Magnetic Field Assisted Micro EDM in Nitrogen Plasma Jet and HVAJ

Aziz Asad, Zuyuan Yu, Rimao Zou, and Congyang Zhang

***Abstract*—Dielectrics play a key role during electrical discharge machining (EDM). Kerosene-based oil, deionized water and gas are traditionally used dielectrics in industries. The process performance of micro EDM mainly based on it. The major drawbacks of liquid-based dielectrics are large ratio of electrode wear and pollution. Micro EDM in gas provides almost zero tool wear. However, the discharge gap is very small, which leads to abnormal discharge during machining. The theme of this research work is an investigation of the micro EDM in nitrogen plasma jet (NPJ) performed in magnetic field for enhancing process performance. In this study, the magnetic field is introduced perpendicular to the current direction, for enhancing the material removal ratio and helping in debris distribution from machining area. Series of experiments have been conducted, by varying magnetic field current and voltage. Experimental outcome shows that this adopted approach significantly improves the material removal rate (MRR) as well as surface roughness (Ra). The presence of Lorentz force has no negative impact on electrode wear.**

***Index Terms*—Electrical discharge machining (EDM), magnetic field, nitrogen plasma jet, machining performance.**

I. Introduction

The gas assisted EDM process is considered a reliable alternative to liquid dielectric-based EDM process. The highly appreciated advantages of the process include-due to low dielectric constant; the formation of plasma is much easier and gives nearly zero electrode wear [1] although the process has low machine efficiency such as erosion rate is 5-10 times lower than the liquid dielectric because of unlimited expansion of plasma in gas dielectric but no corrosion on work surface, impose thinner white layer on machined surface and environmental friendly [2]. Several experimental methodologies have been used to enhance MRR. These include-‘quasi-expansion’ mode machining [2]. In this machining mode the pulse off time reduced to one sixth of pulse on time which provides sufficient time for ejection of material removal and also enhancing the MRR. Ultrasonic assisted EDM were also used to improve the MRR of gas-EDM process [3]. Magnetic field successfully assisted the EDM at both macro- and micro level for gain the MRR of magnetic and non-magnetic materials. At first, the magnetic field was introduced by De Bruijn *et al*. for gap cleaning in EDM [4]. They are summarized that the application of magnetic field helps to increase the evacuation of debris from the machining gap. Recently Ken Heniz *et al.* [5] utilized the directional current to generate external Lorentz force normal to the workpiece surface to affect the melt pool behavior for increased material removal regardless magnetic properties of material. Joshi et al. proposed introducing of pulsating magnetic field directly affect the plasma expansion. They have stated that use of such magnetic field helps to enhance MRR around 130%. There have also been a bundle of specific investigations on use of NPJ as dielectric instead of traditional dry EDM. It is reported the NPJ assisted EDM gives efficient molten material removal than with gas jet, in resulting, material removal rate (MRR) is increased and surface roughness is decreased [6]. The effect of few parameters such as electrical field, voltage (V) and current (I) were only considered for prediction of radius and depth of crater. In spite of these research works, it’s realized that the influence of external factors such as magnetic field could favor the enhancement of machining efficiency which have not been evident so far and there is space for generalized and comprehensive research to define the effect of main EDM parameters as well as external magnetic field on the bases of material removal mechanism would be appreciate able. The purpose of this study is to investigate the effect of mechanical properties of magnetic field assisted-EDM on non-magnetic workpiece materials under the fully supported machining properties of NPJ as a dielectric aimed at enhancing MRR. In this adopted process the flowing current through the electrode workpiece is perpendicular to the lines of magnetic field while the magnetic field is oriented such a way as to generate the external Lorentz force that would directly affect the melt pool behavior. Although the micro EDM process is based on continuous discharge process; however, it is much difficult to define the fundamental behavior of plasma channel as well as the behavior of melt pool during breakdown under these circumstance. Therefore, the series of experiments on different machining parameters and energies supplies have been selected to study the effect of Lorentz force on non-magnetic material workpiece. This research work has been done into two sections; Section I, comparison of magnet assisted and without magnet EDM and the Section II is related to effect of additional Lorentz force regarding MRR, tool wear ratio (TWR), Ra and machining time. SEM and ZYGO equipment are utilized to quantify the MRR, TWR and Ra at different parameters. To study the behavior of external Lorentz force on plasma channel, the discharge carter diameter is measured at different discharge energies and magnet field strength.

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II. Experimental Work

A. Purpose

The basic phenomena behind the material removal mechanism for the EDM process is plasma pressure which exert force on the melt pool to help the ejecting of molten material from machining area [9]. Hence, there is possibility to enhance material ejection with increase in force on the melt pool under the presence of magnetic field. Even though physically, non-magnetic material do not react to any magnetic force, however, if the directional current is passing through the non-magnetic material become perpendicular to the magnet lines of forces, the external force will produce which is known as "Lorentz force". It is recognized by the cross product of directional current and oriented magnetic field. The expected Lorentz force can be calculated from (1).

$$\begin{aligned} F &= J \times B \\ F &= qvB.\mathrm{Sin}\,\theta \\ F &= I.l.B\,\mathrm{Sin}\,\theta \end{aligned} \tag{1}$$

Here J and B are applied current and magnetic field strength respectively. According to above equation, (I) is representing the current passing through the workpiece along perpendicular length (l) in the presence of magnetic field (B). The measured average length (l) of each purposed workpiece under the magnetic field for machining is approximately 28mm (0.028m) and applied current direction considered perpendicular to the magnetic lines of forces. Therefore, the sin θ in (1) is equal to 1. In the Fig. 1, section A, B and C are representing the selected machining area according to measured magnet field strength (B) 0.3T, 0.2T and 0.1T respectively. The Lorentz force is maximized when these two components are perpendicular. Usually in a micro-EDM, the flow of a current is normal to the workpiece surface in plasma channel. From the Fig. 1, $F2$ is the Lorentz force come into extent from the current in the plasma channel $J2$.

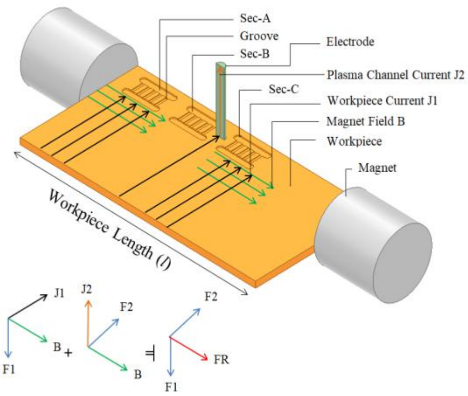


Fig. 1. Schematic diagram of magnetic field with directional current.

There is another possibility to understand the Lorentz force and its direction because when the current enters the workpiece, it shows isotropically dispersive property in the workpiece which eliminate the possibility of producing a Lorentz force. However, if the current is supply preferentially with low resistance path, an additional Lorentz force $F1$ is produced which act on the melt pool. The actual direction of the current flow will be the combination of $J1$ in workpiece and $J2$ in the plasma channel. Similarly, the FR is the combination of $F1$ and $F2$. One thing need clarification, current in the workpiece $J1$ and current in the plasma channel $J2$ are two possibilities for the same applied current.

B. Parametric Setting and Measurements

Before machining process, the magnetic field strength (B) in (1) at each section of oriented workpiece is measured with Gauss meter (TD8620-0.01mT-2000mT) given in Fig. 2.

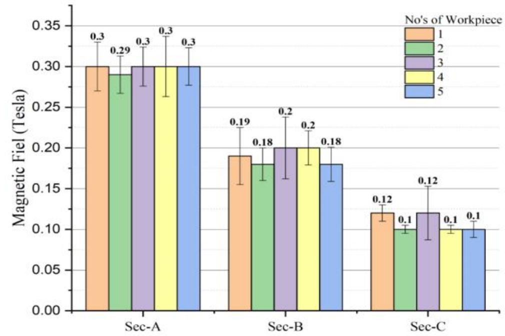


Fig. 2. Magnetic field strength at three different sections.

In this experimental work, the RC circuit is used as discharge supply. The discharge current (I) in the RC circuit is measured for each discharge energy via oscilloscope during the machining process as shown in Fig. 3.

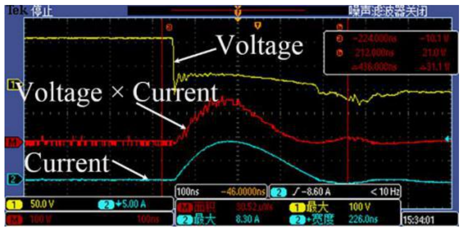


Fig. 3. Measurement of discharge current during machining process.

The external Lorentz force (F) is calculated from (1) at each machining section with different discharge energies listed in Table I. Results are shown in Fig. 4 and listed in Table I. It can be seen that, the Lorentz force (F) increases with the increase of discharge energy and magnetic field strength.

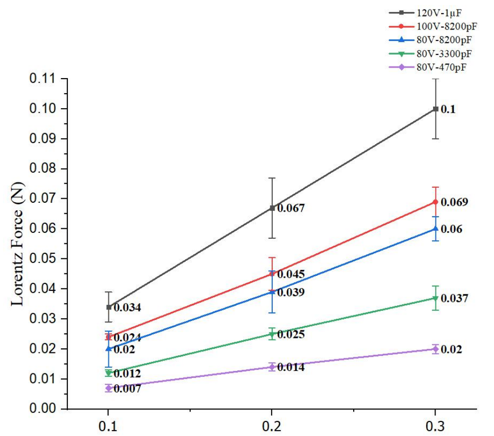


Fig. 4. Magnetic field at each section and external Lorentz force at different discharge energies.

C. Experimental Setup

To explore the machining characteristics of magnetic field assisted micro EDM in NPJ and high velocity air jet (HVAJ), series of test are conducted on a set of self-developed micro EDM equipment. Fig. 5 shows the experimental equipment. It includes a set of XYZ stages of 200 mm travel distance along with unidirectional repeatability of 1 µm to control the tool movement, a high precision spindle to hold the tool electrode with 1µm radial runout, a set of wire electrical discharge grinding (WEDG) unit along with a set of NPJ generator and high velocity air jet (HVAJ) generator [7]. For this research work, a couple of permanent magnets (ndfe35) are placed parallel to the workpiece. The WEDG unit of experimental setup has been used to machine the tool electrode, then it is controlled to move along designated tool path for machining. All the machining parameter such as machining time, dimensions of machined cavity on selected planes is recorded and measured using microscope. It is assured that the reference point on the workpiece surface is electrically connected before and after operation. The position difference of tool electrode considered as the tool electrode length used to calculate the TWR. The depth of machined cavity and surface roughness are calculated using ZYGO equipment.

TABLE I: DETAILED EXPERIMENTAL CONDITIONS AT DIFFERENT PARAMETERS

Electrical Parameters			Magnetic Parameters		Dielectric/Flow rate	
(V)	(I)	Capacitance	Field Strength (T)	Lorentz force (N)	NPJ (slm)	AJ (slm)
120	9.7~12.8	1µF	Sec-A=0.1	0.033	15	50
	mean(11.2)		Sec-B=0.2	0.067		
			Sec-C=0.3	0.1		
100	8.5~10.9	8200pF	Sec-A=0.1	0.022	15	50
	(mean=9.7)		Sec-B=0.2	0.044		
			Sec-C=0.3	0.067		
80	5.5~8	8200pF	Sec-A=0.1	0.030	15	50
	(mean=6.7)		Sec-B=0.2	0.043		
			Sec-C=0.3	0.062		
80	3.3~6	3300pF	Sec-A=0.1	0.012	15	50
	(mean=4.5)		Sec-B=0.2	0.025		
			Sec-C=0.3	0.037		
80	1.3~2.5	470pF	Sec-A=0.1	0.007	15	50
	(mean=1.9)		Sec-B=0.2	0.014		
			Sec-C=0.3	0.021		

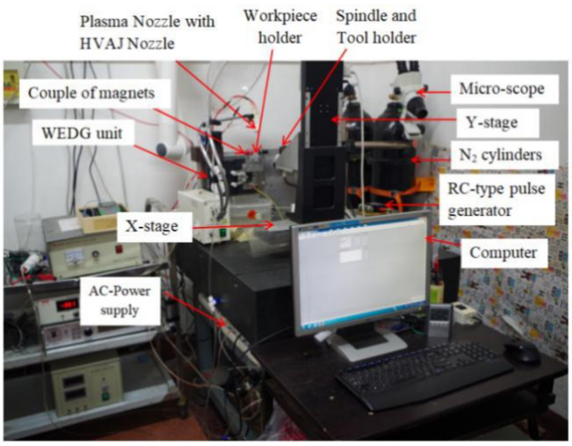


Fig. 5. Experimental equipment.

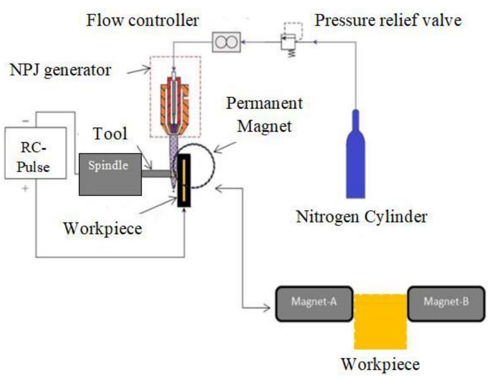


Fig. 6. Schematic diagram of experimental equipment.

D. Experimental Design

In this research study, the experimental work is carried out into two parts. The first part is the clarification of influence of Lorentz force and compares the machining characteristics of NPJ and NPJ- magnet assisted EDM and the second part is comparison of micro EDM in NPJ-HVAJ aided by magnetic field at different discharge energies. Machining parameters for planed experiments are listed in Table I. In order to compare the experimental results with previous research, the experimental work in this search study have been done on milling of vertical grooves on the workpiece in the presence of magnetic field, as shown in Fig. 7.

TABLE II: MACHINING PARAMETERS

Machining conditions	Values
Pulse generator	RC circuit
Tool electrode material	Tungsten
Flow rate of NPJ	15slm
High velocity Air jet	50slm
Workpiece material	Brass H62
Tool diameter	65±5µm
Tool electrode feed depth	30µm
Tool electrode travel distance	500µm
Rotation speed	600rpm
Dielectric	NPJ-HVAJ
Tool polarity	negative

The length of the groove is set 350 µm and the total feed depth is 30 µm. the width of vertical groove is determined by the tool electrode diameter and the discharge gap. Furthermore, the presence of dielectric is ensured to fill the machining area along the direction of groove during machining. The field strength of external magnets around the workpiece is varying according to the distance from the magnet to each vertical groove, thus, the field strength is measured via Gauss meter at each reference point of vertical groove before machining. The electrical parameters, magnetic field strength and expected Lorentz force are given in Table I.

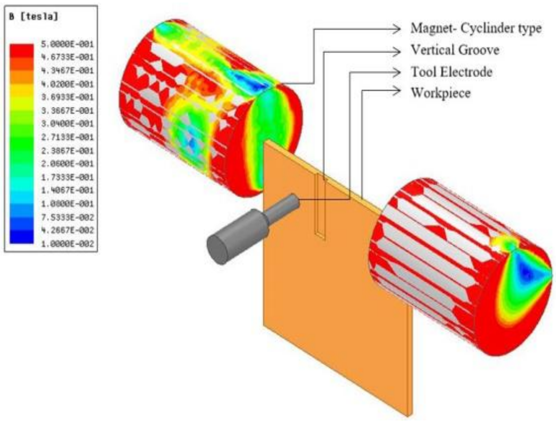


Fig. 7. Schematic diagram of vertical groove milling.

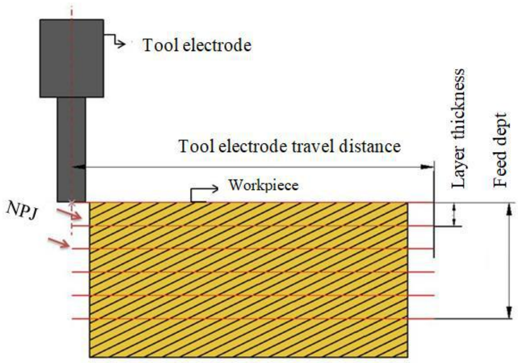


Fig. 8. Tool path for groove milling.

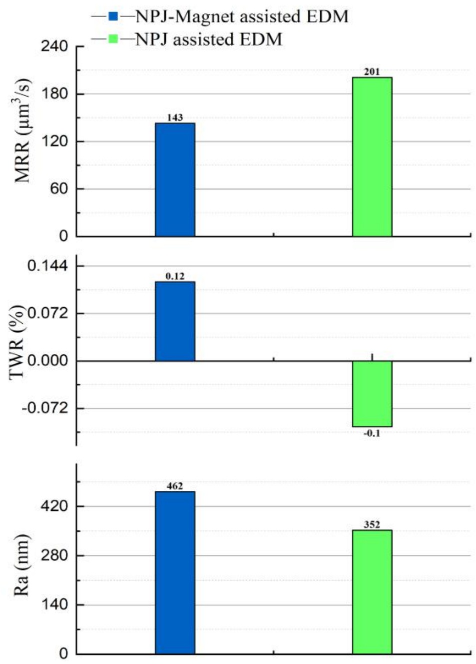


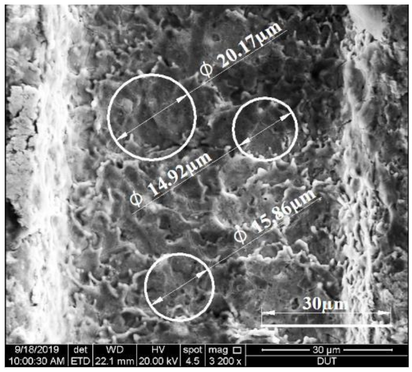
Fig. 9. NPJ and NPJ-Magnet EDM under the open voltage 100V-8200pF.

III. Experimental Results and Discussion

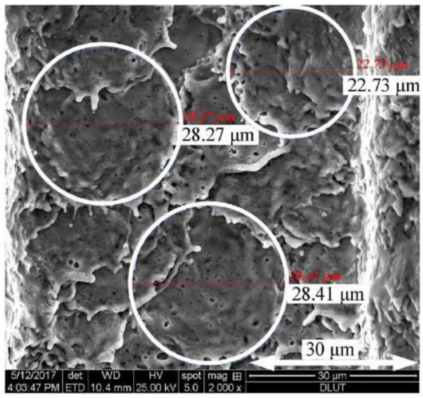
A. Comparison of Machining Properties in NPJ with and without Magnetic Field

P. Govindan *et al*. stated that the EDM with magnet field successfully confine the plasma channel during machining. in resulting, the volume of discharge crater is reduced as compared to without magnet field assisted micro EDM [8]. In order to compare the experimental results without magnet assisted EDM in Nitrogen plasma jet, several test trails are conducted at different range of magnetic field according to experimental conditions-I as shown in Table II except air jet. However, Fig. 9 shows that the only NPJ flow is unable to eject the debris from machining area, in resulting large amount of molten material adhered on tool electrode caused decrease in material removal rate. The TWR and Ra are increased due to influence of magnetic field.

On the other hand, the SEM results show that the size of crater reduced in magnetic field assisted EDM. It is considered a bit of evidence for confinement of plasma channel due to external Lorentz force. On the bases of these outcomes, the high velocity air jet is added to help in debris removal.



(a) In Magnet-NPJ



(b) In NPJ [7]

Fig. 10. Discharge crater in NPJ and Magnet-NPJ under the open voltage 100V-8200pF.

In Fig. 10, scanning electron microscopy (SEM) of machined groove under the same discharge energy shows that the diameter of discharge crater decreased at certain values due to presence of external Lorentz force in machining area. In order to ensure the external Lorentz force can confine the plasma channel during machining process, the crater diameter at different discharge energies is measured. The Fig. 11 shows that the size of discharge crater increases with the increase in discharge energy while at 0.1T to 0.3T magnetic field strength the diameter of discharge crater decreased significantly. It is considered that the plasma channel is confined due to external Lorentz force.

B. Magnetic Field Assisted EDM aided with NPJ-High Velocity Air Jet

Mainly the MRR of micro EDM encountered by two factors, discharge energy and debris flushing from the machining area> However, the flow rate of NPJ is unable to extract the molten material in micro EDM. Increases the flow rate of NPJ directly affect the machining cost. Therefore, high velocity air jet (HVAJ) introduced in the system to assist the removal process. The inner diameter HVAJ nozzle is measured 3mm. In this case study, the flow rate of HVAJ is set to 50 slm, can be seen in Fig. 12.

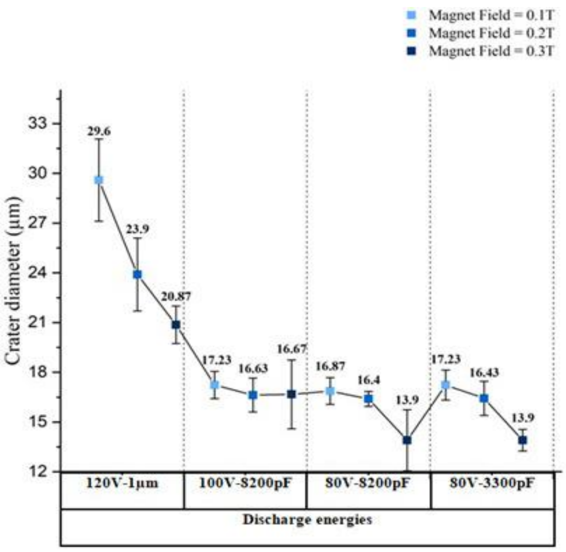


Fig. 11. Comparative plot for average crater diameter at different discharge energies.

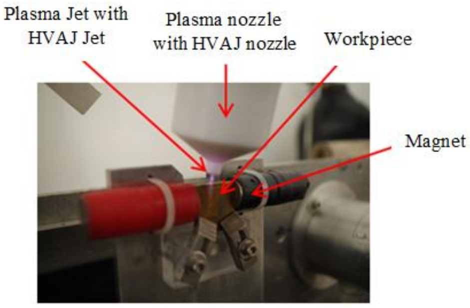


Fig. 12. Setup of magnet around workpiece and NPJ-HVAJ Jet.

To study the influence of Lorentz force in magnetic field assisted EDM, set of experiments for magnet assisted EDM aided with HVAJ are carried out. The workpiece material is brass H62 and the tool material is tungsten. Other experimental conditions and results are evaluated in Fig. 13(a) and Fig. 13(b). To distinguish the machining performance of micro EDM with magnetic field in NPJ and HVAJ, vertical grooves are machined. To perform a comparison between previous studies done by Rimao Zou *et al.*, all the process parameters kept similar as in case of NPJ aided with HVAJ. At this stage of experimental study, the set of test trails are conducted under the open voltage 100V and 8200pF capacitance, including electrical, magnetic and dielectric parameters, as shown in Table I.

C. *Effect of Lorentz Force*

The gained results are strong evidence for the presence and contribution of Lorentz force to enhancing machining efficiency. Furthermore, as compared in case of only NPJ-HVAJ assisted EDM, the average increased in material removal rate in all three magnetic strengths is 36%, 54% and 38% respectively. Therefore, slightly increased in surface roughness occurred as shown in Fig. 13(a). However, it can be seen that the tool ware ratios are very small and randomly distributed even though material removal of oriented workpiece is increased. Some negligible factors such as repeated positioning error of XYZ stages and mainly thermal deformation might be reasons for the error of TWR. Experimental results of Fig. 13(b) are the comparative outcomes of machining process under the open voltage 80V and 3300pF capacitance. The overall increased MRR is around 73% in all three magnet strengths but when the magnetic field increased 0.2T to 0.3T, the average increase in MRR reduced to 65%. This highlights that significantly more material is removed per unit of spark energy going into each discharge under magnetic field is 0.1 T for further clarification, more discharge energies are added to the test tails, as shown in Table II.

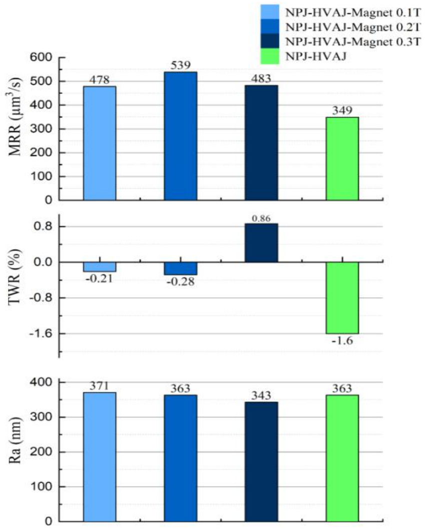


Fig. 13(a). Test trails under-100V-8200pF.

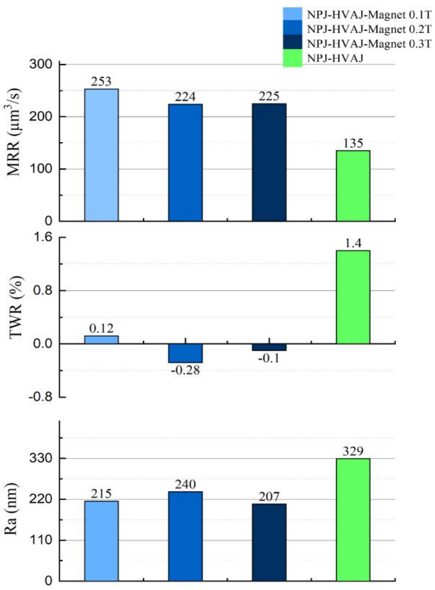


Fig. 13(b). Test trails under-80V-3300pF.

D. *Effect on Plasma Characteristics*

The increase in MRR has been disclosed with Lorentz force pointing into workpiece surface could be the results of any mechanical effects such as increased ejection of debris or thermal effect due to increase in plasma temperature. So, the plasma characteristics has been investigated for seeking any changes form the Lorentz force in the machining process. There is no significant change is occurred in the plasma temperature for all three field strengths [5], although the temperature of nitrogen plasma jet is reported around 30° C at room temperature. When the electric and magnetic fields perpendicularly intersect each other, as stated in this experimental study, the electrons considered to follow the restrictive path than the straight path which is usually seen in electric field. The particles motion that comes in extent as the electron is moving along the electric field as well as the purposed magnetic field lines [9]. As, it can be seen in the Fig. 14, the material removal from the workpiece reduced and surface roughness increased at field strength 0.3T. It is because of decrease in moving electrons densities. The density of electron decreased at higher field strength is likely the result of restrictive path of travel. Due to the restrictive path, fewer amount of electron possibly jumped across the electrode gape, in resulting, decrease in electron density. On the bases of these analyses, it can be stated that the increase of removal rate related to the presence of external Lorentz force is not because of increased plasma temperature or electron density. It can be seen that the increment of MRR in magnet field is significantly enhanced in all types of purposed energies as compared to the previous research work related to NPJ as a dielectric. Therefore, under the open voltage 120V and 1μF capacitance, the surface roughness is very worst. During the machining, it is seen that lot of molten material adhered to the circumference of tool electrode as well as the rim of vertical grooves burned badly. However, the machining time is cut down to one third. The discharge energies 100V-8200pF and 80V-8200pF considered most preferable machining conditions regarding MRR, TWR, Ra and machining processing time. Fig. 15 shows SEM results of successfully machined grooves. Furthermore, Machining is still not available under the open voltage 80V and 470pF due to very small discharge energy.

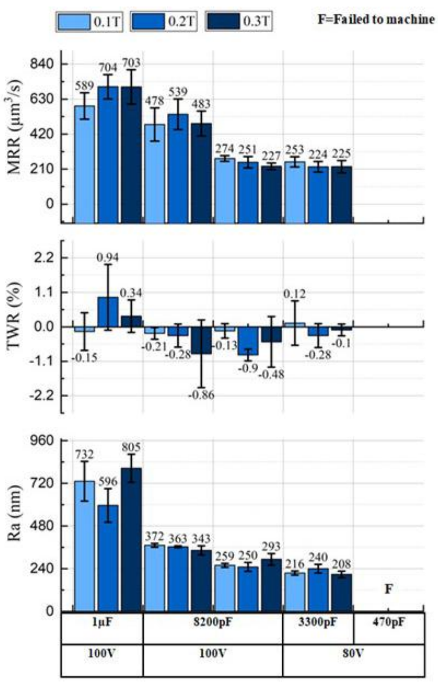


Fig. 14. Machining performance in different magnet fields and discharge energies.

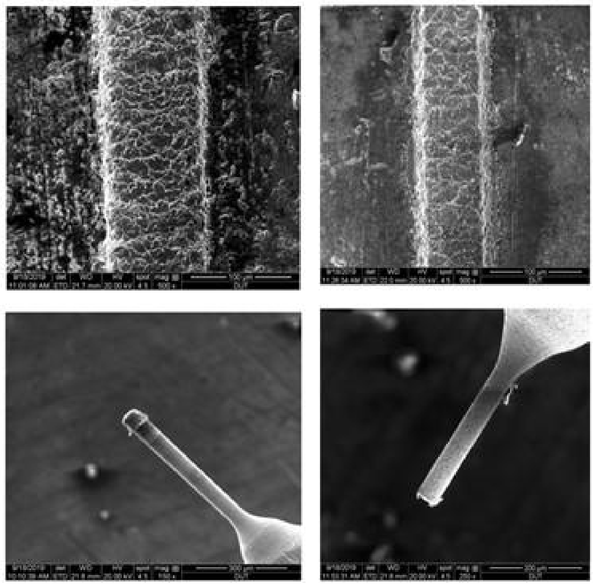


Fig. 15. SEM images of vertical grooves and tool electrode under voltages 100V, 80V and 8200pF capacitance.

E. Material Removal Mechanism in Magnetic Field Assisted Micro EDM

Material removal mechanism in magnetic field assisted is very complicated, involving different forces occurring from electrodynamics, magnetic field and especially fundamental mechanism of material removal in normal plasma jet machining is by etching or sputtering reaction. Sputtering reaction usually recognized by bombardment of highly energetic ions in the plasma [10]. However, in case of external Lorentz force, the confinement of plasma channel considered the reason of increase in MRR and reduces the discharge crater size.

F. Magnet Effect on Tool Electrode Wear

In this study, the tool electrode wear are considerably very low and randomly distributed as shown in Fig. 14. Basically electrical discharge machining in a gas dielectric, the molten material adhered to the tool electrode to protect the electrode from wear. In magnet field assisted micro EDM, the magnet field has no significant effect on tool wear.

IV. CONCLUSIONS

In this paper, magnetic field was proposed as a "catalyst" to assist the micro EDM of non-magnet material in nitrogen and high velocity air jet. In this research study directional workpiece current was used to introduce the external Lorentz force normal to the workpiece surface to alter the plasma channel for augment the material removal. It was found that the addition of external Lorentz force triggered the process of molten material ejection from the machining area.in resulting, significantly increased in MRR and decreased in surface roughness. Furthermore, instead of increase in NPJ flow rates, the application of magnet field has been proved to reduce the machining time as well as the machining cost.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

Author Contributions

Aziz Asad, Idea proposal, Performing experiment, Data collecting, Paper writing.

Zuyuan Yu, Supervising, Data analysis, Paper finalization.

Rimao Zou, Construction of experimental equipment, Experimental design.

Congyang Zhang, Performing experiment, Data collecting.

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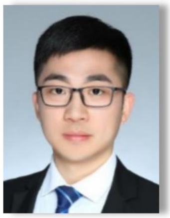

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