APPLICATION OF CRYOGENICALLY TREATED ELECTRODE FOR ENHANCEMENT OF PROCESS OUTCOMES DURING SUSTAINABLE ELECTRIC DISCHARGE MACHINING

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Abstract: Vegetable oil is recently attempted as dielectric fluid in electric discharge machining process. It has similar dielectric properties, erosion concept and gives higher production rate when compared with hydrocarbon oil based working fluid. At the same time, higher electrode wear and poor surface finish are the major drawbacks for vegetable oil as dielectric. To overcome these issues, in this work, cryogenically treated electrode is attempted with vegetable oil based dielectric fluids and their performances are compared with conventional one during the machining of die Steel. Two different categories of dielectrics such as vegetable oil and hydrocarbon oil are used and their process performances are compared. The results observed that higher production rate from vegetable oil based dielectric fluids with reduced electrode wear and surface roughness than conventional dielectric using cryogenically treated electrode. Cryogenic treatment on electrodes is used to enhance the properties of electrodes and reduction in electrode wear and surface roughness.
Key words: electric discharge machining, dielectric fluid, cryogenically treated electrode, machining performance.

1. INTRODUCTION

Electric Discharge Machining (EDM) principle is conceptualized from the phenomenon of a small amount of material eroded from metal pieces due to spark induced between them when electrically connected. This concept is used for machining purpose by controlling the spark energy. Then, it is understood spark with short duration and high frequency leads to efficient material removal. Further, it evolved that the energy can be concentrated into a particular portion for effective material removal when submerged in a dielectric fluid. Hence, EDM is a thermo-electric process [1, 2].
In EDM, dielectric fluid plays a significant role in ionization followed by decomposition, flushing out debris, generation of plasma, cool the electrode and workpiece. Hydrocarbon oil based dielectric fluid generates solid, liquid and gaseous bi-products which are not environment friendly [3]. Researchers have taken steps against these issues and working to convert EDM process as sustainable. Dry EDM, near dry EDM and water as dielectric in EDM process are the important sustainability approaches as attempted by researchers [4-6]. In dry EDM, gas is used as dielectric medium instead of liquid dielectric. The demerits observed in dry EDM process include low stability, micro-crack formation over the machined surface, suspension of debris particle in the machining zone, recirculation of used gas and debris adherence to the electrode surface [4]. Near dry EDM is another approach which uses gas and liquid mixture as dielectric during the process of machining. There is a chance of fire and explosion due to volatile mixture liquid and gaseous elements present in the process [5]. Water based dielectric fluid is also one of the approaches for sustainable EDM [6]. Leao and Pashby [7] reported that water based dielectric has few environmental issues like sludge, de-ionised resin, vapor of water, ozone, carbon monoxide, aerosols and pollution of operator environment. Another problem is observed that electrolysis corrosion of the tool and work materials. There are a few issues to be resolved, though researchers attempted to convert conventional EDM in to sustainable.
In order to have sustainability in EDM, researchers attempted vegetable oil as dielectric fluid for machining [8-11]. Sadagopan and Mouliprasanth [8] used different dielectric fluids (biodiesel, transformer oil and kerosene) and their machining performances were studied. The results showed that biodiesel as dielectric fluid gives good machining performance than other dielectric fluids. Ng *et al.* [9] investigated that vegetable oil as dielectric fluids on EDM process of bulk metallic glass and titanium alloy. The results revealed that the proposed dielectric fluids were having dielectric properties and give good machining

performance. Valaki and Rathood [10] attempted sustainability enhancement in EDM process by applying vegetable oil as dielectric fluid. The results concluded that process performance was enhanced using vegetable oil as dielectric fluid. Mishra and Routara [11] used polanga oil as dielectric fluid in EDM process to achieve sustainability in machining. The study revealed that output parameters were enhanced through polanga oil as dielectric and less aerosol emission rate than the hydrocarbon oil based dielectric fluid.

Vegetable oil has lower breakdown voltage and higher viscosity than conventional dielectric resulting in high spark energy density, longer sparking cycles and confined discharges. This might be improve melting and evaporation. Due to high MRR value of vegetable oil based dielectric fluid, more material melted thus producing crater with different size such as long wide and deep. This could be the reason for higher SR value that is noticed during vegetable oil when used as a dielectric. Higher oxygen content of vegetable oil creates discharge channels which are highly conductive and allowing more ions to strike on electrode surface, also at high value of viscosity create obstacle for heat transfer towards workpiece accumulating more heat thus increasing erosion in electrode [10, 11]. Hence, the drawbacks of the vegetable oil based dielectric fluid must be eliminated to utilize in regular practice. In this work, an effort has been made to reduce the above limitations by cryogenically treated electrode.

Cryogenic treatment is an eco friendly heat treatment method. It is used to enhance the properties like wear resistance, grain size refinement, better electrical properties and residual stresses of electrode material in EDM process. Kumar et al. [12] used cryogenically treated electrode on machinability of Inconel 718 material. The result pointed out cryogenically electrode was used to reduce the electrode wear rate during machining. Murali et al. [13] conducted machining performance analysis of cryogenically treated electrode on EDM process. The results mentioned that treated electrode enhanced machining performance. Jafferson and Hariharan [14] performed that micro EDM process using cryogenically treated and untreated electrodes. The results have shown reduction in TWR. Also, it was noticed that electrical conductivity and micro hardness were improved by cryogenically treated electrodes. Mohanty et al. [15] optimized process parameters using TOPSIS based algorithm. In their work, electrodes were cryogenically treated on machining of Inconel 718. Process parameters considered were discharge, current, voltage, and pulse on time, duty factor and flushing pressure. The results revealed that improved machining characteristics were noticed using cryogenically treated electrodes. Pragdish and Kumar [16] studied that performance of rotary EDM process using cryogenically treated electrode on AISI D2 steel. In their research, enhanced MRR was observed with less electrode wear and surface roughness.

2. EXPERIMENTAL SETUP

Die-sinking EDM machine is used to perform the experiments. AISI D2 steel is considered as work-piece materials which are used for making moulds and dies [2]. Figure 1 shows the Energy-Dispersive X-ray Spectroscopy (EDS) image of AISI D2 steel. Copper is used as electrode (diameter of 12 mm) and this is cryogenically treated subsequently tempered with the temperature of -196ºC and 150ºC respectively. Figure 2 shows the cryogenic and tempering cycle on copper electrode. Table 1 shows the properties of electrode material before and after cryogenic treatment. In this work, two categories of dielectric fluids are used namely conventional dielectric fluid (EDM oil) and vegetable oil based dielectric fluid (sunflower oil). Table 2 shows the important properties of dielectric fluids. Generally, tank capacity of EDM machine is 300 to 400 liter, in this work a small tank with a capacity of 40 litre is designed and fabricated to perform the experiments. Process parameters considered are pulse on time, pulse off time, current and voltage. In this work, six sets of energy levels are used and they are selected based on preliminary studies and from the literature. Table 3 shows the selected process parameters and their value. The value of depth of cut for all experiments is kept constant and the value is 1.0 mm. Figure 3 shows the machined samples.

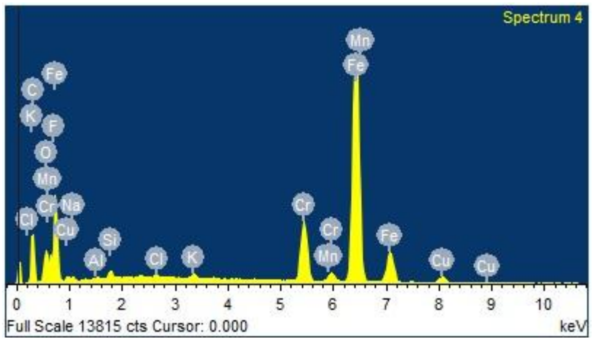


Fig.1. EDS analysis on AISI D2 steel

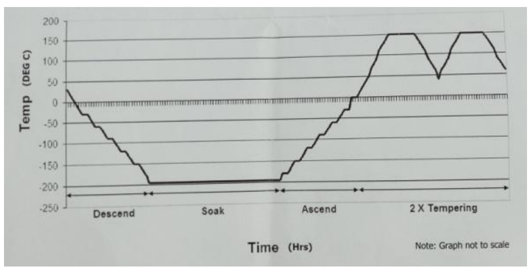


Fig. 2. Cryogenic cycle followed for copper electrode

Table 1. Properties of electrode material

Sl. No	Properties	Tested by	Non treated copper electrode	Cryogenically treated copper electrode
1	Micro hardness in Hv	Vickers micro hardness tester	120	165
2	Wear rate (×103 mm^3/m)	Pin on disc wear test machine	1.2	0.924
3	Grain size	Scanning Electron Microscopy	Coarse	Fine
4	Electrical conductivity at room temperature $(\Omega\ m)^{-1}$	Volt meter and Ammeter	6.1	6.5

Table 2. Dielectric property of dielectric fluids

Sl. No	**Properties**	**EDM Oil**	**Sunflower oil**
1	Viscosity (at 27° C) in cSt	1.2199	5.2
2	Density [g/ml]	0.802	0.879
3	Flash point [°C]	47	330
4	Fire point [°C]	52	355
5	Dielectric constant	4.7	3.0
6	Thermal conductivity [W/m·K]	0.15	0.152
7	Specific heat [kJ/kg K]	2.01	1.833
8	Break down voltage [kV/ mm]	48	14
9	Oxygen content [% wt]	0.05	0.24

Table 3. Process parameters and their levels

Sl. No	Levels	Values
1	Level 1	Pon = 300 µs; Poff = 100 µs; Current = 4 Amp; Gap voltage = 40 V
2	Level 2	Pon = 400 µs; Poff = 200 µs; Current = 5 Amp; Gap voltage = 45 V
3	Level 3	Pon = 500 µs; Poff = 300 µs; Current = 6 Amp; Gap voltage = 50 V
4	Level 4	Pon = 600 µs; Poff = 400 µs; Current = 7 Amp; Gap voltage = 55 V
5	Level 5	Pon = 700 µs; Poff = 500 µs; Current = 8 Amp; Gap voltage = 60 V
6	Level 6	Pon = 800 µs; Poff = 600 µs; Current = 9 Amp; Gap voltage = 65 V

Performance parameters such as Material Removal Rate (MRR), Tool waer rate (TWR) and Surface Roughness (SR) are found out using the following procedures. Mass difference between before machining and after machining of workpiece and electrodes are noticed using weighing machine and the equation (1) is used to calculate the MRR [10] and equation (2) is used to calculate TWR [16]. A precise weighing machine is used to measure the mass difference between before and after machining of tool and workpiece.

$$MRR = \frac{M_{wbm} - M_{wam}}{t \times \rho_w} \quad mm^3\ /min \qquad (1)$$

$$TWR = \frac{M_{ebm} - M_{eam}}{t \times \rho_e} \quad mm^3\ /min \qquad (2)$$

where,
M_{wbm} = mass of the workpiece before machining (g),
M_{wam} = mass of the workpiece after machining (g),
M_{ebm} = mass of electrode before machining, (g),
M_{eam} = mass of electrode after machining t is the machining time (min), (g),
ρ_w and ρ_e are the density of workpiece and electrode material (g/cm^3) respectively.

Surface roughness of the machined components is analyzed by Talysurf surface roughness tester. The measurements are repeated three times in a machined sample and the average values are considered. Table 4 shows the results of experiments conducted.

Fig.3 Machined samples

Table 4. Experimental results

Levels	Non treated electrode With EDM oil as dielectric (NT with EDM oil)			Non treated electrode with sunflower oil as dielectric (NT with Sunflower oil)			Cryogenically treated electrode with sunflower oil as dielectric (CT with Sunflower oil)		
	MRR [mm^3/ min]	TWR [mm^3/ min]	SR [μm]	MRR [mm^3/ min]	TWR [mm^3/ min]	SR [μm]	MRR [mm^3/ min]	TWR [mm^3/ min]	SR [μm]
Level 1	1.35	0.152	3.12	5.76	0.431	4.91	6.21	0.092	2.98
Level 2	3.43	0.217	4.51	8.34	0.636	6.12	8.67	0.131	4.06
Level 3	4.92	0.282	6.32	10.61	0.771	8.06	11.12	0.197	6.28
Level 4	5.83	0.396	6.94	11.92	0.829	9.12	12.67	0.219	5.89
Level 5	6.67	0.414	8.23	13.23	1.129	10.32	15.11	0.279	7.96
Level 6	7.23	0.529	10.12	14.91	1.472	12.14	16.32	0.321	9.85

3. RESULTS AND DISCUSSIONS

In this investigation, AISI D2 steel is machined with EDM process using conventional and vegetable oil based dielectric fluids. Six sets of process parameters are chosen and the output parameters MRR, TWR and SR are analyzed. MRR influences the rate of production, TWR influences the accuracy of required shape reproduction and SR influences the functional life of the machined components. Figures 4-6 presents the performance of non treated and cryogenically treated different electrode materials with EDM oil and sunflower oil based dielectric fluids.

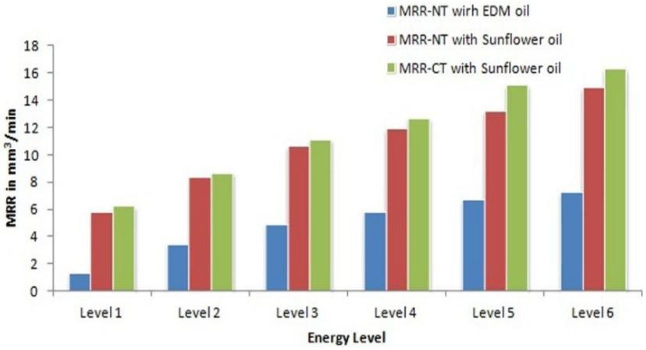


Fig. 4. Result of MRR

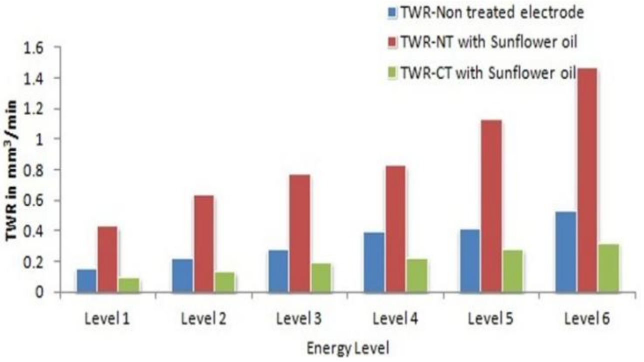


Fig. 5. Result of TWR

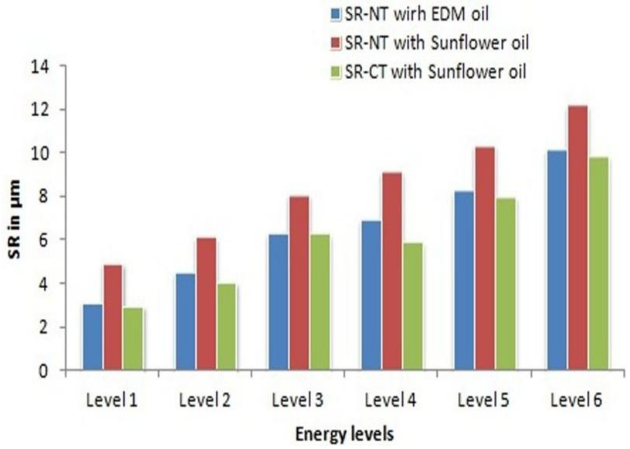
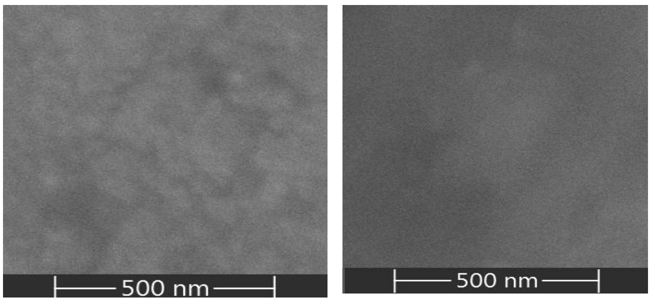


Fig. 6. Result of SR

Increased MRR is observed using sunflower oil as dielectric fluid than EDM oil. This is due to low breakdown voltage and high viscosity of vegetable oil based dielectric having high spark energy density. Also, it has higher oxygen content that generates higher plasma channel, hence improved melting and vaporization. Higher thermal conductivity and low specific heat of sunflower oil as dielectric fluid leads to retain ionization state for a long time during machining [17, 18]. Sunflower oil has higher viscosity and higher thermal conductivity than conventional dielectric fluid. The results reveal that high value of TWR is observed with sunflower oil based dielectric. Higher TWR is observed using vegetable oil as dielectric because of high oxygen content creating strong conductive discharge channel. Also, high viscosity of dielectric accumulates more heat and thus increased erosion in electrode. But lower TWR value is observed with EDM oil as dielectric fluid due to the presence of higher number of carbon atoms. The carbon atoms decompose and deposit on the electrode surface, hence low value of TWR is observed with EDM oil but vegetable oil has a lower number of carbon atoms thus having higher TWR [17].

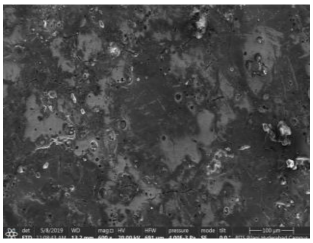
Process parameters such as pulse on time with higher level, producing intense number of electrons and striking the work surface thereby more erosion of workpiece material. Also, increase of pulse on time widens the discharge channel thus extends the melting and vaporization of material. Higher current density leads to more temperature and pressure in the plasma channel which results more erosion. Hence, it is observed that high value of MRR using higher value of pulse on time and current with vegetable oil as dielectric fluid [19, 20]. TWR is affected by pulse on time and current, by striking more positive ions on the electrode surface which leads to high value of TWR [19, 21]. More melting and vaporization producing deeper crater surface, hence high SR value is observed when pulse on time is high. Higher current value increases the penetration of more energy in to the workpiece material during machining. Both pulse on time and current producing higher value of SR while vegetable oil used as dielectric [19, 21].

In EDM process, electrode material gets affected by its surface and metallurgical properties because of high temperature during the process. Cryogenic treatment on electrodes enhances, wear resistance and thermal properties by formation of hard carbide compounds on electrode surface and refinement of grain size. Figure 7 (a) and (b) shows the SEM image of electrodes before and after cryogenic treatment. From the SEM images, cryogenically treated electrodes show high grain size refinement. Figure 4 shows the comparison of MRR while machining with vegetable oil as dielectric fluid with cryogenically treated electrode. It is clearly observed that treated electrode gives better results. Approximately 55% to 78 % enhancement in MRR compared with the plain vegetable oil and EDM oil as dielectric fluid. Increased MRR is noticed with cryogenically treated electrode. This might be due to machining zone heat that is effectively transferred to the workpiece material [12]. Tool wear is an important machining performance characteristic which directly influences the dimensional accuracy, surface quality and cost. There is a reduction of 43% to 65% of TWR value using cryogenically electrode with vegetable oil as dielectric fluid. Cryogenically treated electrode may generate certain density of electrode emission current than untreated electrode. It is used to provide electric filed strength to the electrode which leads to minimum electrode wear [13, 14]. Also, cryogenic treatment facilitates easy movement of electrons in a metal. It is due to thermal vibration of atoms and weakness at low temperature in cryogenic treatment. It leads to increase an electrical conductivity of electrode and it avoids large heating of electrode material. Thermal conductivity of a metal increases as electrical conductivity of metal increases. It uses faster removal of heat from the electrode and reduces excessive melting and vaporization. Hence, less TWR is noticed during the process. Surface finish is one of the important parameter for functional life, interaction and aesthetic look. A good surface profile of the machined component indicates better working performance with good tribological conditions. The result of 2% to 11% reduction in surface roughness (Ra) is noticed with cryogenically treated electrode with vegetable oil as dielectric fluid. Cryogenically treated electrodes provide uniform spark distribution. Another advantage is fine grained smooth electrodes by cryogenic treatment. Hence, re-solidification occurred smoothly and good surface finish is obtained with cryogenically treated electrode [15]. Figure 8 (a)-(c) shows the SEM photographs of machined samples with cryogenically treated and non treated conditions. It is observed that micro cracks are less with cryogenically treated condition than conventional electrode. In all the cases (conventional, vegetable oil as dielectric and cryogenically treated electrode with vegetable oil as dielectric) cracks are clearly visible. But, in cryogenically treated electrode provide lesser crack than the other conditions. This happens as, cryogenically treated electrode provides average temperature around crater and uniform stresses in the machined surface. Cryogenic treatment on copper electrode enhances the heat dissipation capacity. It influences heat transfer rate and uniform molten material which is deposited on the machined surface smoothly. It can be concluded that better surface conditions are observed with cryogenically treated electrodes.

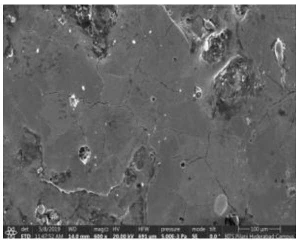


a) b)

Fig. 7. SEM image of electrode a) before cryogenic treatment and b) after cryogenic treatment



a)



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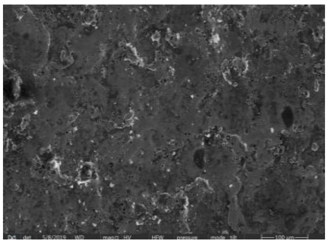

c)

Fig. 8. Machined sample SEM photographs: a) conventional EDM oil as dielectric; b) sunflower oil as dielectric; c) cryogenically treated electrode with Sunflower oil as dielectric

4. CONCLUSIONS

The following conclusions are drawn from the investigations.

- Sunflower oil is used as dielectric showed higher MRR than EDM oil. Also, TWR and SR resulted in higher value during the process.
- Machining performance is better when sunflower oil with cryogenically treated electrode compared to EDM oil as dielectric. The experimental results observed that, 55% to 78% enhancement in MRR, 43% to 65% reduction of TWR and 2% to 11% reduction in surface roughness.
- Cryogenic treatment on copper electrodes gives enhancement in properties of electrodes and shows reduction in electrode wear and surface roughness. This treatment provides grin size refinement and uniform spark distribution which can be useful for re-solidification become smoothly and leads to reduced surface roughness. Also, it provides higher electrical conductivity, electric flied strength and thermal conductivity which facilitates faster removal of heat from the electrode and reduces excessive melting and vaporization.
- Vegetable oil is natural and biodegradable which could be used as dielectric fluid because of its dielectric properties and erosion mechanism as compared with EDM oil.

5. ACKNOWLEDGEMENT

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