Study on material removal rate and surface roughness using graphene as dielectric additives in micro-electric discharge machining

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KEYWORDS

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ABSTRACT

Micro-electric discharge machining is the most distinguished micro-manufacturing process for engineering micro-parts of different geometric features. The slow material removal rate owing to the low energy short-pulsed electric discharge is the major bottleneck of the process in batch scale production. This paper is an attempt to increase the material removal rate (MRR) and enhance the surface integrity in micro-EDM using graphene as an additive in dielectric liquid. Graphene sheets synthesized using Hummers method followed by reduction and subsequent heating was dispersed in hydrocarbon based dielectric liquid by ultrasonication at temperature near to the flash point. The INCONEL 718 workpiece electrode has been immersed in the graphene suspended dielectric medium where as tungsten carbide of diameter 200µm has been used as tool electrode. It has been found that the MRR increases by 47 % in terms of volume of material removed and the surface roughness reduces by 73 % for graphene additive based dielectric medium as compared with dielectric without additive.

1. Introduction

Micro-Electric Discharge Machining (Micro-EDM) has emerged as one of the most promising manufacturing process for batch production of micro parts due to its exceptional capability of non-conventional machining of wide range of conductive materials including difficult to machine materials (Jahan et al., 2009; Prakash et al., 2019). The typical applications of Micro-EDM include manufacturing of micro-dies, moulds, surgical tools, ultra fashioned jewelleries, and finishing of parts for aerospace and automotive industry (Rajurkar & Yu, 2000; Yu et al., 1998; Nguyen et al., 2014). In Micro-EDM process high frequency pulses with low energy of discharge (~150 µJ) are imposed between the electrodes with a spark gap of less than 10 µm for material removal and generation of micro-scale craters on the samples. The low energy pulses leads to lower material removal rate (MRR) which restricts the widespread use of the process where higher material removal rate is desired (Unune & Mali, 2015). Furthermore achieving appropriate surface finish in Micro-EDM is essential as well as challenging (Kurnia et al., 2009).

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The performance of Micro-EDM processing is considered by the measure of material removal rate (MRR), tool wear rate (TWR), and surface roughness (SR). The recent time literatures, reveals material removal rate in Micro-EDM is in the order of 0.6-6mm^3/hr, that leaves a lot from the desired from the production point of view, amongst other processes of micro machining. The Micro-EDM process is stochastic in nature, the performance parameters depends on several process parameters such as discharge voltage (Yeo et al., 2009), spark gap (Behrens & Ginzel, 2003), discharge energy (Nagahanumaiah et al., 2009), pulse duration (Son et al., 2007), duty cycle including the breakdown mechanism of dielectric liquid (Mahendran et al., 2010).

Several researchers have attempted to enhance the MRR in Micro-EDM using various approaches like understanding of plasma and its effect on materials lattice (Nagahanumaiah et al., 2009), influence of electro-thermal energy and generation of pulse, rotation of tool electrode (Tan & Yeo, 2011), reversing the polarity of the electrodes (Pradhan & Bhattacharyya, 2008; Gangadhar et al., 1992), optimization of process parameters (Pradhan & Bhattacharyya (2009), and use of additives in dielectric (Chounde & Pawar, 2014). In the midst of all approaches, suspended particles in dielectric as an additive is the current research trend to enhance MRR in Micro-EDM (Talla et al., 2017). Furthermore, dispersion of various particles in dielectric as well as stability of the dispersed particles is a challenging area of research.

2. Existing Literature

MRR plays a vital role in Micro-EDM, Wang et al., (2014) reported that in the presence of dielectric, MRR is increased as dielectric limits the expansion of plasma channel, that is the force used for removal of molten metal. Kibiria et. al. (2010) addressed the issues of Micro-EDM with different dielectrics like kerosene, deionized water with suspending boron carbide powder as additive. It was explained that there was enhancement of MRR and TWR with the addition of boron carbide in de-ionised water on (Ti-6Al-4V) work-piece. Yeo et. al. (2007) stated the effects of using powder additives in dielectric for crater characteristics for Micro-EDM. Thus, the various additives mixed in the working fluid were Al, Cr, Cu and SiC suspended in de-ionised water and di-electric oil (Jahan et al., 2010). Talla, et al. (2017) found that the concentration, size, density, electrical resistivity, and thermal conductivity of powders significantly affect the machining performance.

In recent past, graphite powder mixed with dielectric fluid was used as a part of study in micro-EDM experiment wherein with doubling the graphite powder concentration, an increase of 39 % in MRR was observed. However, it was also found that increased graphite concentration the surface roughness of the machined craters increases by 27% (Kolli & Kumar, 2015). Though increase in MRR on the use of bulk graphite powder was commendable, however higher surface roughness is not desirable. Inspired by the results on use of graphite and with the argument that graphene which is a single layer of graphite with exciting properties, the authors used graphene in EDM oil to study the effects on MRR and surface roughness.

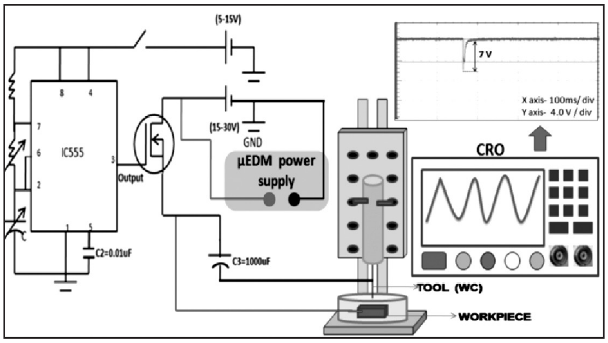

Fig. 1. Schematic diagram of the experimental set up with discharge curve for micro-EDM experiments.

In this research, authors have attempted to use graphene as an additive in dielectric for Micro-EDM to enhance MRR and reduce the surface roughness that would enable Micro-EDM for batch production of micro parts. A dispersion of graphene flakes in dielectric was used during µ-EDM.

3. Material and Methods

In this experimental study, an in-house developed Micro - EDM set up was used and is shown in Figure 1. The setup houses three axis linear translation stages with resolution of 1µm (Holmarc make- Model No. TSV 75 Mu01-01). Tungsten carbide electrode of 400µm diameter fixed to Z axis was used as Micro-EDM tool and a flat INCONEL-718 sample immersed inside the graphene dispersed dielectric acted as work piece. Graphene-EDM oil dispersion was synthesized using following steps. Graphite oxide was synthesized from bulk graphite using Hummer's method. Graphene oxide (GO) was synthesized using sonication of graphite oxide solution. The graphene oxide (GO) solution was reduced in presence of 20% hydrazine hydrate for 24 hours to form reduced graphene oxide (rGO) (Venkanna & Chakraborty, 2014). The rGO was then lyophilised to generate thin sheets of graphene. The synthesized graphene sheets were characterized using FESEM (field emission scanning electron microscope) images. Thereafter 67.8 mg of graphene sheets were added in 60 ml of hydrocarbon oil while ultrasonication and the temperature was maintained near to flash point of EDM oil (92°C). A suspension of graphene sheet in EDM oil was synthesized in the process. Maintaining flash point temperature during ultrasonication is crucial to form a stable dispersion as found during the synthesis procedure. The RC-circuit based controller was developed in-house to regulate the pulsed electric discharge. As shown in Figure 1, IC555 timer was used to generate the high frequency square wave, which was fed to the comparator (LM358) for amplifying the signal. Further, the amplified output signal of comparator was used as gate signal in the MOSFET, which was used for switching purpose.

The output of MOSFET was fed to the capacitor, which was finally connected to the electrodes. The discharge feedback as seen using digital phosphor oscilloscope (Tektronix Make, Model

Table 1
Experimental conditions for micro-EDM machining.

Exp. No.	Volt. (Vs)	Pulse on time (Controlled by varying Capacitance and R_1 and R_2)			
		Capacitor C_1 (µF)	R_1 in kΩ	R_2 in kΩ	T_{on} (µ-sec)
1	20	0.0047	3.9	14.7	60
2	20	0.047	0.59	2.2	90
3	20	0.47	0.068	0.301	120
4	25	0.0047	5.7	22	90
5	25	0.047	0.68	3.01	120
6	25	0.47	.039	0.147	60
7	30	0.0047	6.8	30.1	120
8	30	0.047	0.39	.00147	60
9	30	0.47	0.057	0.220	90

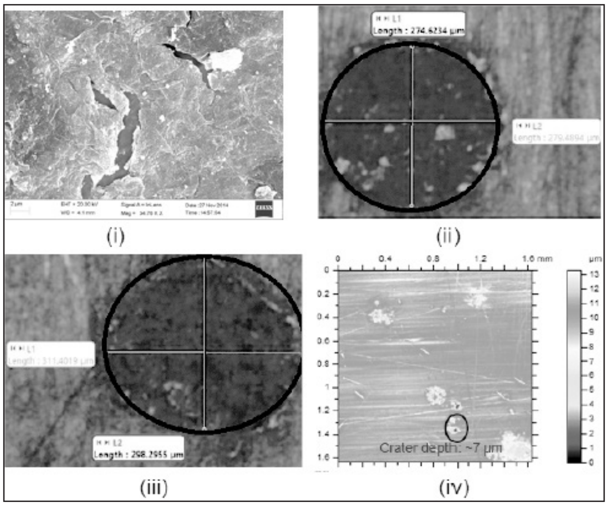

Fig. 2. (i) FESEM image of the synthesized graphene sheets showing layered structures (ii) Crater size measured under optical microscope machined without graphene additive (iii) Crater size measured under optical microscope machined with graphene additive (iv) Optical profilometer image showing the topographical map of the machined crater.

No- DPO7104) is shown in Figure 2. The resultant breakdown voltage has been calculated using equation 1.

$$V_b=V_s-V_g \qquad \text{....................(1)}$$

The supply voltage and pulse-on-time were taken as process variables and experiments were conducted using L-9 orthogonal array as shown in Table 1. In order to get the desired pulse-on-time the capacitor and resistances (R1 and R2) were varied offline calculated using the equation 2.

$$T_{on} = .693\,(R_1 + R_2)\,C \qquad \text{....................(2)}$$

All of the experiments were conducted for 100 seconds. MRR was computed based the difference in weight of the work piece measured before (wa) and after (wb) the experiment. Microbalance (Make: Sartorius) having weighing range 0 – 31 gm with least count of 1 µg was used for weight measurement. The MRR in volume of material removal per second was calculated using equation (3).

$$MRR = \frac{wb\text{-}wa}{\rho * T} \qquad \text{..................(3)}$$

Where,

wb = weight of the work piece before experiment

wa = weight of the work piece after experiment

T = Time for single discharge.

ρ = Density of INCONEL 718 (8.192gm/cm^3)

The collected debris for EDM dielectric and graphene sheet dispersed EDM dielectric was characterized using FESEM. The machined craters were analyzed for their surface roughness (Ra) using a profilometer (Make: Taylor Hobson, Model: PGI 400). The diameters of the craters were measured using microscope OLYMPUS BX51M and its associated software MOTIC IMAGES.

4. Results and Discussions

The FESEM image for synthesized graphene sheets, microscopic image for crater diameter for experiment 9 with and without using graphene in EDM oil and optical profilometer image

Table 2
MRR, surface roughness, and measured discharge voltage using EDM dielectric and graphene sheet additive dispersed EDM dielectric.

Exp. No.	Material Removal Rate (mm^3/s)			Surface Roughness (µm)		Discharge Voltage (v)	
	With additive	Without additive	Enhancement in %	With additive	Without additive	With additive	Without additive
1	0.00273	0.00225	21.33	0.226	0.317	14	6
2	0.00252	0.00196	28.57	0.212	0.342	10	7
3	0.00383	0.00312	22.75	0.288	0.401	18	5
4	0.00262	0.00183	43.16	0.214	0.325	11	7
5	0.00215	0.00159	33.22	0.201	0.314	7	7
6	0.00309	0.00237	30.38	0.231	0.320	13	8
7	0.00268	0.00201	33.33	0.238	0.367	11	8
8	0.00293	0.00217	35.02	0.251	0.345	14	9
9	0.00243	0.00166	46.38	0.211	0.364	8	11

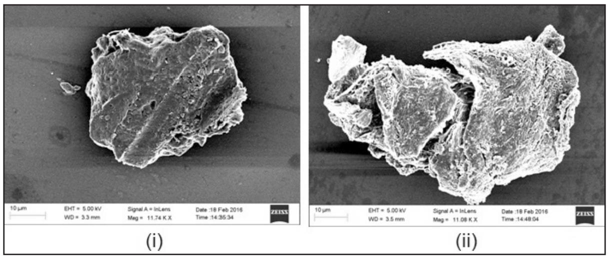

Fig. 3. FESEM image of the debris (i) using EDM oil (ii) using graphene additive in EDM oil.

for evaluating depth of the crater machined with experimental condition 9 is shown in Figure 3. The MRR, surface roughness, and measured discharge voltage for EDM dielectric and graphene sheet additive dispersed EDM dielectric is shown in Table 2. The FESEM images for the synthesized graphene sheets, debris collected when EDM dielectric was used and debris collected when graphene additive dispersed EDM dielectric was used is shown in Fig 4.

Following could be inferred from the experimental results.

(a) The maximum increase in MRR was 46.38% on use of graphene sheet additive in dielectric as compared to use of EDM dielectric. The enhancement in MRR could be due to higher breakdown voltage and imposition of higher energy on the work surface when graphene additive in dielectric is used (Table 2).

(b) Though the MRR increases in case of graphene additive, however the Ra reduces in case of graphene additive (Table 1). A maximum surface roughness reduction of 73% was observed when graphene additives were used. This is supported by Fig 4 where it could be observed that the collected debris is bulky and single particle in nature when EDM oil is used. When graphene additive is used in EDM oil, layered structure in the debris could be observed.

(c) This clarifies the fact that distribution of heat occurs slowly in layers in the workpiece. Furthermore, due to layered nature of the debris the dissipation of heat generated during EDM process dissipates rapidly rendering lower surface roughness.

(d) The measured discharge voltage is higher for graphene added dielectric (Table 1). This might be due to thin graphene layers between the electrode and work which acts like a large number of parallel plate capacitors in series. Due to such arrangement, the effective capacitance of the spark gap increases requiring higher discharge voltage. This also justifies the fact that graphene based dielectric oil has the capability to retain higher energy for longer duration which enhances the MRR and causes slow rate of energy dissipation leading to lesser surface roughness of crater.

5. Conclusion

The research has demonstrated an effective method by using graphene dispersed in EDM oil for Micro-EDM machining. The proposed dielectric could render higher MRR and lower the surface roughness of machined workpiece significantly. The method proposed in this research for dispersion is simple, cost effective, fast and eco friendly as compared to synthesis of dispersions which require higher energy and time. As graphene is available in abundance and industrial methods for synthesis of bulk amount of graphene is underway, graphene additive can have promising application as EDM additive. In addition graphene is non toxic and does not leave any harmful residue. The proposed graphene additive based dielectric is hence suitable for micro-EDM applications at shop floor where continuous requirement for enhanced MRR and reduction of surface roughness is desired.

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