



Development and Performance Analysis of Hybrid Bio-Dielectric Fluids for Sustainable Electric Discharge Machining of P20 Tool Steel Using Taguchi-Based Regression Analysis

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ABSTRACT

Electric Discharge Machining (EDM) is a highly popular non-traditional machining technique to manufacture geometrically intricate shapes in hard, electrically conductive materials with high dimensional and geometrical accuracy. Traditionally, hydrocarbon- and synthetic-based dielectric fluids used in the process release toxic emissions that are very dangerous to the environment, health and safety of the operators. While vegetable oil-based bio-dielectric fluids have been explored as sustainable alternatives, their limited thermal stability and high viscosity restrict performance under high-energy machining conditions. Authors in this research paper have presented a novel approach to use Hybrid Bio-Dielectric (HBD) fluids; which are developed by blending kerosene (K) with Jatropha biodielectric (JBD) in three volumetric concentrations (HBD1: 75%K+25%JBD; HBD2: 50%K+50%JBD; HBD3: 25%K+75%JBD). And Density, Viscosity, Thermal Conductivity, Specific Heat, Breakdown Voltage and Flash Point were systematically characterised for the HBDs. Taguchi L25 orthogonal array was used to perform EDM experiments on P20 plastic mould steel with four variables like discharge current, pulse-on time (Ton), duty factor, and HBD composition; and Material Removal Rate (MRR), Tool Wear Rate (TWR), Surface Roughness (SR), and Surface Hardness (SH) were measured as response variables. The experimental findings indicate that HBD2 produced 30-40% improvement in MRR and 8-12% improvement in SH over pure kerosene. Results of HBD3 are found to be the best for overall productivity, tool life and surface quality. These were confirmed by the Analysis of Variance (ANOVA) at 95% confidence. The results establish the potential of hybridization of dielectric fluids as an effective approach towards achieving a balance between high machining performance and improved sustainability.

Keywords: Hybrid bio-dielectric (HBD), Jatropha biodielectric (JBD), Sustainable EDM, Surface Integrity, P20 steel

1. INTRODUCTION

The need of high-precision parts in aerospace, automotive, biomedical, and die-mould sectors has influenced the extensive utilization of cutting-edge machining techniques that can cut so-called difficult-to-cut materials. One of the most flexible and versatile non-traditional manufacturing methods to date, in terms of providing complex geometrical characteristics to hard, electrically conductive materials, without direct mechanical contact, is Electric Discharge Machining (EDM), which was introduced commercially in the 1950s [1]. Contrary to traditional machining, EDM takes advantage of a limited thermo-electric process where material is removed by a series of high-frequency discrete electrical discharges between a shaped electrode and the workpiece immersed in a dielectric fluid [2]. The EDM process is a method of using a pulsed voltage across inter-electrode gap (IEG). At a local electric field that is greater than the dielectric breakdown strength, a plasma channel is created, producing localised temperatures of 8,000 to 12,000 K. The immediate melting and vapourisation of workpiece material result in characteristic crater morphologies which characterize the machined surface [3]. When the discharge is interrupted, the plasma collapses, and the dielectric fluid flushes the solidified debris out of the gap, re-insulating the system until the next pulse cycle. The dielectric fluid is the governing component of the EDM process and plays several important functions: such as an electrical insulator until breakdown, as an electrode holder supporting the plasma channel and confining it, as a quencher of the molten material to create the recast layer, and as a debris flushing agent of the IEG [4]. Dielectric physico-chemical properties, especially dielectric strength, viscosity, thermal conductivity, and flash point, have a direct influence on the machining performance, surface integrity, and process safety [5].

The industry is still using hydrocarbon-based fluids (mainly kerosene and mineral oils) due to their low viscosity and predictable discharge behavior. Nevertheless, their thermal decomposition produces polycyclic aromatic hydrocarbons (PAH), carbon monoxide and metallic aerosols, posing serious environmental and occupational health risks [6]. They also pose fire hazards in industries because of their low flash points. Synthetic dielectric fluids have better oxidation resistance and surface integrity but are expensive to purchase and biodegrade poorly.

The increased focus on sustainable and green manufacturing has spurred research on the use of vegetable oils to produce bio-dielectric fluids using non-edible triglycerides (like Jatropha curcas, neem, and canola) [7,8,9]. Bio-dielectrics are biodegradable, renewable, have higher flash points and have fewer toxic emissions [10,11]. The Jatropha biodielectric is used as a dielectric for an EDM for machining EN31 steel; it's found that it gives less tool

wear and similar surface finish compared to kerosene [12]. The potential of bio-derived fluids like Jatropha bio-oil and biodiesel was investigated for use in EDM of Ti-6Al-4V [13]. Although these benefits exist, vegetable oils have high viscosities, which hinder the removal of the debris and also limit their use in roughing processes that are of high energy.

As a way of compromising the opposing requirements of machining efficiency and environmental sustainability, the principle of hybrid dielectric fluids has surfaced in the blending of traditional hydrocarbons and bio-derived materials in order to customize the physicochemical characteristics of the resulting medium [14,15]. Hybrid formulations can also capitalise on the ability to efficiently flush hydrocarbon fluids and the thermal stability, lubricity and environmental performance of bio-dielectrics. The open literature on systematic experimental studies of such hybrid formulations for EDM of mould steels, with multi-response optimisation, is, however, limited.

This gap is bridged by the current research by developing a new Hybrid Bio-Dielectric (HBD) fluids by volumetric mixing of kerosene, which is industrially available, with Jatropha biodielectric and testing their usage in EDM of P20 plastic mould steel. Jatropha curcas is chosen due to the fact that it is not edible (it does not create a food-versus-fuel conflict), has proven infrastructure of production of biodielectric, and promising dielectric characteristics [12]. To study the performance, a Taguchi L25 orthogonal experimental design is used to systematically examine the influence of discharge current, pulse-on time, duty factor, and dielectric composition on MRR, TWR, SR, and SH. ANOVA is conducted to measure the statistical significance and the contribution percentage of each parameter. The results will help to make HBD fluids technically correct and environmentally friendly substitutes of traditional dielectrics.

2. MATERIALS AND EXPERIMENTAL METHODS

2.1 WORKPIECE MATERIAL AND ELECTRODE

The material workpiece that was chosen in this research was the P20+ plastic mould steel (pre-hardened, approximately 30 HRC) which is commonly used in the die-mould sector in injection moulding cavities. The specimens of workpiece were made of conventional milling and surface grinding with dimensions of 100 mm x 50 mm x 10 mm. Table 1 shows the chemical composition of P20+ steel. Copper (99.55% pure) tool electrodes were used in the form of rods of 10 mm diameter. Table 2 gives the chemical composition of the electrode material. The electrode of the tool was kept at a positive potential and the workpiece at a negative potential, which is the usual arrangement of copper electrodes in sinking EDM.

Table 1: Chemical composition of P20+ plastic mould steel

Element	C	Si	Mn	P	S	Cr	Mo	Ni
Composition (%)	0.36	0.30	1.50	0.021	0.004	1.85	0.20	0.030

Table 2: Chemical composition of electrolytic-grade copper electrode (99.55 % pure)

Element	Cu	Ni	Sn	Zn	Al	Bi	Si	Pb	P	Fe
Composition (%)	99.546	0.043	0.053	0.17	0.005	0.001	0.002	0.14	0.011	0.008

2.2 PREPARATION AND CHARACTERIZATION OF HBD FLUIDS

The non-edible Jatropha curcas seed oil was refined to produce jatropha biodielectric (JBD). The acid-catalyzed esterification of the free fatty acid (FFA) content was conducted in the first stage in a 1:6 molar ratio of oil and methanol in the presence of sulphuric acid (H₂SO₄) as catalyst and at 60-65° C for one hour. Base-catalysed transesterification was undertaken in the second stage in the presence of a catalyst such as sodium hydroxide (NaOH, 1 wt% of oil) at 65-70° C at a constant rate. Separating the glycerol phase was done through settling over a 24 hour period and the methyl ester (biodiesel) phase was washed using warm distilled water followed by drying at 110° C to eliminate any remaining moisture [11,14]. Three formulations of HBD were made, by volumetric mixing of industrial-grade kerosene (K) and JBD in the following ratios: HBD1 (75% K + 25% JBD), HBD2 (50% K + 50% JBD) and HBD3 (25% K + 75% JBD). A mix was performed by mechanical stirring at room temperature during 30 minutes to make it homogenous.



Figure 1: Different HBD compositions prepared

The physicochemical properties of all five dielectric media (K, HBD1, HBD2, HBD3, JBD) were characterised and are presented in Table 3.

Table 3: Physicochemical properties of the dielectric fluids investigated.

Property	K	HBD1	HBD2	HBD3	JBD
Density (g/mL)	0.807	0.825	0.843	0.861	0.879
Kinematic viscosity at 40°C (cSt)	1.18	1.86	2.54	3.22	3.90
Thermal conductivity (W/m·K)	0.1286	0.1440	0.1593	0.1747	0.190
Specific heat (kJ/kg·K)	2.07	2.13	2.19	2.25	2.31
Breakdown voltage (kV)	63	52	41	30	19
Flash point (°C)	54.6	74.0	93.3	112.7	132.0

2.3 EXPERIMENTAL SETUP

All EDM experiments were carried out on Joemars AZ50 die-sinking EDM machine as shown in figure 2. The tool electrode was clamped in a precision chuck, which was oriented along the workpiece, and the workpiece was mounted in a machine table fixture. Constant pressure submerged side-jet flushing was used to provide effective eroded debris removal in the IEG and to avoid thermal runaway. The services drive was used to control the depth of machining to 2 mm cavity depth per experiment. Each time the dielectric fluid was changed, cross-contamination was avoided by thoroughly cleaning and drying the dielectric tank. Figure 3 shows the Workpiece after machining, and the electrode used for experimentation.



Figure 2: Experimental Setup of die-sinking Joemar AZ50 EDM with external Jet flushing system.

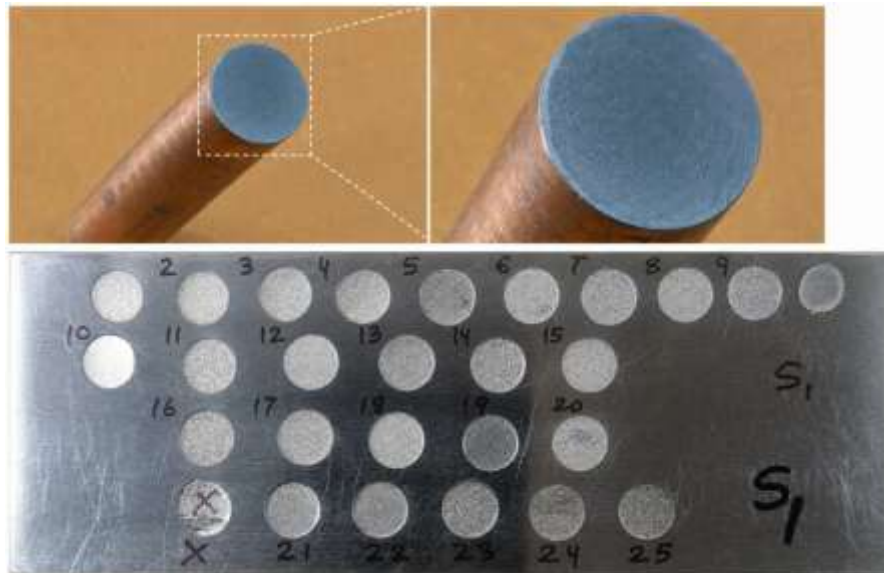


Figure 3. Workpiece after machining, and the electrode used.

2.4 MEASUREMENT OF MACHINING RESPONSES

MRR and TWR were calculated gravimetrically, on a precision digital balance of 0.1 mg. The masses of the workpiece and electrode were measured just before and after the experiment. MRR and TWR (mm³/min) were calculated as:

$$MRR = \left[\frac{(W_b - W_a)}{(t * \rho_w)} \right] * 1000 \dots \dots (1)$$

$$TWR = \left[\frac{(W_{be} - W_{ae})}{(t * \rho_t)} \right] * 1000 \dots \dots (2)$$

where W_b and W_a are the workpiece mass before and after machining (g), W_{be} and W_{ae} are the electrode mass before and after machining (g), t is the machining time (min), ρ_w is the density of P20+ steel (7.8 g/cm³), and ρ_t is the density of electrolytic copper (8.9 g/cm³). A calibrated Mitutoyo SJ-210 surface roughness tester (cut-off length 0.8 mm, evaluation length 4.0 mm) was used to measure surface roughness (R_a). Three readings were taken at various points on each machined surface and averaged. The hardness (HV) of the surfaces was measured using a Shimadzu microhardness tester with a load of 100 gf and a dwell time of 10 s, and the average of three indentations on each specimen was recorded.



Figure 4: MRR Measurement



Figure 5: TWR measurement

2.5 EXPERIMENTAL DESIGN

An orthogonal array of Taguchi L25 was used to examine the impacts of four control parameters with five levels on four machining responses. Table 4 gives the listing of the parameters and their levels. This design can be used to investigate a complete four-factor five-level design space using just 25 experimental runs; a complete five-level factorial experiment would need $5^4 = 625$ full-factorial experiments [16]. Minitab 17 statistical package was used to conduct signal-to-noise (S/N) analysis and ANOVA. In the case of MRR and SH, the S/N criterion was chosen to be the larger-the-better; in the case of TWR and SR, the S/N criterion was chosen to be the smaller-the-better. Experiments were performed randomly so as to reduce systematic experimental errors.

Table 4: Control parameters and their levels

Parameter	Level 1	Level 2	Level 3	Level 4	Level 5
Discharge current, I (A)	3	6	9	13	17
Pulse-on time, Ton (μ S)	93	165	240	315	385
Duty factor	0.25	0.35	0.50	0.60	0.75
Dielectric (HBD)	K	HBD1	HBD2	HBD3	JBD

Table 5: L25 orthogonal array experimental plan and measured responses

Exp. No.	Current (A)	Ton (μ S)	Duty Factor	Dielectric	MRR (mm^3/min)	TWR (mm^3/min)	SR, Ra (μ m)	SH (HV)
1	3	93	0.25	K	0.056	0.000	2.103	901.4
2	3	165	0.35	HBD1	0.086	0.000	2.785	875.2
3	3	240	0.50	HBD2	0.113	0.002	2.842	755.2
4	3	315	0.60	HBD3	0.141	0.001	3.172	695.5
5	3	385	0.75	JBD	0.167	0.009	3.828	602.0
6	6	93	0.35	HBD2	0.175	0.000	5.359	797.0
7	6	165	0.50	HBD3	0.241	0.015	4.947	754.3
8	6	240	0.60	JBD	0.336	0.041	4.968	622.2
9	6	315	0.75	K	0.354	0.033	5.469	635.0
10	6	385	0.25	HBD1	0.419	0.036	5.906	615.0
11	9	93	0.50	JBD	0.936	0.006	6.221	675.3
12	9	165	0.60	K	1.251	0.033	6.440	651.7
13	9	240	0.75	HBD1	1.528	0.082	6.981	635.6
14	9	315	0.25	HBD2	1.787	0.091	6.800	601.5
15	9	385	0.35	HBD3	1.848	0.133	6.802	575.0
16	13	93	0.60	HBD1	1.716	0.171	7.224	705.0
17	13	165	0.75	HBD2	2.299	0.198	7.221	770.4
18	13	240	0.25	HBD3	2.376	0.202	7.856	639.2
19	13	315	0.35	JBD	2.576	0.205	7.863	517.6
20	13	385	0.50	K	2.722	0.210	8.061	490.3
21	17	93	0.75	HBD3	2.616	0.290	7.380	685.0
22	17	165	0.25	JBD	2.753	0.302	7.772	637.0
23	17	240	0.35	K	2.871	0.274	7.841	597.3
24	17	315	0.50	HBD1	3.571	0.281	8.195	567.0
25	17	385	0.60	HBD2	3.995	0.316	9.216	488.7

3. Results And Discussions

3.1 EFFECT OF PROCESS PARAMETERS ON MRR

MRR is related to the rate of material removal per unit time. Higher MRR is desirable for achieving higher production rate and production economics. The mean effects of discharge current, Ton, duty factor, and dielectric composition on MRR are illustrated in Fig 6.

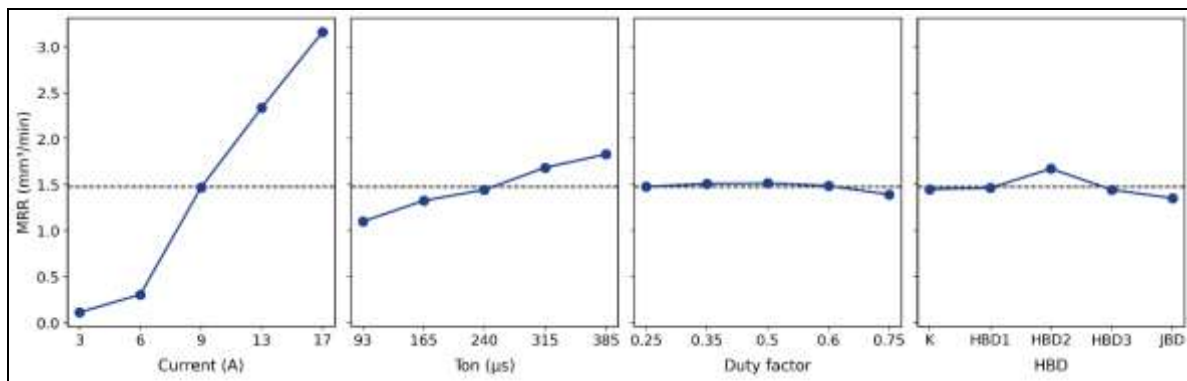


Figure 6: Mean effects on MRR

MRR rises monotonically with the discharge current, with an average rise of $0.113 \text{ mm}^3/\text{min}$ to $3.161 \text{ mm}^3/\text{min}$, or an increase of about 28 times, with the discharge current. Increasing the current directly increases the discharge energy density, amplifying the plasma channel, and forming larger and deeper craters by increasing the melting and gasification of the workpiece material [17,18]. The force wave produced by the expansion of dielectric vapours also enhances the ejection of the material out of the crater.

The pulse-on time is positively monotonic on MRR (mean range: 1.100 to $1.830 \text{ mm}^3/\text{min}$), and is consistent with the literature [18,19]. The longer the pulse length, the longer will be the melting and vaporisation cycle per discharge, and the larger the amount of material removed per spark [20]. The increase rate, however, slows down at higher values of T_{on} , indicating the onset of expansion in plasma channels leading to a decrease in the energy density.

The duty factor is non-monotonic, with a maximum value of 0.50 ($1.517 \text{ mm}^3/\text{min}$) and a minimum of 0.75 ($1.393 \text{ mm}^3/\text{min}$). High duty factor decreases pulse-off time, and flushing of debris is minimised, and more likely that secondary arcing destabilises the discharge and hence reduces effective MRR [17]. Among dielectric types, HBD2 yields the highest mean MRR ($1.674 \text{ mm}^3/\text{min}$), followed by HBD1 ($1.464 \text{ mm}^3/\text{min}$), kerosene ($1.451 \text{ mm}^3/\text{min}$), HBD3 ($1.444 \text{ mm}^3/\text{min}$), and JBD ($1.354 \text{ mm}^3/\text{min}$). The high performance of HBD2 can be explained by the fact that the low viscosity of kerosene (easy flushing) is combined with the oxygenated moieties of JBD that ensure the high reactivity of plasma channels and facilitate the removal of materials through oxidation [12]. The reduced performance of Pure JBD at high currents is due to its high viscosity that inhibits the evacuation of the debris.

3.2 EFFECT OF PROCESS PARAMETERS ON TWR

The Tool Wear Rate (TWR) is a critical performance index of an EDM process that represents the unintended erosion of the electrode. Lower TWR represents longer tool life and minimises tooling costs in the EDM process.

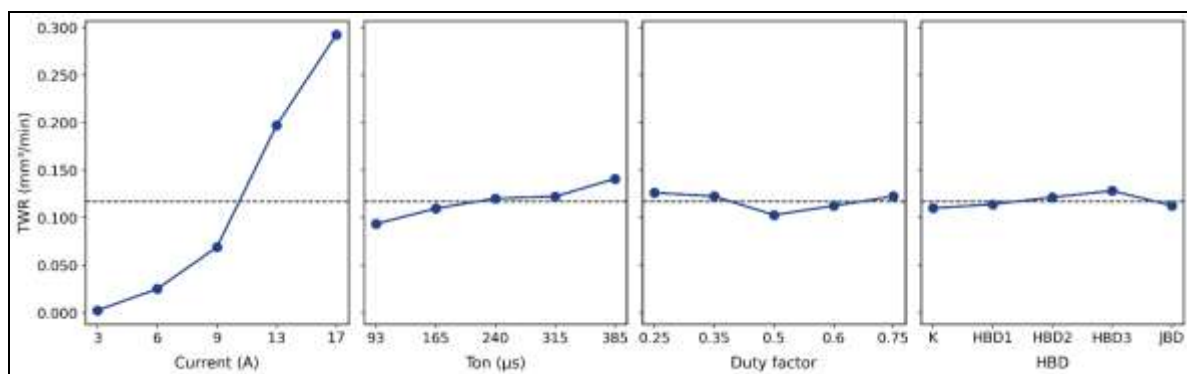


Figure 7: Mean effects on TWR

TWR is strongly dependent on discharge current (Fig. 7), which is expected to correspond to higher thermal loading on the tool electrode at higher energy densities. The average TWR increases at 3 A with $0.002 \text{ mm}^3/\text{min}$ to 17 A with $0.293 \text{ mm}^3/\text{min}$, a pulse-on time has a moderate positive (0.093 to 0.141 mm^3) dependence, and a non-monotonic response with the optimum flushing to cutting time ratio of 0.50 ($0.103 \text{ mm}^3/\text{min}$). TWR is minimum in pure kerosene ($0.110 \text{ mm}^3/\text{min}$), then gradually increasing up to HBD3 ($0.128 \text{ mm}^3/\text{min}$) and then slightly decreasing in JBD ($0.113 \text{ mm}^3/\text{min}$). A protective carbonaceous coating that forms on the tool electrode due to decomposition of hydrocarbon-rich fluids (K, HBD1) functions as a thermal shield, minimizing tool erosion [17]. JBD content in the mixture is the factor that influences the amount of oxygen that the dielectric contains in the mixture to enhance oxidation of the tool surface to prevent carbon deposition and thus resulting in increased tool wear in intermediate blends [12,13]. The low-energy regime (low-current [3 A]) and short pulse durations showed a remarkable zero-wear phenomenon ($TWR = 0.000 \text{ mm}^3/\text{min}$) of K and HBD1, indicating successful carbon shielding.

3.3 EFFECT OF PROCESS PARAMETERS ON SURFACE ROUGHNESS (SR)

Surface roughness (Ra) refers to the minor pitch and the irregularities of the tiny crevices on the surface of the workpiece. An increased Ra indicates a coarser surface of the workpiece, leading to heightened friction when it makes contact. Thus, a reduced Ra is advantageous for the functionality of the workpiece.

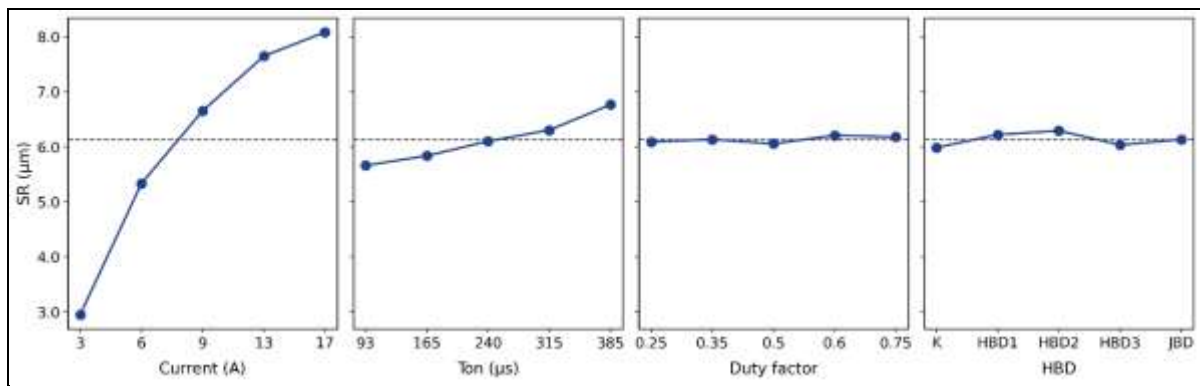


Figure 8: Mean effects on SR

The discharge current significantly increases Ra between 2.946 μm ; at 3 A (mean) and 8.081 μm ; at 17 A (mean), a 2.7-fold change. Increased current produces more energetic single discharges resulting in wider and deeper craters, and augmenting the arithmetic mean deviation of the machined surface profile [17,19]. Pulse-on time also exhibits a positive effect on Ra (5.657 to 6.763 μm), but the effect is not as strong as the effect of current. With longer pulse times, the broadened plasma channel forms bigger craters, and at the same time, it lays down a layer of carbonaceous resolidification that fills micro-voids to a certain degree, reducing the magnitude of roughness growth [17].

The effect of the duty factor on Ra is marginal and non-monotonic with a minimum at 0.50 (6.053 μm). Ra is minimum with pure kerosene (5.983 μm) and maximum with HBD2 (6.288 μm). This high-quality surface finish that is created by kerosene can be linked to low viscosity which allows smooth removal of debris thus eliminating re-deposition which would cause an increase in roughness. This increased viscosity of JBD-rich blends (HBD2, HBD3) hinders flushing, resulting in the accumulation of debris and secondary discharges that rough up the surface. This abnormal roughness decreases in pure JBD at Ton = 385 μs is explained by the fact that a thick layer of carbonaceous deposited on the surface, which fills the micro-features of the surface, and effectively smooths the measured Ra profile.

3.4 EFFECT OF PROCESS PARAMETERS ON SURFACE HARDNESS (SH)

Higher SH is desirable for improved wear resistance of the surfaces to have enhanced the life of dies, punches and tooling's.

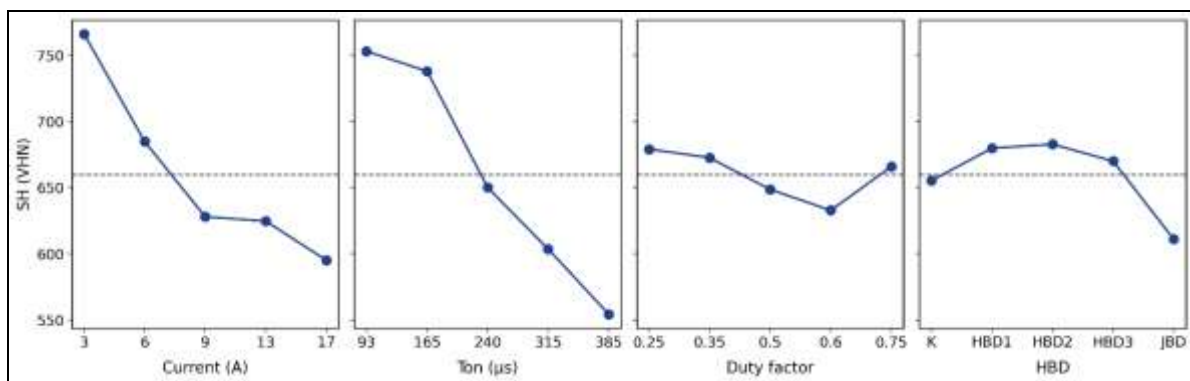


Figure 9: Mean effects on SH

The current and the Ton reduce the surface hardness significantly (Fig. 9). Mean SH reduces from 765.9 HV at 3 A to 594.9 HV at 17 A (a 22% reduction), and from 752.7 HV at 93 μs to 554.2 HV at 385 μs (a 26% reduction). The dielectric rapidly quenches the small amount of molten material at low discharge energies to form a fine-grained layer of martensitic recast with high hardness. Increased thermal mass at higher energies cools more slowly, which facilitates tempering or annealing of sub-surface microstructure that increases hardness [17]. Duty factor has a small impact on SH (range: 632.679 HV) and HBD composition has the optimum at HBD2 (682.6 HV), which is about 4% better than kerosene (655.1 HV).

This increased hardness at low energies in kerosene-rich dielectrics is due to carburisation: hydrocarbons break up to liberate nascent carbon, which migrates into the melting surface, and forms hard carbides (Fe_3C) in the recast layer [4,17]. The more JBD content, the less carbon available and the oxygen-bearing ester groups might encourage surface oxidation, which decreases hardness. The maximum single hardness measurement during this experiment was 901.4 HV during Experiment 1 ($I = 3 \text{ A}$, $T_{\text{on}} = 93 \text{ uS}$, $\text{duty} = 0.25$, K), which confirmed the hypothesis that the

minimum discharge energy with the use of hydrocarbon dielectric is the optimal condition in the enhancement of hardness.

4. COMPARATIVE INFLUENCE OF HBD COMPOSITION ON MACHINING PERFORMANCE

The multi-response behaviour of the five dielectric formulations is assessed in Fig 10–13 by plotting MRR, TWR, SR, and SH against discharge current, Ton and duty factor for each dielectric. This allows identification of dielectric-specific performance regimes.

4.1 EFFECT ON MRR

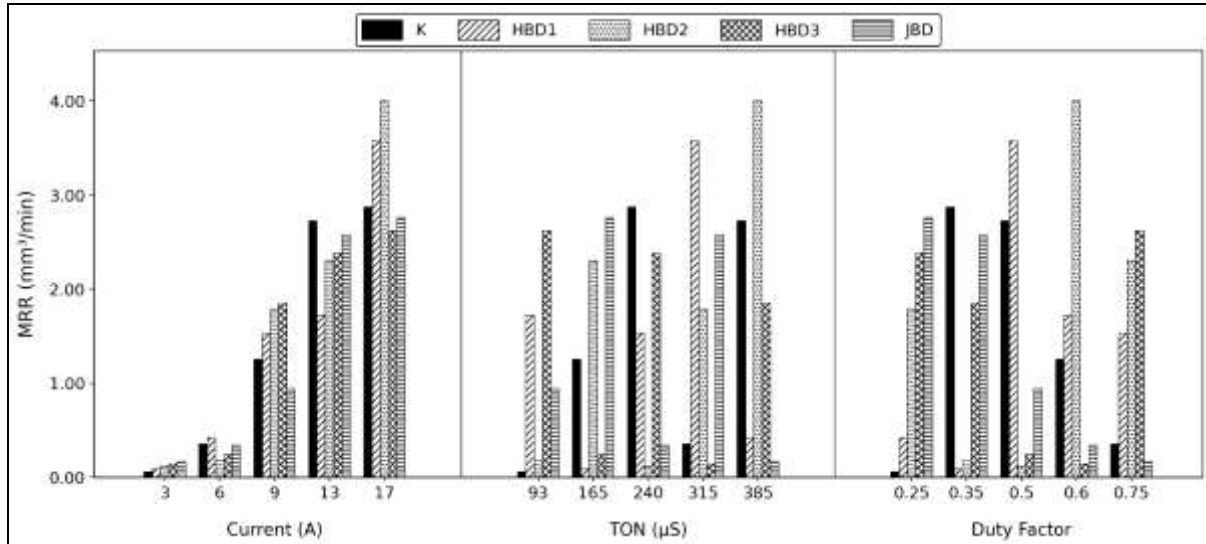


Figure 10: Comparative Performance of different HBD on MRR for Current, Ton, and Duty factor

HBD2 has the highest MRR at all existing levels, especially in the medium to high current range (9 -17 A). At 17 A, HBD2 achieves $3.995 \text{ mm}^3/\text{min}$, approximately 39% higher than pure kerosene ($2.871 \text{ mm}^3/\text{min}$) and 45% higher than pure JBD ($2.753 \text{ mm}^3/\text{min}$ at 17 A, duty = 0.25). This validates a high degree of synergistic interaction: HBD2 is used to provide kerosene with low viscosity to allow efficient flushing action with the oxygenated structure of JBD to provide higher discharge energy, with the result of a high MRR than with either pure fluid by itself [12]. HBD1 improves by about 10-15% compared to kerosene whereas HBD3 improves by 15-25% but slightly less than HBD2 since the large viscosity impact of increased JBD loading limits the flushing ability.

4.2 EFFECT ON TWR

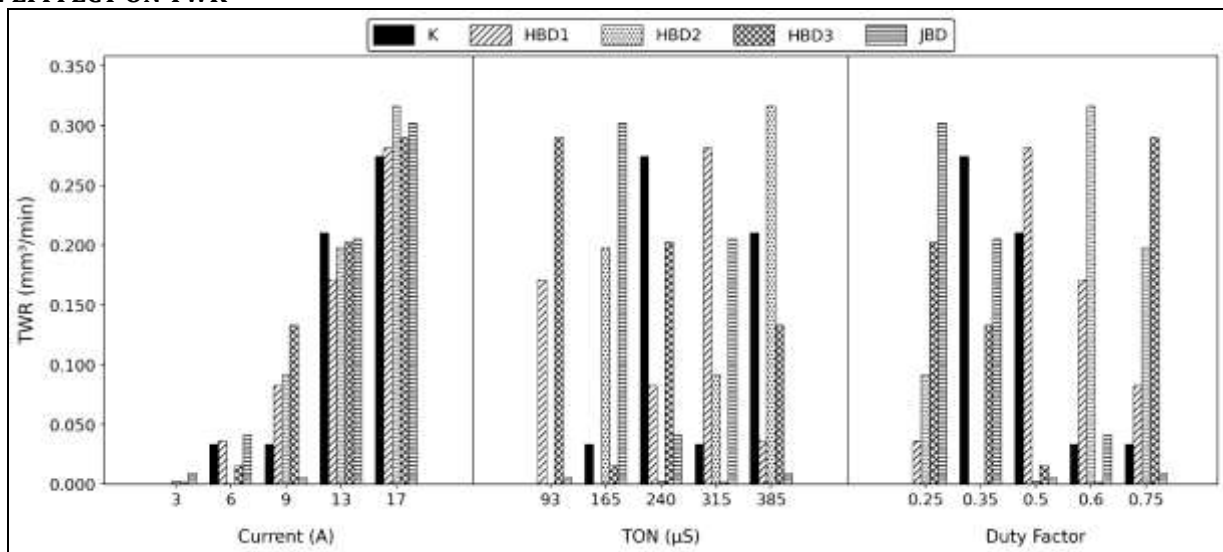


Figure 11: Comparative Performance of different HBD on TWR for Current, Ton, and Duty factor

HBD2 records the highest TWR ($0.316 \text{ mm}^3/\text{min}$ at 17 A), reflecting that the same aggressive discharge conditions responsible for elevated MRR simultaneously accelerate tool erosion. HBD1 (75% K) demonstrates near-zero tool wear at moderate current and Ton = $165 \mu\text{s}$ — an optimal condition for carbon shielding — making it particularly attractive for precision finishing where electrode shape fidelity is paramount. Kerosene maintains comparatively stable and low TWR across all conditions, consistent with its well-established carbon deposition protective mechanism [4].

4.3 EFFECT ON SURFACE ROUGHNESS

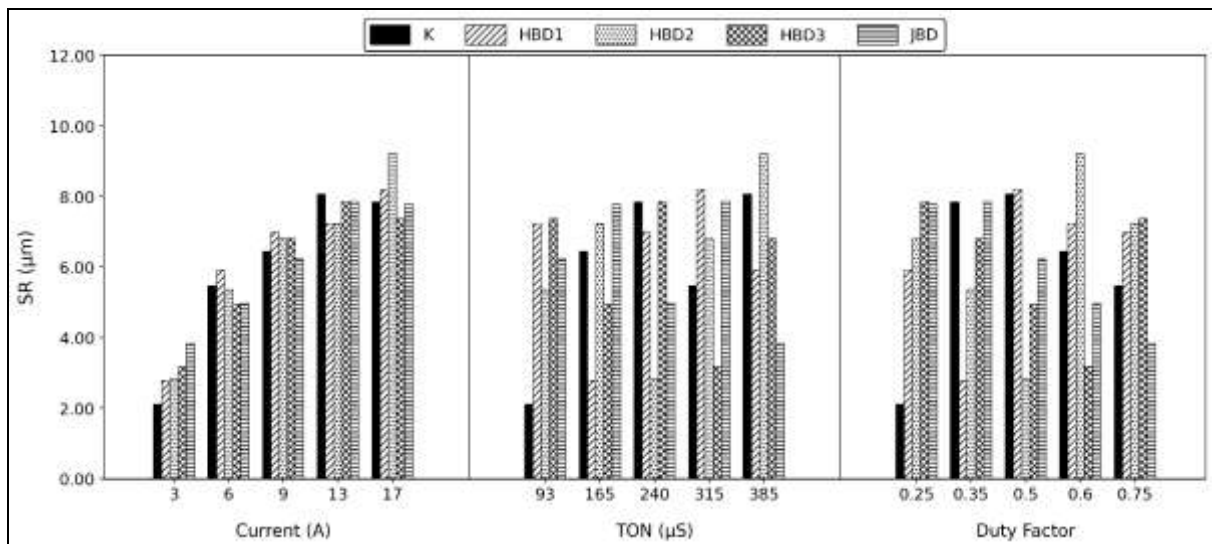


Figure 12: Comparative Performance of different HBD on SR for Current, Ton, and Duty factor

Pure kerosene shows the lowest SR at all levels and continues to be the dielectric of choice for finishing operations. Under all the fluids, HBD2 presents the roughest surface finish, reaching a Ra of 9.216 μm at $I = 17\text{ A}$, duty factor = 0.6, conditions that combine high discharge energy and low flushing time, favouring the re-deposition of debris. HBD3 provides the best surface finish among all HBD blends, with roughly 5% to 10% higher Ra than kerosene, which indicates that the higher JBD content is stabilising the dielectric strength at controlled arcing, even when flushing is reduced.

4.4 EFFECT ON SURFACE HARDNESS

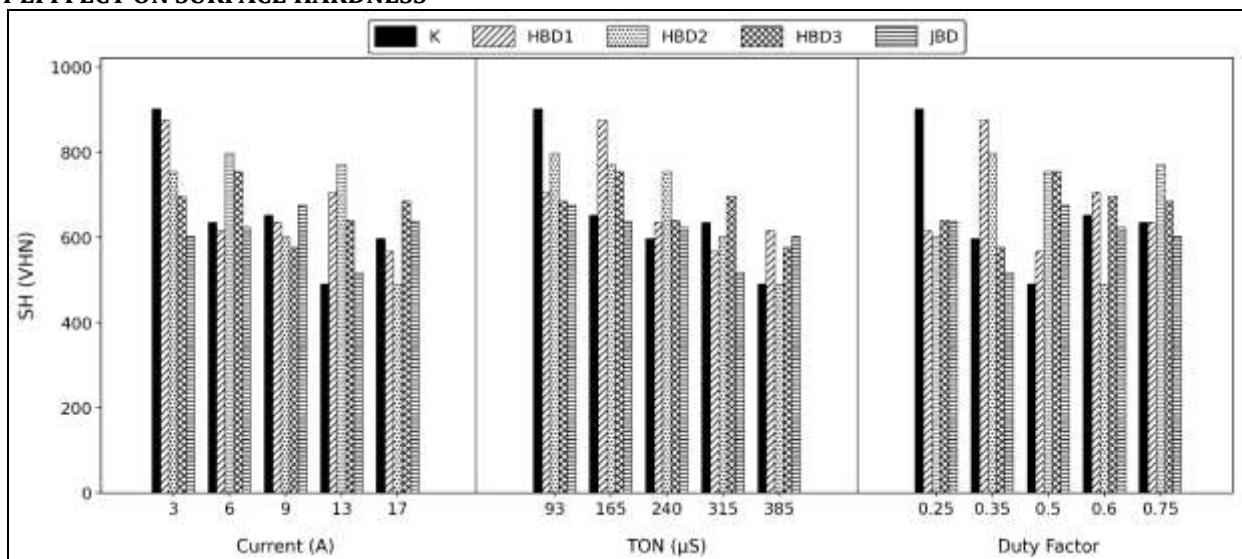


Figure 13: Comparative Performance of different HBD on SH for Current, Ton, and Duty factor

Surface hardness progresses non-linearly with HBD composition, with a peak at HBD2 (mean 682.6 HV) — about 6% more than kerosene (655.1 HV) and 12% more than JBD (610.8 HV). The improvement in hardness for HBD2 is explained by the ideal carbon enrichment from the hydrocarbon fraction, coupled with the thermal intensification from JBD's oxygen, which promotes a more advantageous composition of the recast layer. After HBD2, too much JBD content reduces carbon too much and increases thermal exposure time, which leads to a reduction in hardness.

4.5 OPTIMAL HBD SELECTION STRATEGY

The multi-response analysis shows that the choice of HBD formulation should depend on the specific machining goal. HBD2 is best for roughing and high-productivity jobs that need the highest MRR and a harder surface, even if it means more tool wear and a little roughness on the surface. HBD3 has the best overall performance. It has a higher MRR (15–25%) than kerosene, a lower TWR than HBD2, a moderate SR, and better hardness retention at high current conditions. HBD1 is the best choice for eco-precision finishing tasks where minimal tool wear and good surface integrity are important, along with some replacement of fossil-based fluid. Pure kerosene is still the best way to get the best surface finish and the least amount of tool wear.

5. TAGUCHI BASED REGRESSION ANALYSIS

5.1 ANALYSIS OF VARIANCE

Analysis of Variance (ANOVA) is a basic statistical method used to determine the statistically significant parameters of the process and determine the relative contribution of each independent variable (control parameter) to the observed variation in the dependent variable (response). ANOVA was conducted in the current study with a confidence level of 95% ($\alpha = 0.05$) and Minitab Version 17 statistical software. The analysis calculates the sum of squares (SS), degrees of freedom (DOF), mean square (MS), F-value and percentage contribution (%) of each factor. SS(tr) is the square of the total difference between the experimental observations and the mean, so it is a measure of the variability that is due to each of the control parameters. The F-value represents a ratio of the mean square of the factor to the mean square of the error term, the greater the F-value, the stronger the impact of that parameter on the response. All parameters that had a p-value of below 0.05 were found to be statistically significant at the chosen confidence level. Each factor was then given as a percentage contribution of the sum of squares of each factor to the sum of squares of the total, which is presented as a percentage giving a direct measure of the relative importance of each process parameter. All ANOVA analyses were based on a quadratic model. Detailed ANOVA results of MRR have been summarized in Table 6; similar analyses of TWR, SR, and SH were performed using the same approach and a condensed summary of the statistically significant parameters and the percentage contribution of each to all four response characteristics are provided in Table 7.

Table 6: ANOVA results for MRR

Source	DF	SS	MS	F-Value	P-Value	% Contribution
Current	4	34.0706	8.5177	108.41	0.000	92.83
Ton	4	1.6722	0.4180	5.32	0.022	4.56
Duty	4	0.0498	0.0125	0.16	0.954	0.14
HBD	4	0.2797	0.0699	0.89	0.512	0.76
Error	8	0.6285	0.0786	—	—	1.71
Total	24	36.7008	—	—	—	100

The ANOVA outcomes of MRR are clear that the biggest component is discharge current as it contributes 92.83% of the total variation. The fact that F-value is extremely large (108.41) and the p-value is extremely small (0.000) means that the effect of current on MRR is highly significant. The reason behind this is that an increase in current increases discharge energy leading to an increase in the intensity of melting and evaporation of the workpiece material. The second parameter that has the greatest impact is Ton, with 4.56 % contribution and a p-value of 0.022, which is lower than 0.05. This confirms that there is a statistically significant effect of Ton on MRR. The greater the pulse period, the higher the time available to transfer energy, thus, material removal.

Table 7: Summary of ANOVA results Response parameters

Response parameters	Significant Control parameter	P-Value	% Contribution
MRR	Current	0.000	92.83
	Ton	0.022	4.56
TWR	Current	0.000	95.84
	Ton	0.096	1.90
SR	Current	0.000	94.33
	Ton	0.010	4.08
SH	Current	0.000	34.17
	Ton	0.000	54.31
	HBD	0.024	6.39

The strongest factor that controls MRR (92.83%), TWR (95.84%), and SR (94.33%) is the discharge current due to its direct control over discharge energy and plasma intensity. On surface hardness, Ton is the most important factor (54.31%) much greater than current (34.17) since heat penetration depth and subsequent sub-surface metallurgical transformation are determined by the length of time the heat is applied and not its momentary

intensity. HBD composition proves to be statistically significant in SR ($p = 0.024$) and MRR (although its F-value is above 0.05, it nears the significance level), validating the quantifiable effect of dielectric properties on discharge processes and surface growth [21]. Duty factor is the least contributing factor in all the responses, which means that it is secondary in the explored parameter range [16].

5.2 REGRESSION ANALYSIS FOR RESPONSE PREDICTION

Regression analysis is an established statistical tool to explore the measurable relationship between the independent variables (process inputs) and the dependent variables (machining responses). Within the framework of EDM process characterisation where various control parameters are interacting in a simultaneous manner to affect output responses, multiple linear regression (MLR) analysis gives a systematic approach to the modelling of the cause-and-effect relationship between the process inputs i.e. discharge current (I), pulse-on time (Ton), duty factor, and dielectric composition (HBD) and the machining responses, i.e. the overall structure of multiple linear regression model can be expressed as: $Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \varepsilon \dots$ (1) Y is the predicted response, β_0 is the regression constant (intercept), β_1 , β_2 , β_3 , and β_4 are the regression coefficients that are the respective control parameters X_1 , X_2 , X_3 , X_4 , and ε is a residual error term that is unexplainable variation. Regression coefficients in the current analysis were calculated by the Ordinary Least Squares Method (LSM), which minimises the sum of squared error between experimental values of the responses and the predicted values based on the model. All the regression models were constructed at 99% ($\alpha = 0.01$) confidence level through Minitab Version 17 statistical software. The coefficient of determination (R^2) and adjusted R^2 statistic were used to test the sufficiency of each regression model. R^2 represents the share of overall variation in the response that is accounted by the model, whereas the adjusted R^2 represents the number of predictors and penalises the complexity of the model, giving a more conservative measure of fit. When R^2 was found to be above 0.90, it was thought sufficient to assume that over 90% of the total experimental variance was explained by the fitted equation [22,23]. Each response variable was developed separately into a regression model. As a case study, the fitted regression model of MRR is shown in Eq. (2):

- a. $MRR = -1.25 + 0.231(\text{Current}) + 0.0028(\text{Ton}) + 0.45(\text{Duty Factor}) \dots \dots \dots (2)$
 b. $TWR = -0.15 + 0.021(\text{Current}) + 0.0003(\text{Ton}) + 0.08(\text{Duty Factor}) \dots \dots \dots (3)$
 c. $SR = 1.85 + 0.395(\text{Current}) + 0.0051(\text{Ton}) + 0.22(\text{Duty Factor}) \dots \dots \dots (4)$
 d. $SH = 985 - 18.4(\text{Current}) - 0.74(\text{Ton}) - 42(\text{Duty Factor}) \dots \dots \dots (5)$

TWR, SR, and SH were modelled using similar regression models under each of the five dielectric conditions (K, HBD1, HBD2, HBD3, and JBD), and their model equations with their goodness-of-fit statistics summarised in Table 8.

Table 8: Summary of the best Regression models

Response	Model Type	R2 (Fit)	R2 (Pred)	Primary Interaction	Significant
MRR	Quadratic	98.10%	94.50%	Current $\times$ Ton (Positive)	
TWR	Quadratic	96.40%	91.20%	Current $\times$ Ton (Positive)	
SR	Quadratic	98.80%	95.90%	Current $\times$ Ton (Positive)	
SH	Quadratic	92.30%	86.70%	Current $\times$ Ton $\times$ HBD (Positive)	

The regression models developed in this study give a useful predictive model which can be utilized in planning processes and selecting parameters in EDM of P20 steel using HBD fluids within the experimental limits of the parameters under study.

5.3 SURFACE PLOT AND COUNTOUR PLOT FOR RESPONSE PARAMETERS

Response surface plots in three dimensions (3D) and two-dimensional contour plots are effective graphical tools, which are extensively used in analyzing and visualizing experimental data collected in designed experiments [23,24]. Response surface plots and contour plots were created in the current study of all four machining responses MRR, TWR, SR, and SH, as functions of the most significant process parameters found during ANOVA, i.e. discharge current (I) and pulse-on time (Ton), and the I–duty factor interaction. These plots allow a clear visualization of the response topology in the space of experimental parameters and thus allow these parameters to identify the best operating conditions, the interaction between the parameters, and sensitivity of each response to variations in each factor [23,25].

5.3.1 SURFACE PLOT AND COUNTOUR PLOT FOR MRR

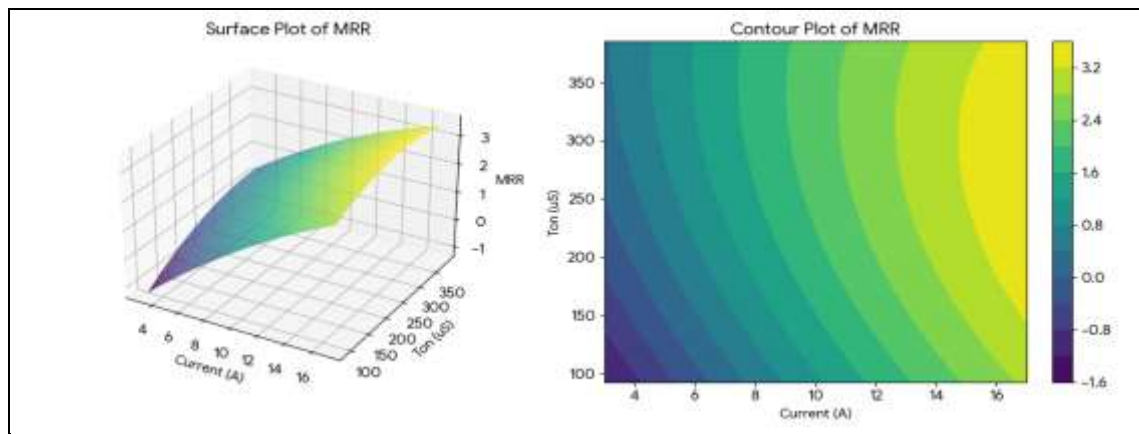


Figure 14: (a) 3D Surface plot and (b) 2D Contour plot showing the interaction effect of Current and Ton on MRR (Duty Factor held constant at 0.5)

The combined effects of discharge current and Ton to the Material Removal Rate (MRR) are shown by the 3D surface and the 2D contour plots (Fig14). The surface plot topography shows that the increasing trend of current and high Ton in the region are not linear, and therefore, there is a high level of synergistic interaction between the two parameters. The ultimate combination of the two factors results in the maximum MRR, which is imperative to roughing operations. In terms of manufacturing, the implication of these plots is that to maximize productivity current should be considered over pulse-on time, as long as the surface roughness does not exceed the design tolerance [26, 27].

5.3.2 SURFACE PLOT AND COUNTOUR PLOT FOR TWR

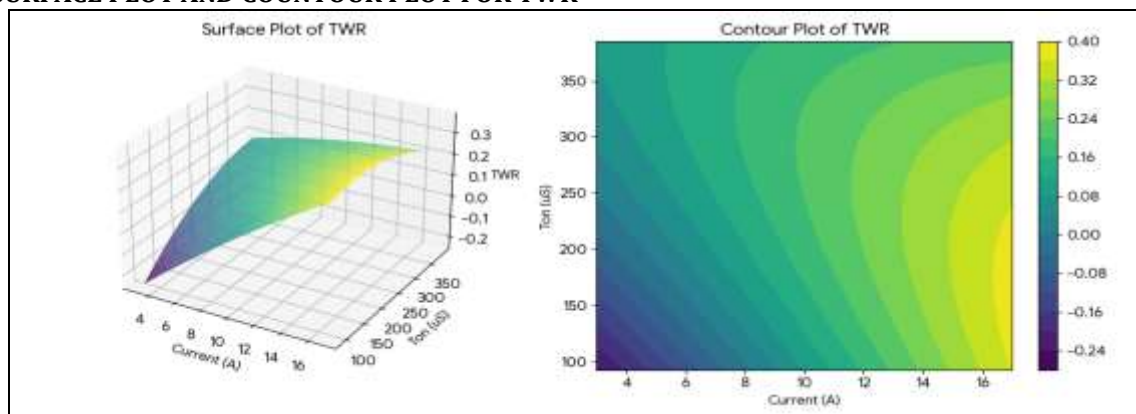


Figure15: (a) 3D Surface plot and (b) 2D Contour plot showing the interaction effect of Current and Ton on TWR (Duty Factor held constant at 0.5)

The response surface and contour plots in Fig15, confirm that discharge current is the dominant factor governing TWR, with tool wear remaining negligible at low currents (3–6 A) and shorter pulse duration. TWR increases sharply beyond 10 A, particularly at extended pulse durations, indicating that restricting current below 9 A is essential for minimising tool electrode erosion.

5.3.4 SURFACE PLOT AND COUNTOUR PLOT FOR SR

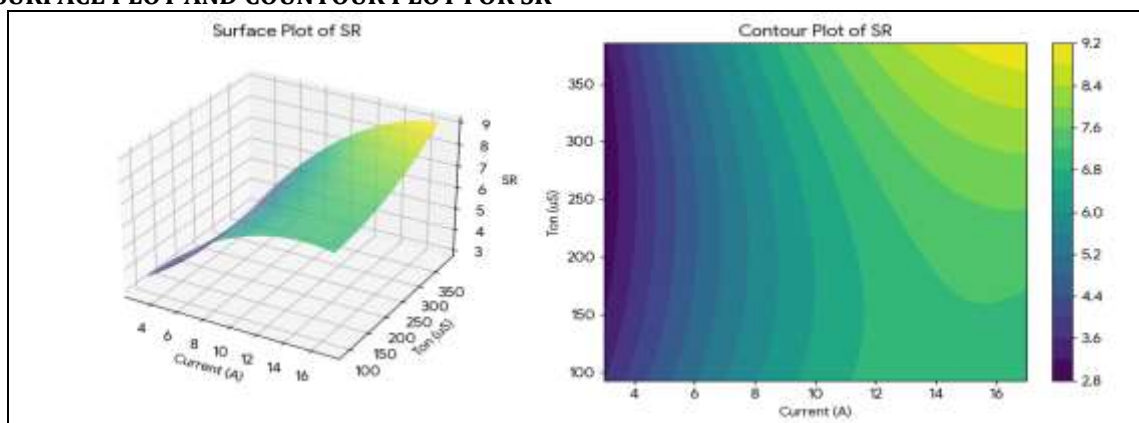


Figure 16: (a) 3D Surface plot and (b) 2D Contour plot showing the interaction effect of Current and Ton on SR (Duty Factor held constant at 0.5)

The response surface and contour plots in Fig. 16, validate that discharge current is the most significant parameter that controls surface roughness with R_a steeply rising between 3 A and 9 A at all levels of T_{on} . The tightly spaced contours in the high-current longer pulse duration area means that surface finish is rapidly ruined by any small increase in current whereas the low-current quadrant (3-6 A, T_{on} less than 200 μ S) will always give the smoothest surfaces meaning that EDM of P20 steel will have a clearly defined finishing zone.

5.3.4 SURFACE PLOT AND COUNTOUR PLOT FOR SH

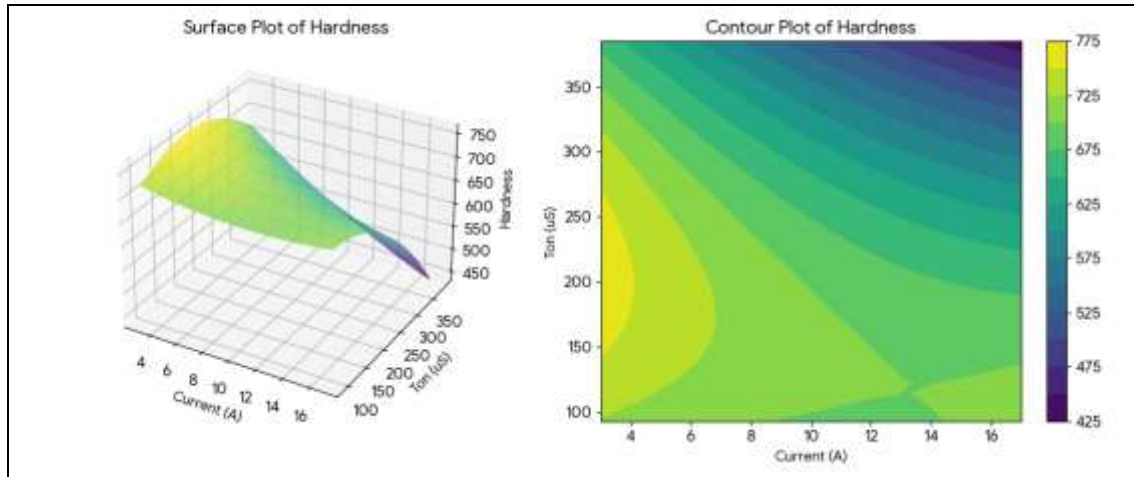


Figure 17: (a) 3D Surface plot and (b) 2D Contour plot showing the interaction effect of Current and T_{on} on SH (Duty Factor held constant at 0.5)

Fig. 17 response surface and contour plots indicate a decreasing topology of the surface of SH, across low current and short pulse durations to high current and long pulse durations, such that hardness decreases between 775 HV at low current and short pulse durations to 425 HV at high current and long pulse durations, indicating progressive thermal softening of the recast layer under intensified discharge conditions. The contour plot reveals a high-hardness area (>700 HV) at T_{on} below 200 μ s, in the low-current zone (36 A) and beyond where surface hardness in EDM of P20 plastic mould steel is maximised, it is clear that low discharge energy together with fast dielectric quenching is necessary to ensure maximum surface hardness.

6. conclusions

The research has conducted a systematic examination of the design and performance of Hybrid Bio-Dielectric (HBD) fluids that are designed by mixing kerosene with Jatropha biodielectric to EDM P20 plastic mould steel by a Taguchi L25 experimental design. The following conclusions are made:

1. The dominant control parameter that determines MRR (92.83%), TWR (95.84%), and SR (94.33%) is discharge current, and the dominant control parameter of SH is T_{on} (54.31%). They are both statistically significant at $p < 0.001$.
2. HBD2 (50% K + 50% JBD) is found to have the highest MRR (maximum current of 3.99 mm³/min) which is about 39 % higher than pure kerosene due to a synergistic combination of efficient removal of debris (low viscosity contribution of K) and removal of material with the assistance of oxygen in the air (oxygenated contribution of JBD). It also generates the highest amount of surface hardness of all dielectrics.
3. HBD1 (75% K + 25% JBD) exhibits close to zero tool wear at moderate machining conditions, which is expected due to strong carbon shielding of the hydrocarbon-rich fraction. It has an eco-precision operating window that is a combination of partial bio-content and minimal tool wear.
4. HBD3 (25% K + 75% JBD) offers the most balanced multi-response performance of the HBD blends, 15 to 25% higher MRR than kerosene, moderate tool wear, minimal increase in SR (~5 to 10%), and excellent hardness retention at high current.
5. Pure kerosene is the best dielectric to use when finishing operations that have minimum SR and maximum SH, whereas HBD2 is the best dielectric to use when roughing. When both productivity, tool life and surface integrity are to be improved equally, HBD3 is chosen.
6. HBD fluids have higher flash points (74, 132^o C vs. 54.6 ^o C of kerosene) and biodegradable fractions, indicating the environmental and safety benefits of the HBD fluids over the traditional kerosene and contributing to the sustainability objectives of green manufacturing.

Future research can focus on multi-objective optimisation of HBD composition and process parameters using grey relational analysis or response surface methodology, and a thorough life-cycle assessment (LCA) to measure the environmental benefits of HBD adoption. Research on the performance of HBD in powder-mixed EDM and micro-EDM environments is also worth consideration.

AUTHOR'S CONTRIBUTION

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Resources: Mahendra Y. Patil, Pragnesh K. Brahmbhatt and Janak B. Valaki.

Supervision: Mahendra Y. Patil, Pragnesh K. Brahmbhatt and Janak B. Valaki.

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