardness number (BHN) of 355–359 and size of the sample as 100 mm× 50 mm×15 mm ($l\times b\times t$). Electrolytic grade, 99.73 % copper rods of 20-mm diameter were used as electrodes for the experiments. Esterified waste vegetable oil (WVO) and kerosene were used as dielectric fluids for the research study. Chemical composition of the work piece and electrode material are shown in Tables 2 and 3 respectively, and properties of waste vegetable oil based dielectric fluid used are shown in Table 4.

4.2 Machine tool

The experiments were performed using Sparkonix make die sinking EDM machine, as shown in Fig. 1.

The EDM machine was supported by MOSFET controller, having a current rating of 25 A, as a pulse generator for the process.

Table 1 Qualitative assessment for suitability of bio-oils as EDM dielectric

Desired Property	Justification	Bio oils	Mineral oil
High breakdown voltage	For minimum arcing (random and uncontrolled low energy arc, higher energy utilisation ratio)	Higher	Lower
Low relative permittivity/dielectric constant	For min. Energy loss, For lower electrostatic energy to minimise magnetic field effect, prevent localised spark reoccurring	Higher	Lower
Low dissipation factor	For minimum power loss, prevent aging and deterioration	Higher	Lower
Higher density	For better flushing effect	Higher	Lower
Lower viscosity	For better cooling capacity	Higher	Lower
Higher flash and fire points	For fire prevention	Higher	Lower
Lower pour point	For better flow characteristic at low temp	Higher	Lower
Higher oxidative stability	For longer working life of fluid	Lower	Higher
Lower sulphur, iodine and acid numbers	For better personnel health	Lower	Higher
Higher oxygen content	For minimum combustion hazard release	Higher	Lower
Higher biodegradability	For environment protection	Higher	Lower
Higher thermal conductivity and specific heat	For better cooling of electrode and work material and material integrity	Higher	Lower

4.3 Experimental procedure

An experimental setup was developed to supply dielectric using a submerged type single jet nozzle, which included a dielectric supply system with a submersible pump. This configuration allowed an efficient gap cleaning during machining and also prevented fire explosion by submerging the full sparks. Influence of four control parameters, vis. pulse current, gap voltage, pulse on time and pulse off time (six levels of each), as shown in Table 5, on three response parameters, vis. material removal rate (MRR), electrode wear rate (EWR) and tool wear ratio (TWR), was investigated. A total of 24 sets of experiments were performed for the study with 10-min material erosion time for each set. Absolute weight difference method was used to determine MRR and EWR using 20 mg accuracy digital weighing scale. TWR was calculated taking the ratio of EWR/MRR.

5 Experimental results and discussion

5.1 Influence on material removal rate

The comparative response behaviour of kerosene- and WVO-based dielectric for MRR under the influence of selected control parameters is depicted in Fig. 2a–d. MRR is termed as machining time per unit volume of material removed, which is related to production cost. A higher MRR is desirable for achieving more economical production.

Figure 2a indicates the comparative response trends showing the influence of current on the behaviour of MRR for the given experimental condition for the two dielectric fluids used. It is found that with increase in current values, MRR increased for all levels of current for both fluids which is attributed to higher pulse energy at higher current. This finding show that waste vegetable oil behaves similar as dielectric fluid to hydrocarbon-based dielectric, i.e. kerosene. For the current range used, WVO resulted in higher MRR than kerosene. This can be attributed to higher discharge energy density [41], due to higher breakdown voltage and intense oxidation due to higher oxygen content [42] of WVO compared to kerosene. High BD voltage retards early sparking, and also minimises unwanted arcing which results into efficient sparking cycles.

Figure 2b shows the comparative response trends for the influence of gap voltage (sparking gap) on the behaviour of MRR. Results obtained show that with increase in gap voltage, WVO resulted in declining pattern for MRR as those of kerosene. However, for any gap voltage, WVO resulted in significantly higher MRR than kerosene. It may be associated with the fact that the delayed dielectric breakdown would have resulted into increased discharge density and hence higher MRR in case of WVO.

The comparative response trends shown in Fig. 2c highlight the effect of pulse on time (T_{on}) on the behaviour of MRR. Results obtained show that WVO exhibited a similar

Table 2 Electrode material composition

Element	Cu	Ni	Tin	Zn	Mn	Al	C	Si	Lead	P	Ar	Su
Composition (%)	99.71	0.019	0.005	0.13	0.001	0.007	0.03	0.002	0.01	0.038	0.002	0.029

Table 3 Work Material composition

Element	C	Si	Mn	P	S	Cr	Mo	Ni	Al
Composition (%)	0.36	0.28	1.52	0.008	0.001	1.88	0.22	0.95	0.021

pattern for MRR to kerosene but resulted remarkably in higher MRR than kerosene for the same T_{on} value. This may be attributed to the fact that because of higher BD voltage, oxygen content, viscosity and thermal conductivity of WVO, even for the same discharge energy level, intensified ionisation state of dielectric in the discharge gap would have sustained for a longer time resulting in improved melting and evaporation phenomenon. Hence, higher MRR is obtained for WVO than kerosene.

Figure 2d shows the influence of pulse off time (T_{off}) on the behaviour of MRR. It can be observed from the results that WVO shows the similar response pattern for various T_{off} values. However, MRR was significantly higher with WVO than kerosene at the same value of T_{off}. It may be a sign that because of higher BD voltage and lower heat conductivity, WVO sustains ionised state for longer duration due to higher viscosity and lower specific heat than kerosene. Controlled behaviour of ionised and deionised states of WVO with T_{off} portrays its suitability for EDM process.

It can be summarised that for selected experimental conditions, WVO resulted in higher MRR than kerosene. Also, the patterns of various responses are similar to that of kerosene and also in line with the results of other researches for the same control parameters [43–45]. Results indicated that the dielectric breakdown, material melting and evaporation phenomenon may be similar as that of kerosene. Moreover, WVO resulted in significantly higher MRR for the control parameters used for the experiments.

5.2 Influence on electrode wear rate

Electrode wear takes place in EDM due to impingement of high-speed electrons on the softer electrode surfaces (tool). Wearing of electrode surfaces alter the dimensional and geometrical accuracies of the cavities to be generated, which eventually demand replacement of the worn-out electrodes, as reconditioning or reshaping is not possible. Hence, minimum EWR is desirable from the electrode cost point of view.

Figure 3a–d shows the comparative response trends for the influence of current, gap voltage, T_{on} and T_{off} on the behaviour of EWR for the given experimental conditions. Results shown in Fig. 3a demonstrate that EWR increased with an increase in current, for both the fluids. Moreover, WVO resulted in higher EWR than kerosene for the same value of current. Gopalakannan and Senthilvelan [46] have reported the similar trend for EWR using kerosene. WVO produced substantially higher EWR for higher current values than kerosene. Higher EWR at higher current value was an indicator of stronger electron impingement on electrode surfaces due to improved oxidation and conductive discharge channel.

Figure 3b shows the influence of gap voltage on the behaviour of EWR. Results indicate that both fluids exhibited a similar response pattern of EWR. However, for any gap voltage, WVO resulted in higher EWR than kerosene. The result obtained suggests that, as gap voltage increases, discharge density reduces due to widened sparking gap. Hence, the intensity of electrons, which are striking on the electrode surfaces increase, which in turn increases EWR. However, higher viscosity and oxygen content of WVO maintains discharge density for longer period than kerosene.

The comparative response trends for the influence of T_{on} on the behaviour of EWR is shown in Fig. 3c. Results indicated that WVO and kerosene behave similarly under the influence of T_{on}. However, electrode surfaces worn more in case of WVO, compared to kerosene for the same T_{on} values. This behaviour attributes to the fact that more T_{on} means more time available to dispense the pulse energy resulting into lesser discharge energy density. Also, dependence of discharge energy density on plasma channel diameter minimises the intensity of striking electrons on electrode surfaces.

Figure 3d shows the influence of T_{off} on the behaviour of EWR. Results obtained for WVO and kerosene show the similar response trends. Moreover, for the same value T_{off}, WVO resulted in higher EWR than kerosene. The reason for such behaviour is due to higher viscosity and thermal conductivity of WVO. Higher viscosity confines the plasma channel [47, 48] and higher thermal conductivity ensures better heat

Table 4 Properties of waste vegetable oil and kerosene based dielectric fluid

No.	Dielectric	Density (gm/ml)	Viscosity at (40 °C)	Thermal conductivity (W/m·K)	Specific heat (kJ/kg·K)	Flash point (°C)	BD voltage (kV/2.5 mm)	Dielectric constant
1	Waste Vegetable oil	0.8932	9.55	0.20	1.67	171	26	2.86
2	Kerosene	0.80	2.71	0.15	2.01	81	18	4.7

Table 5 Experimental parameters and its levels

Pulse current (A)	3, 6, 9, 12, 15, 18
Pulse ON time (μs)	21, 50, 100, 200, 400, 600
Pulse OFF/interval time (μs)	6, 11, 20, 30, 40, 75
Gap voltage (kV)	30, 40, 50, 60, 70, 80
Polarity	Positive (electrode +ve)

transfer and electron movement toward the electrode side, which eventually increased EWR in case of WVO. Also, process shows instability due to insufficient deionisation time of the dielectrics, which resulted into higher EWR at lower T_{off} values [49]. At higher T_{off} values, due to the high pulse energy density, electrons attack electrode surface more strongly which increases electrode wear rate [50].

It can be summarised that for selected experimental conditions and influence of control parameters, WVO resulted in higher EWR than kerosene. Also, the patterns of various responses are similar to that of kerosene and also in line with the results of other researches for the same control parameters [46, 51, 52]. It indicates that the dielectric breakdown, material melting and evaporation phenomenon may be similar as those of kerosene. Moreover, WVO resulted in significantly higher EWR for the control parameters used for the experiments. In spite of higher EWR values, the similarity of the response trends for WVO with kerosene indicates operational feasibility of WVO.

5.3 Influence on tool wear ratio

Tool wear ratio signifies the relative wear between electrode and workpiece. It relates to tooling cost of the process. Higher values of the ratio indicate higher tooling cost and higher overall production economics. It is desirable to have lower TWR for EDM process.

Figure 4a shows comparative response trends for the influence of current on the behaviour of TWR. It can be seen that as current increases, TWR decreases for initial values and increases thereon for higher current values for both fluids. The reason for such behaviour could be answered as, for lower current levels, lower electrical conductivity of the partially ionised state of the plasma channel hinders the electron movement towards electrode surface resulting in the decrease of TWR [53]. But, beyond 9-A current, plasma channel becomes highly conducting, allowing electrons to strike back on electrode surfaces, eroding electrode material at a faster rate which results in higher TWR. WVO resulted in better TWR up to 9-A current than kerosene.

Comparative response trends in Fig. 4b show the influence of gap voltage on the behaviour of TWR. Results obtained show that both fluids exhibit similar response patterns. However, with up to 50-kV gap voltage, TWR performance was found to be better with WVO dielectric than with kerosene.

Figure 4c shows the influence of T_{on} on the behaviour of TWR. Results obtained indicate that as the T_{on} increases, the TWR decreases for both fluids. However, WVO resulted in better TWR than kerosene. These results are attributed to the reason that longer pulse duration, due to more energy and time available, results in the larger crater formation and hence demonstrates higher MRR. On the other hand, due to higher thermal conductivity of copper electrode, crater size would be very small due to dispersion of more heat for copper electrode.

Figure 4d shows the influence of T_{off} on the behaviour of TWR. Results obtained show that WVO generated similar response pattern as like kerosene. Also, lower T_{off} values up to 20 μs resulted in better TWR for WVO. The results obtained for TWR using WVO and kerosene

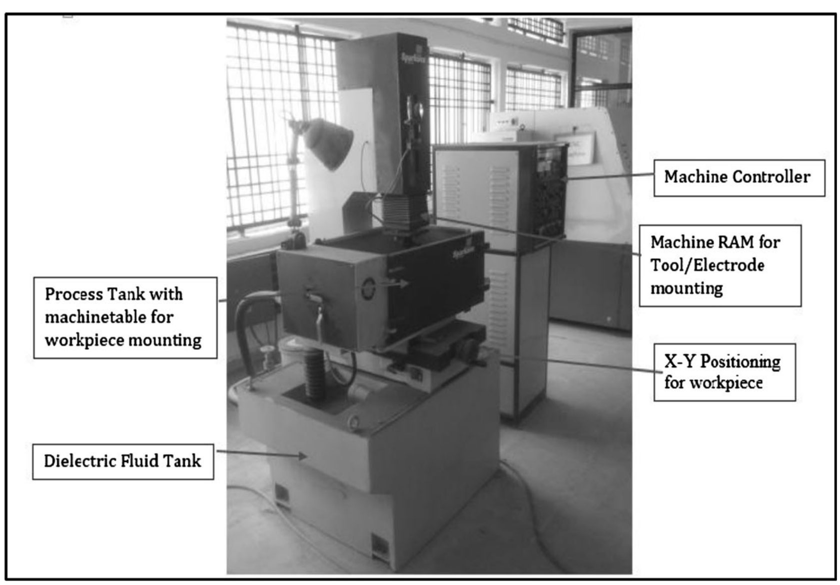
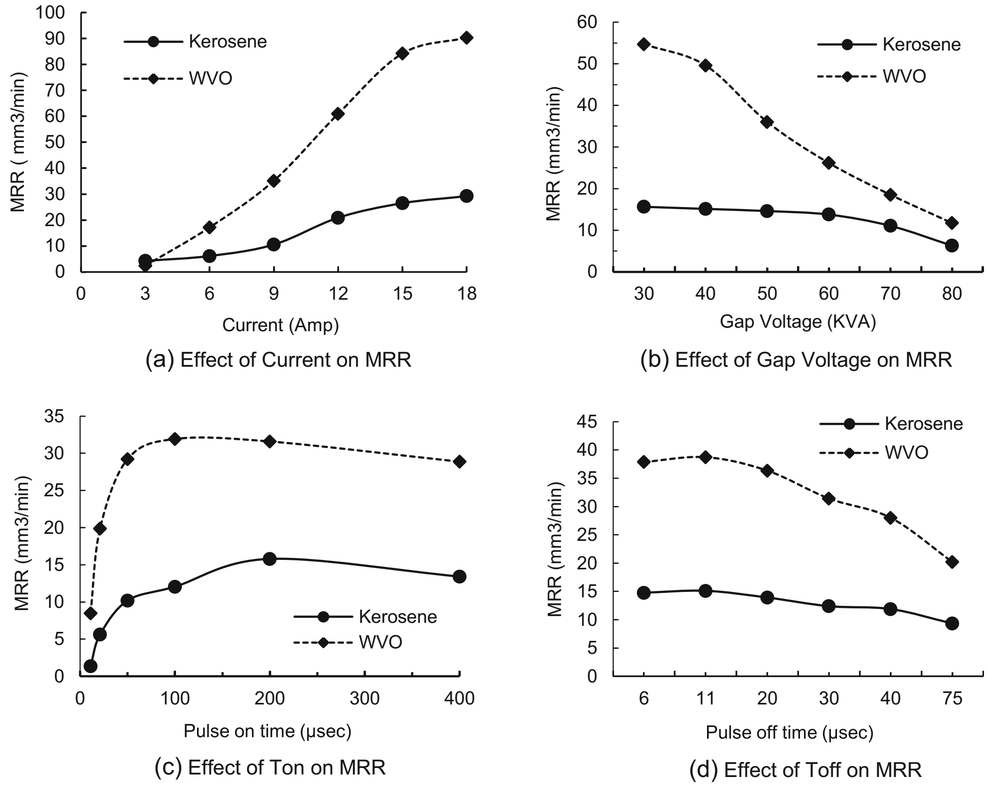


Fig. 1 EDM machine used for the experiment

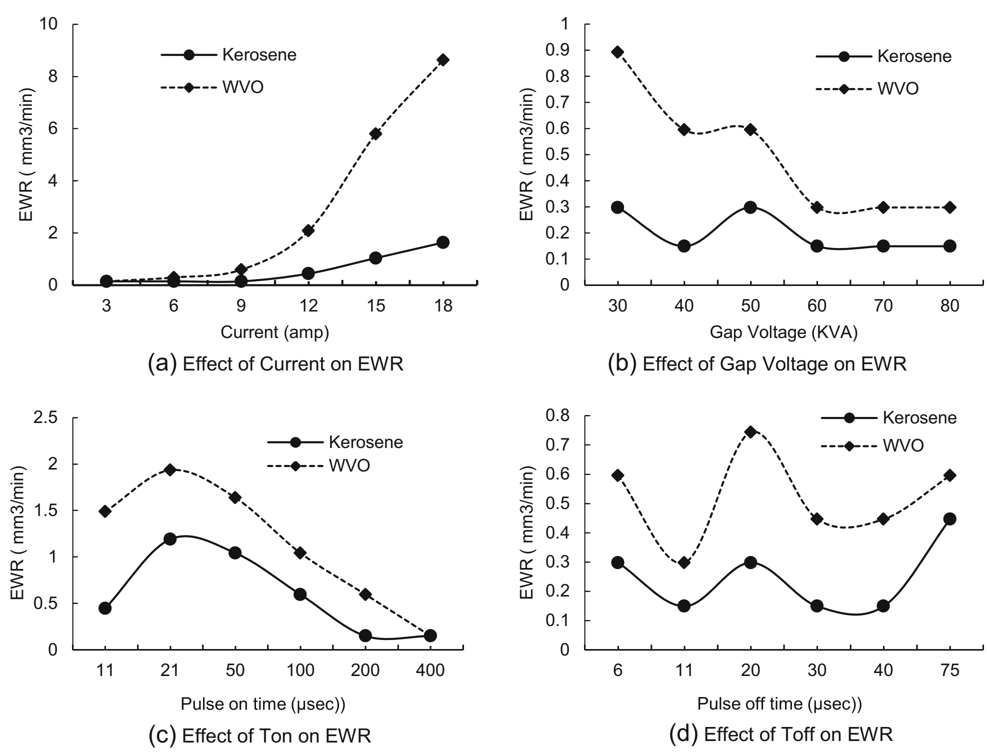
Fig. 2 a–d Influence of current, gap voltage, T_{on} and T_{off} on MRR



in this study were in line with the behaviour patterns of hydrocarbon- and water-based dielectrics as researched by other researchers [43, 45, 51].

It can be summarised from the above discussion that WVO performed better as dielectric fluid than kerosene in terms of TWR under the influence of T_{on}. Moreover,

Fig. 3 a–d Influence of current, gap voltage, T_{on} and T_{off} on EWR



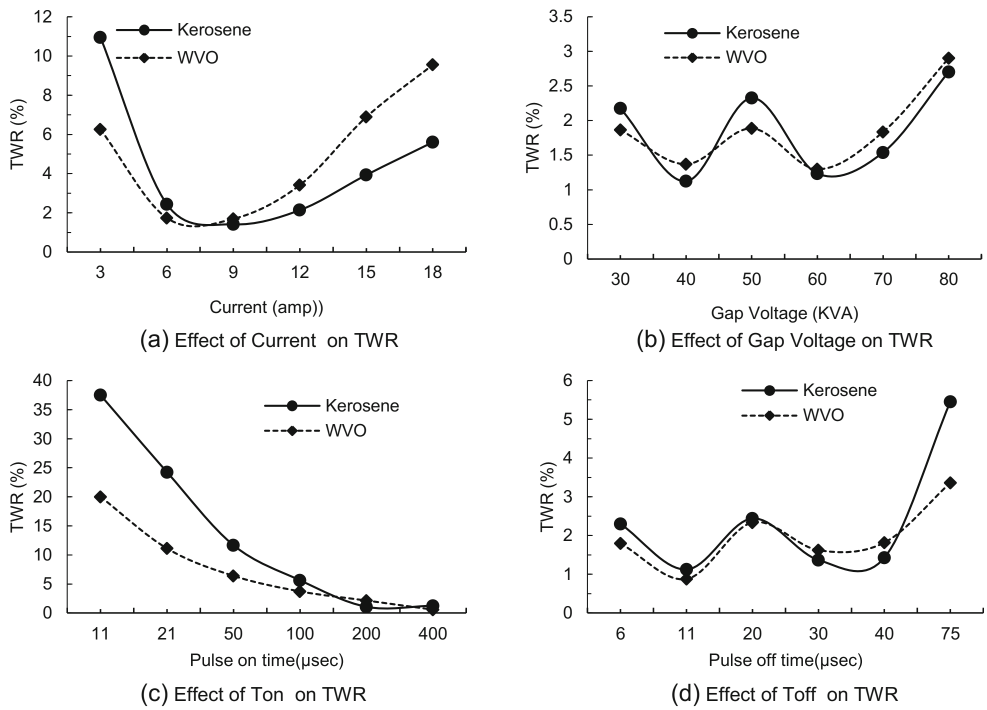


Fig. 4 a–d Influence of current, gap voltage, T_{on} and T_{off} on TWR

WVO performed better than kerosene for lower values of current, gap voltage and T_{off}.

6 Conclusion

Research related to EDM process seems more skewed towards either improvement of process performance or expanding the application domain of the process. Adopting sustainable manufacturing practices is a proven socio-cost benefit component for manufacturing industries due to growing awareness amongst society. Moreover, due to emergence of ISO 14000 series environment management standards, manufacturing industries are compelled to implement sustainable manufacturing practices. Application of WVO-based bio-dielectric fluid in EDM process is considered with a view to improve sustainability of EDM process. The comparative results obtained in this research show that from the operational feasibility point of view, WVO dielectrics can be used as an alternative to hydrocarbon-based dielectric fluid, i.e. kerosene. Trends of response parameters, i.e. MRR, EWR and TWR, obtained using WVO indicate similarity with results of kerosene. Besides the successful trials for operational feasibility assessment, qualitative assessment carried out for assessing suitability of WVO for EDM process suggests that WVO can be a cleaner, greener and safer solution for improving sustainability of EDM process. In addition, WVO-based dielectric fluid improves environmental friendliness, operational safety and personal health issues of the process.

7 Further work

Besides the operational feasibility carried out by the authors in this work, authors have identified some research areas, to explore and exploit for improving sustainability of the EDM process, as highlighted below.

- *Comparative assessment of* the performance of other bio-dielectrics with hydrocarbon oils
- *Surface quality evaluation* of micro-cracks, crack density and wear resistance for bio-dielectrics
- *End of life prediction of dielectric fluid* to identify conditions for bio-dielectric fluid for the EDM process to help in decision making for end of life for the dielectric fluid
- To *recycle, recondition and reuse* the used conventional and bio-dielectric fluid
- *Operator risk evaluation* to determine the emission levels in the operator breathing zone for maximum operator safety

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Conflict of interest The authors declare that they have no conflict of interest.

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