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Shashank Shukla

Indian Institute of Technology (ISM) Dhanbad

Mangal Singh Sisodiya

Indian Institute of Technology (ISM) Dhanbad

Vivek Bajpai (✉ vivek@iitism.ac.in)

Indian Institute of Technology (ISM) Dhanbad <https://orcid.org/0000-0003-4811-6611>

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Characterization and evaluation of novel maglev EDM with existing EDM

Shashank Shukla, Mangal Singh Sisodiya, and Vivek Bajpai*

Department of Mechanical Engineering

Indian Institute of Technology (ISM) Dhanbad, India

*email of the corresponding author: vivek@iitism.ac.in

Abstract

At present, the machining performance of the existing EDM technology depends upon the commonly used pulsed power supply and gap control mechanism. The complexity and the higher cost of the above said vital components, reflected in the product cost. A simple electrical circuit has been applied to control the voltage and the electric magnet so that the tool electrode can levitate over the workpiece at the desired distance (electrode gap). A prototype is fabricated with the DC power supply and the maglev levitation mechanism. To evaluate novel maglev EDM technology with the existing EDM technology, experiments were conducted on Ti-6Al-4V alloy with a brass tool.

The discharge waveform of maglev EDM has shown the discharge voltage and current and the absence of short-circuit at high duty factor. A predictive model is formulated by dimensional analysis based on MRR and average surface roughness. The experimental result of conventional EDM from the literature were used to prepare the model. The maglev EDM is showing higher MRR and surface roughness than the prediction. Surface morphology showed similar surfaces as formed in EDM. The specific energy analysis showed that the developed maglev EDM performs in reported data range. It is noted that the proposed technology is in its early stage and the performance is significantly comparable with the existing technology. Therefore, it is expected that the research in this area may help to develop an economically sustainable alternative to the existing costly and complex EDM technology.

Keywords: EDM; servo mechanism; power supply; voltage-current

1 INTRODUCTION

Electric discharge machining (EDM) machining has the advantage that it can machine any electrically conductive material regardless of its hardness and strength into complex shape without physical contact with the workpiece. EDM has been evolved in many variants such as die-sink EDM, dry EDM, wire EDM, wire electro discharge grinding (WEDG), micro EDM and electrical arc machining (EAM) [1]. In the EDM process, after the deionization of dielectric fluid, electric discharge plasma is formed inside the dielectric medium, which evaporates material from workpiece and tool as well. However, it is desirable that the material should be removed from the workpiece only. This vaporized material forms the spherical chips and is suspended between both electrodes. These suspended chips are the cause of short circuit and low duty cycle during EDM processes, resultantly; decrement in material removal rate (MRR) and surface finish of workpiece is occurred. Hence, inter-electrode gap, servo mechanism and removal of debris particles play an essential role in providing continuous machining with high MRR during the EDM process [2].

The evolution of the servo mechanism has occurred since 1943, when two Russian scientists have discovered the breakthrough evolution in EDM. They have developed a controlled servo mechanism through which machining can be done by utilizing the destructive property of electrical discharges into the constructive application. In 1950 resistance –capacitance (R-C) type power supply circuit had employed to control the system, which was introduced by Lazarenko [2] and currently, they are applied in micro EDM as a single resistance -capacitance discharge [3]. In the previous year's various researchers have tried to modify and develop EDM servo mechanism, which can control inter electrode gap to achieve higher MRR, surface finish and dimensional accuracy. In the 1980's computer numerical control (CNC) and adaptive control were coupled with EDM to improve control efficiency [4]. In these computer added adaptive control systems researchers have added computer adaptive control strategy with EDM monitor and achieved an improved EDM self-tuning servo regulator with a combination of proportional integral control [5]. Many researchers have developed hybrid EDM machining methods to improve the machining efficiency of the EDM. In their studies, they have achieved higher MRR and surface finish than the conventional EDM process. Rajeswari and Shunmugam [6] have evaluated the EDM machining method between graphite powder mixed EDM (PMEDM) and

ultrasonic assisted EDM (USED) to enhance MRR. They have achieved better results in the case of PMEDM than USED for MRR (increment of 20.8%) with 215 J discharge energy and 0.227 performance factor. Shabgard et al. [7] have applied fuzzy system in EDM and USED; and observed that with increase in pulse duration and discharge current, MRR and surface roughness of workpiece have increased. Khosrozadeh and Shabgard [8] have evaluated the conventional EDM with PMEDM, USED and combination of both. They have achieved better MRR in all three methods than conventional EDM. Although, surface finish was highest during PMEDM process; while vibration during USED to remove debris particles had increased the surface roughness of workpiece. Ghoreishi and Atkinson [9] have done assessment between rotary, vibratory and vibro-rotary EDM process and established that vibration can reduce the instability of conventional EDM mechanism. They have observed that MRR, TWR and surface roughness of workpiece is increased, therefore; high MRR can be attained by compromising with surface finish of it, and that is the limitation of their outcome. Chung and Chu [10] have tried to improve the machining capability of micro EDM by introducing inductance and high frequency bipolar pulse generator into it. They have observed that low inductance was giving better results in terms of tool wear, workpiece surface and inter-electrode gap than high inductance. There were improvement in machining stability, controllability and surface finish by low inductance, although it was not improving the MRR of workpiece; which is a key drawback of their developed EDM process. To achieve advancement in EDM mechanism, Fu et al. [11] have designed a novel piezoelectric self-adaptive system. In this mechanism they have achieved self-elimination of short circuit and reduced the number of short circuit. Although, they have attained good surface finish with poor MRR than conventional EDM process. Kou and Han [12] have applied moving electric arcs with high speed EDM milling and they have achieved very high MRR with poor surface finish. Recently, hybrid novel mechanism is developed by Han and Kunieda [13] and in this method they have combined micro electrochemical machining (ECM) with micro EDM. Initially micro EDM then micro ECM was applied; to achieve high MRR and high surface finish respectively. Although, during this hybrid machining method MRR was lesser than conventional EDM method. Recently, Zhang et al. [14] have placed the magnets to obtain Lorentz force and Ampere force to gain increment in the stability of the plasma channel and current density. In their research they have achieved increment in MRR and decrement in energy consumption, hence they have achieved economical method to improve the WEDM process.

Therefore, it is concluded from studies that improved servo mechanism can increase the machining efficiency as well as stability of EDM processes significantly.

It is observed from studies that inter-electrode gap condition controls the performance (MRR and surface finish) of EDM extensively [15]. Optimum gap between electrodes is fixed upto a limit; therefore, pulse width (pulse on time) is the better option to increase the discharge energy to achieve higher MRR. Various attempts have been done to improve EDM mechanism, although there is no significant modification is achieved on servo mechanism of EDM process. The current EDM machines are highly developed and efficient; however, there are certain limitation such as complex electrical circuit of pulse power supply, expensive servo mechanism and maintenance of the system.

In the current work concept of maglev levitation has been incorporated to diminish above explained limitation. Maglev levitation has been in development as an alternative since 1912 when Graeminger invented an electromagnetic suspension device in, magnetic levitation (suspension) for a contactless operational system. Since then maglev levitation has been applied on various fields such as railway application, clean conveyor, rope-less elevator, passenger transport, cargo conveyor and aerospace systems [16]. In recent past years some researchers have applied magnet assisted EDM, although; they have not tried to control the inter electrode gap with magnets. Their research work were chiefly focused on assisting the conventional servo mechanism to increase MRR by increasing stability of plasma channel or by increasing the debris removal process [14, 17, 18]. Zhang et al. [19–22] have developed maglev actuator to attach on micro EDM with brush, PI controller, R-C circuit and they have controlled the inter electrode gap by it; to achieve high speed micro EDM. To do so, they have placed the maglev actuator into the conventional EDM machine and given initial position of the electrode through conventional machine. In their experimental system the magnetic actuator was floated on a magnetic bearing and motion was controlled by voice coil electric magnet. Though, in their experiment they have used existing EDM which made their system complex and more costly. Therefore, in presented research work researcher have substituted the costlier conventional pulse power supply and servo mechanism; with DC power supply and maglev levitation EDM mechanism to achieve a sustainable manufacturing method. The maglev EDM mechanism has

been explained in the next section, which is completely different from the mechanisms, which were applied on existing EDM machines.

2 Principle and experimental procedure of maglev EDM mechanism

2.1 Principle of maglev EDM mechanism

The principle of maglev EDM is established on the concept of maintaining balance between repulsive forces of two sets of magnets. The combination of electric magnet (E) with movable permanent magnet (M) and fixed permanent magnet (F) with M magnet are employed to acquire the two sets of magnetic repulsion forces (see Fig. 1(a)). Repulsive force (F_1), between magnets E and M, is working as a force to move M downwards and the repulsive force between magnets M and F is working as a restoring force (F_2) to drive the magnet M upwards. A detailed explanation of gap control is shown in fig. 1 (b). In fig 1(b) two connection of DC power supply is shown, a: Positive connection of DC power supply with E magnet and workpiece in parallel, b: negative connection of DC power supply with E magnet and tool. It can be observed from fig 1(b) that DC power supply has formed parallel connection with electric magnet E and electrodes (tool negative and workpiece positive). Hence, as per Kirchhoff's voltage law the summation of potential difference between the electrodes, the electric magnet E and voltage of DC power supply must be equal to zero. Resultantly, Discharge reduces the potential difference of power supply resultantly, decrement in voltage applied to the electric magnet and electrodes is witnessed.

Fig.1 (a) Illustration of positions of the magnets, (b) mechanism of maintaining electrode gap and the movement of the magnets

In fig 2 three curves have been shown, (a): voltage between the electrodes which is same as voltage applied to the electric magnet, (b): the repulsive force F_1 by the electric magnet; which drives the tool towards the workpiece, (c): the restoring force F_2 that transfers the tool away from the workpiece. The process starts from the extreme left position (see point 1 in Fig. 2), when the electrode gap is significantly high and the potential difference between the electrodes is equal to the open circuit voltage and there is no current flow through the electrodes. At this situation the electric magnet is at its full strength, therefore; the tool electrode starts moving in downward direction towards the workpiece electrode and the distance between the repulsive magnet increases. Resultantly, increment in gap distance between the magnets decreases the repulsive force F_1 (see point 1 to 2 in Fig. 2).

Fig.2 Schematic representation of principle of maglev EDM process

This reduction in force F_1 decreases the inter-electrode gap and it reaches to the breakdown limit. Ionization start at this situation; resultantly rapid reduction in the applied voltage is observed. The reduction in the applied voltage reduces the magnetic strength of the electric magnet and the rate of reduction of the repulsive force increases (from point 2 onwards). Meanwhile, the distance between the permanent magnet was decreasing and the restoring force was increasing (curve c in Fig. 2). If m_1 , m_2 and m_3 is magnetic strength of electromagnet, movable permanent magnet and fixed permanent magnet respectively, then this phenomenon can be understand as follows by Coulomb's law

$$F_1 \propto \frac{m_1 m_2}{d_1^2} \quad (1)$$

And,

$$F_2 \propto \frac{m_2 m_3}{d_2^2} \quad (2)$$

After a certain movement of the tool, the electrode gap will reach the point 3¹, where discharge starts. At point 3¹ eq. 1 and eq.2 is having following relation. At this situation, the value of m_1 and d_2 is decreasing and d_1 is increasing, subsequently the voltage drops continuously; while other values are not changing.

$$\frac{m_1 m_2}{d_1^2} > \frac{m_2 m_3}{d_2^2} \quad (3)$$

After particular fraction of time with continuous change in values of m_1 , d_1 and d_2 ; point 3 is occurred, which is the target electrode gap. At this point eq.1 and eq.2 are having following relation; which is the target point where the repulsive force and the restoring force are equal.

$$\frac{m_1 m_2}{d_1^2} = \frac{m_2 m_3}{d_2^2} \quad (4)$$

Again after a movement of the tool, the electrode gap will reach the point 3², which is the minimum discharge voltage. At point 3² eq. 1 and eq.2 is having following relation

$$\frac{m_1 m_2}{d_1^2} < \frac{m_2 m_3}{d_2^2} \quad (5)$$

It is expected that the tool should stay at point 3 to achieve smooth and continuous discharge. However, as a result of the inertia of moving tool and magnet; it crosses the location 3 where the restoring force is higher than the repulsive force. Resultantly, the tool started to return back to the upward direction and the electrode gap (d_2) increases, which return the position of tool from eq. 5 to eq. 4. As it continue, the tool starts oscillation around the equilibrium point (point 3 is the targeted point). The oscillation distance is shown by play distance in Fig 2. From the above explanation a satisfactory electrode gap has been maintained which is responsible to achieve the continuous electrical discharge. The targeted electrode gap can be controlled by controlling the initial distance between magnetic couples and initial electrodes gap.

2.2 Experimental method

Fig. 3 (a) and (b) shows the image of the DC Power supply and maglev EDM with magnified view of spark zone during machining process of the maglev EDM. Two electrodes have been selected, one as workpiece (anode) and another as tool (cathode) throughout the EDM process. The workpiece electrode is fixed and dipped in deionized water and the tool electrode can do up and down motion to control the gap between the electrodes. The tool electrode is attached to M magnet with an arrangement and E magnet is fixed above the tool electrode to create upward–downward motion of tool. F magnet is attached below the moving magnet to keep it away from the workpiece. The workpiece can move in the vertical direction with the help of a manual linear stage to decide the initial inter electrode gap. Titanium alloys mainly Ti-6Al-4V has wide application in the area of biomedical, aeronautical and marine industries; as it has several excellent properties such as high strength to weight ratio, high corrosive resistant, high wear resistant and high strength at higher temperature. Ti-6Al-4V alloy has low machinability since it has low thermal conductivity, chatter and high strength. Therefore, feasibility of maglev EDM can be detected by machining difficult to cut Ti-6Al-4V alloy with tool of soft brass (in comparison to Ti-6Al-4V) rod of 2 mm diameter. From fig 3(b) a clear plasma of the spark is visible during the machining of Ti-6Al-4V alloy with a brass tool. Still de-ionized water is applied as dielectric medium to observe the short circuit occurrence and competency of maglev EDM and it is environmental friendly. Preliminary experiment is done and optimum initial electrode gap distance attained 1 mm in 12 V open circuit voltage and 2 A peak current. Then three repetition is conducted with 10 min and 1 mm initial gap distance to form circular dimples.

Fig 3(a) Image of the experimental setup, (b) Magnified view of spark zone of maglev EDM

2.3 Discharge waveform

There have been various shapes of pulse revealed on studies, which were depended upon type of pulse generator applied during EDM process. These pulses have exposed significant effect on MRR and surface roughness of workpiece [23]. Therefore, pulse shape plays crucial part to confirm that the newly developed maglev EDM is working properly in continuation manner. The discharge waveform during maglev EDM process during single pulse and multiple pulses are shown in Fig. 4(a) and 4(b) respectively, which is taken on digital storage oscilloscope. In Fig 4(a) and 4(b) time vs. voltage and current graph is shown. In this graph time is changing in X-axis; while voltage (yellow line) and current (blue line) are in Y-axis. From Fig. 4 (a) it is visible that the average discharge voltage and current are 6 volt and 1.2 Amp respectively. In maglev EDM short circuit is not obtained, since the minimum voltage in the waveform is above the zero volt (see in Fig. 4(a) and (b)). Thus, stability during maglev EDM (without short circuit) is higher than the conventional EDM process (presence of short circuit).

Fig. 4 Discharge waveform of maglev EDM process (a) Single pulse; (b) Multi-pulses

In Fig. 4 (a), it is illustrated that the pulse width or pulse on time is very high in comparison to pulse off time and the ignition delay is clearly reduced. Therefore, discharge energy occurred from maglev EDM is very high in comparison to conventional EDM method, since discharge energy is dependent upon pulse width. Resultantly, shorter ignition delay has produced higher discharge energy between the inter electrode gap within the pulse duration. Therefore, larger volume of material is removed within given amount of input power through maglev EDM. In

Fig.4 (b), the normal discharge waveform is observed in continuous manner without any interruption. It is observed that during maglev EDM process debris are not occurred between inter electrode gap, hence; stable discharge is achieved during entire machining time.

3 Predictive modelling

In analytical approach researchers have tried to develop a thermal model to predict MRR and surface roughness aimed at single spark or pulse, then they have multiplied it with number of pulses to predict the final MRR and surface roughness. Although, in these approaches they have taken various assumptions such as size of plasma channel, crater size, temperature distribution and mode of heat transfer etc. Therefore, these models are validated through certain definite type of EDM process. In present modelling, dimensional analysis approach is taken through Buckingham's π theorem [24] and multi-variable regression analysis [25] to find out values of power index and linear coefficient. Various researcher have done mathematical modelling of EDM process through dimensional analysis. In their studies they have taken discharge energy and workpiece material property during mathematical modelling. Although, in actual practice dielectric medium and tool material is affecting the MRR and average surface roughness (R_a) of EDM process, which is observed on several studies [26–28]. Therefore, in present work during dimensional analysis workpiece material properties such as melting point temperature, density and thermal conductivity are taken as non-variable by taking identical workpiece in modelling. These values of workpiece materials are going to be included in the value of linear coefficient and power index constant of Buckingham's π theorem.

It is understood by the previous studies [27, 28] that MRR and R_a are influenced by energy density of plasma (dependent upon tool material characteristics which are represented by A and σ), the dielectric medium (represented by D_s and α); and the EDM machining condition parameters (represented by T_{on} , I_d , V_d , P and D_f). These symbols have usual meaning which are given below in Table 1. From these parameters a complete dimensionally independent (CDI) subset or repeating variables are selected to form group of dependent variable and other independent variables as non-dimensional π terms. The four parameters T_{on} , A , V_d , and P are selected as CDI subset and remaining 5 independent parameter are selected to form non dimensional π parameter indicated below in Table 1.

Table 1 Dimensions of parameters applied on dimensional analysis

Parameter Category	Parameter	Symbol	Dimension (MKSA)
CDI Subset	Discharge Time	T_{on}	T
	Surface Area of tool	A	L^2
	Discharge voltage	V_d	$ML^2T^{-3}I^{-1}$
	Flushing pressure	P	$ML^{-1}T^{-2}$
Independent term	Discharge current	I_d	I
	Duty factor	D_f	-
	Thermal diffusivity	α	$M^{-1}L^{-3}T^3I^2$
	Dielectric strength	D_s	$MLT^{-3}I^{-1}$
	Tool electrical conductivity	σ	$M^{-1}L^{-3}T^3I^2$
Dependent term	Material removal Rate	M_r	MT^{-1}
	Surface roughness	R_a	L

The MRR and R_a can be expressed in a relationship as follows-

$$M_r = f(T_{on}, I_d, V_d, P, D_f, A, \sigma, D_s, \alpha) \quad (6)$$

$$R_a = f(T_{on}, I_d, V_d, P, D_f, A, \sigma, D_s, \alpha) \quad (7)$$

From Eq. (6) and (7); it is evident that both the dimensionless homogeneous equations have 10 variable with 4 fundamental dimensionless coefficient, therefore according to Buckingham's π theorem [24] the solution can be given in the form of a product of six independent dimensionless π_s equations.

By applying Buckingham's π theorem each dimensional π_s term can be stated as shown in Eq. (8) to (13)

$$\pi_1 = T_{on}^{a1} A^{b1} V_d^{c1} P^{d1} M_r \quad (8)$$

$$\pi_2 = T_{on}^{a2} A^{b2} V_d^{c2} P^{d2} R_a \quad (9)$$

$$\pi_3 = T_{on}^{a3} A^{b3} V_d^{c3} P^{d3} I_d \quad (10)$$

$$\pi_4 = T_{on}^{a4} A^{b4} V_d^{c4} P^{d4} D_f \quad (11)$$

$$\pi_5 = T_{on}^{a5} A^{b5} V_d^{c5} P^{d5} \alpha \quad (12)$$

$$\pi_6 = T_{on}^{a6} A^{b6} V_d^{c6} P^{d6} D_s \quad (13)$$

By solving above equations as per the Buckingham's π theorem [24] and replacing dimensionless parameters π_s , the equations can be rewritten as follows-

$$f\left(\frac{M_r}{T_{on} A^{0.5} P}, \frac{I_d T_{on} V_d}{A^{1.5} P}, D_f, \frac{\alpha T_{on}}{A}, \frac{D_s A^{0.5}}{V}, \frac{\sigma T_{on} V^2}{P}\right) = 0 \quad (14)$$

$$f\left(\frac{R_a}{A^{0.5}}, \frac{I_d T_{on} V_d}{A^{1.5} P}, D_f, \frac{\alpha T_{on}}{A}, \frac{D_s A^{0.5}}{V}, \frac{\sigma T_{on} V^2}{P}\right) = 0 \quad (15)$$

Applying power law to evaluate the eq. (14) and (15) gives

$$\frac{M_r}{T_{on} A^{0.5} P} = K_1 \left(\frac{I_d T_{on} V_d}{A^{1.5} P}\right)^{v1} (D_f)^{w1} \left(\frac{\alpha T_{on}}{A}\right)^{x1} \left(\frac{D_s A^{0.5}}{V}\right)^{y1} \left(\frac{\sigma T_{on} V^2}{P}\right)^{z1} \quad (16)$$

$$\frac{R_a}{A^{0.5}} = K_2 \left(\frac{I_d T_{on} V_d}{A^{1.5} P}\right)^{v2} (D_f)^{w2} \left(\frac{\alpha T_{on}}{A}\right)^{x2} \left(\frac{D_s A^{0.5}}{V}\right)^{y2} \left(\frac{\sigma T_{on} V^2}{P}\right)^{z2} \quad (17)$$

Eq. (16) and (17) are the final equations from which prediction of MRR and R_a is achievable after finding the values of linear coefficients and power indexes of both the equations. To find the values of constants ($K_1, K_2, v1, v2, w1, w2, x1, x2, y1, y2, z1$ and $z2$) multi-variable regression analysis [25] is applied with the help of experimental values of previous published results. It is observed from various predictive models that; they were simply applying experimental values of their own EDM setup [29–31]. Resultantly, their predictive models were not feasible to other EDM setup since servo mechanism or control mechanism changes during every setup. Therefore,

in current predictive modelling experimental results of different EDM setup were taken into consideration. Table 2 is showing the experimental values of certain previous published results [32–36] ; which were applied in multi-variable regression analysis. Identical units were taken throughout the parameters to find the values of linear coefficients and power indexes.

Table2 Parameters and their values applied to develop mathematical model

Parameter	Kao et al 2010	Tang and Du 2014	Rahul et al (2018)	Kolli and kumar (2018)	Nair et. al (2019)
Discharge Time (min)	3.33E-06	8.33E-07	0.000005	1.08E-06	2.50E-06
Surface Area of tool (mm ²)	78.57	78.57	78.57	154	50.29
Discharge voltage (V)	200	20	25	115	75
Flushing pressure (Kg/mm ²)	0.005	0.00005	0.021414	0.005	0.0153
Discharge current (Amp)	20	20	10	20	6
Duty factor	0.3	0.5	0.85	0.6435	0.03
Thermal diffusivity (mm ² /min)	5.34	8.58	4.428	4.428	4.428
Dielectric strength (V/mm)	18000000	80000000	4700000	4700000	4700000
Material removal Rate (Kg/min)	2.243E-05	2.979E-05	2.37E-05	3.04E-05	2.641E-06
Surface roughness(mm)	4.49E-03	2.65E-03	6.88E-03	5.38E-03	7.39E-03

4 Results and discussion

4.1 Model validation and prediction

By multivariable regression analysis values of linear coefficients and power indexes are found, hence eq. (16) and (17) are established as follows-

$$M_r = 5.585E - 10(T_{on}A^{0.5} P) \left(\frac{I_d T_{on} V_d}{A^{1.5} P} \right)^{1.0614} (D_f)^{0.3123} \left(\frac{\alpha T_{on}}{A} \right)^{-1.6954} \left(\frac{D_s A^{0.5}}{V} \right)^{0.8303} \left(\frac{\sigma T_{on} V^2}{P} \right)^{-0.3235} \quad (18)$$

$$R_a = 14.289(A^{0.5}) \left(\frac{I_d T_{on} V_d}{A^{1.5} P} \right)^{0.1914} (D_f)^{0.0067} \left(\frac{\alpha T_{on}}{A} \right)^{0.1556} \left(\frac{D_s A^{0.5}}{V} \right)^{-0.2394} \left(\frac{\sigma T_{on} V^2}{P} \right)^{-0.2483} \quad (19)$$

Equation (18) and (19) are the concluding equations of mathematical modelling, which were obtained with the help of Buckingham's π theorem and multi-variable regression analysis.

This model is unique from earlier, since it includes experimental values of different experimental setup to facilitate the diversity of the EDM setup. This model includes properties which were not taken on previous modelling and they affect the MRR and R_a with great extent. Experimental MRR of maglev EDM is calculated by the following formula-

Experimental MRR= (Final weight of workpiece - initial weight of workpiece) / Machining time

Fig.5 Experimental vs. Predicted result during different EDM process (a) MRR; (b) Average surface roughness

Prediction results of MRR and R_a are excellently matched with the experimental results of EDM setup which were taken into consideration during calculation of constant of model. Although; prediction results were not matched with maglev EDM setup results and difference in prediction and experimental result of maglev EDM setup is observed. Thus, evaluation of maglev EDM setup from other conventional EDM setup can be achieved. Fig. 5 (a) & (b) shows the experimental vs. predicted value of MRR and R_a respectively. It is observed from Fig. 5(a) that the experimental and predicted value of MRR is maximum during Kolli and Kumar [35] experimental setup while minimum in maglev EDM. The key factor is discharge voltage and current, which is minimum during maglev EDM process. Additionally, several other parameters are affecting the MRR and R_a since maximum discharge voltage and current were given during

Kao et al experiment, although; maximum MRR and R_a is not observed during their experimental setup. These parameters are duty cycle, pulse on time, dielectric medium, plasma density and tool electrode material which were included in present mathematical modelling. Experimental result during maglev EDM is 66.23% higher than prediction result, which is showing that this setup is giving better result than expected result in terms of MRR.

Experimental R_a in machined surface of maglev EDM is obtained from profilometer Zygo new view 9000 and it is explained below in 4.2 characterization of surface morphology. From Fig. 5(b) it is observed that experimental value of maglev EDM were varying higher than predicted value. Minor variation in R_a during prediction and experimental result can be concluded as the effect of deviation in quenching rate, which was not included in mathematical modelling. Moreover, during maglev EDM process MRR result (66.23%) is increased higher than R_a (38.1%) result. Average % error in prediction of MRR and R_a is observed less than 1% in EDM setup, which were included during mathematical modelling. Hence; excellent prediction results were achieved through mathematical modelling. It is a general trend that during EDM process increment in MRR of material will increase R_a . Although, by observing fig 5 (a) and (b), it can be concluded that general trend is wrong and MRR is not directly proportional to R_a of material. There are certain other factors on which R_a and MRR of material is dependent such as tool material, dielectric medium, quenching rate and energy density of plasma. In maglev EDM process small tool diameter is used and energy density of plasma is too high as we can see from plasma of fig 3(b). Plasma energy density during maglev EDM is maximum, resultantly; highest % error in prediction is obtained during R_a . Therefore, it can be concluded from mathematical modelling that MRR in maglev EDM is achieved more than expected or predicted result, without ample increment in R_a of workpiece material.

4.2 Characterization of surface morphology

The 3D machined surface on maglev EDM are characterized and analyzed using optical profilometer Zygo new view 9000. Fig 6 (a) & (b) depicts the three-dimensional surface topography taken on it. In this figure height of the lump and depression on machined surface can be seen. In Fig.6 (a), it can be observed that the diameter of material removed from the machined surface was approximately 2 mm. From Fig 6(a), it can be concluded that the value of overcut is quite low during maglev EDM process. In maglev EDM process, continuous sparking

phenomenon has removed material to form craters and these craters acts key role to elaborate about surface topography. From Fig. 6 (a) & (b) maximum height of machined surface can be observed approximately 250 μm . Highest valley and peak can be seen from fig 6 (b) in $173.347 \times 173.347 \mu\text{m}^2$ area and it can be observed that approximately micron size semi-spherical shapes craters has been achieved through maglev EDM process.

Fig.6 Surface morphology during maglev EDM (a) 3D profile map of whole texture; (b) 3D profile map of machined surface

Fig. 7 shows the 2D profiles with different scale taken from optical microscope Olympus BX-52 and Zeiss field emission scanning electron microscope (FESEM) of machined surface. Fig. 7 (b) shows the image occupied from the optical microscope and 7(c) shows the FESEM image of inside area of machined surface. During maglev EDM process de-ionized water was filled inside workpiece holder and combination of still water with concentrated discharge energy has produced oxides layer on the workpiece upper surface. In Fig. 7(b) and (c) long micro cracks, micro pores, material accumulation and metal globules are perceived. The difference of contraction stress within surface has surpassed the material ultimate tensile stress, therefore long micro cracks are formed. It can be observed from surface morphology revealed in Fig.7 (b) and (c) that the surface irregularities enhances and colour changes with an increase in discharge power. Heat affected zone (HAZ) can be seen in Fig 7(a) & (b), since Ti-6Al-4V has low thermal

conductivity and surface layer is heated up during EDM process however material not removed. From Fig 7 (c) it can be seen that too much amount of micro-debris are collected on machined surface in the form of spherical nodules material. The quantity of micro size debris are excessive since in maglev EDM still deionized water is used, therefore; debris of micron size are not removed from machined surface while debris of macro size were removed by the oscillation motion of tool electrode.

Fig.7 Surface morphology during maglev EDM (a) 2D profile of whole dimple (b) 2D profile with 20 µm scale of maglev EDM taken from microscope (c) 2D profile with 3 µm scale of maglev EDM taken from FESEM

Fig.8 is plotted with the help of the optical profilometer Zygo new view 9000 and as per the ISO 4288-1997 standards, to measure the R_a between 2 -10 µm the sampling length should be between 2.5-12.5 mm. Although, machining is achieved by 2 mm diameter tool therefore, 4 slices of 2 mm length were made in machined area to measure the average value in iteration 1, 2 and 3. Filter was applied in the period of 0 to 1 mm to measure the surface profile without form. In fig 8 root mean square roughness (R_q), skewness (R_{Sk}), R_a and Kurtosis (R_{ku}) of the machined area has shown. R_a is signifying the average deviation of asperities roughness from mean line throughout sampling length. Maximum R_a is observed in iteration 2 since the MRR is higher in it than other two. Moreover, there is additional reason of high R_a in iteration 2 in comparison to iteration 1 and 3 is high pulse on time. Since the higher pulse on time crater size is unavoidably larger which results in higher R_a of workpiece. R_q is showing the standard deviation of distribution of surface heights and maximum R_q is observed in iteration 3 then in iteration 2.

Which displays that surface heights of machined surface during iteration 3 is more randomly distributed. Skewness of a profile is showing the balance of the profile about the mean line which means if number of peaks and valley are equal then it will show the zero skewness. Positive skewness value shows high peaks and negative shows deep scratches or more valleys.

Fig.8 Roughness values observed on machined surface during maglev EDM by Optical profilometer

During maglev EDM in all three iterations negative skewness is detected, therefore; it can be concluded that maglev EDM is constructing the craters and removing asperities, which were existent before the machining on workpiece surface. This phenomenon of current maglev mechanism is displaying a perfect characteristic of EDM process. Moreover, minimum skewness value is observed in iteration 2 and maximum in iteration 1, therefore; this skewness value is giving validation that the surface roughness is minimum in iteration 1 and MRR is maximum in iteration 2. Kurtosis value is termed as a sharpness of the probability density of a profile. According to it; value lower than three means less number of high peaks and low valleys present in profile, while value more than three indicates higher number of high peaks and low valleys. During maglev EDM process kurtosis value shows minimum number of high peak and low valley in iteration 2 and this approves high MRR value during iteration 2 [37].

4.3 Evaluation of the specific Energy

In present work specific energy is termed as the minimum amount of energy (in Joule) required to remove a unit mass (in μgm) of workpiece material (Ti-6Al-4V). Minimum the value of

specific energy means higher the MRR with less amount of discharge power supply, therefore; performance of different experimental setup is evaluated on the basis of it. According to it experimental setup has minimum value of specific energy is best and vice versa. In this calculation duty cycle is included to exclude the amount of discharge power which is wasted during pulse off time.

The formula to calculate specific energy consumed to remove unit material is given by-

$$\text{Specific energy of material removal} = [\text{Discharge power (in J/sec)} \times \text{Duty cycle}] / \text{MRR (in } \mu\text{gm/sec)} \quad (20)$$

$$\text{And Discharge power} = \text{Discharge voltage (in volt)} \times \text{Discharge current (in Amp)} \quad (21)$$

Fig.9 Specific energy comparison of different experimental setup

To achieve evaluation on the basis of specific energy to remove material five published research article is taken into account with maglev EDM results. From eq. (20), (21) and Table 2 specific energy to remove material from Ti-6Al-4V is calculated and their assessment can be seen on Fig 9. It can be seen from fig. 9 that specific energy required to remove material during EDM process of Kao et al. is approximately 5 times more than maglev EDM process. It can be observed that they have applied copper tool of 10 mm diameter with high amount of input power. However duty cycle, excessive voltage and dielectric medium (kerosene) is increasing the specific energy required to remove material. Excessive voltage is developing arcing more than beneficial discharge pulses, hence input power is going into wastage. Whereas kerosene with higher amount of input power enhancing the formation of carbide layer on upper surface;

resultantly increasing the wastage of discharge energy to remove it. In the assessment it is seen that Tang and Du EDM setup has taken less amount of specific energy than maglev EDM. They have achieved that since optimum amount of discharge voltage, current, dielectric medium (water) and duty cycle is applied. Main cause of difference between specific energy of their and maglev EDM are observed tool material (copper vs. brass) and diameter (10 vs. 2 mm), which has influenced the amount of plasma energy density excessively. By assessment it is observed that Rahul et al. have applied cryogenically treated copper tool of 10 mm diameter with high flushing pressure. High flushing pressure has reduced the occurrence of number of short circuit and formation of debris in the upper surface. By cryogenic treatment of copper tool they have achieved improvement in electrical and thermal conductivity [34]. Resultantly, they have achieved approximately 5 times less specific energy to remove material than maglev EDM. Kolli and Kumar have achieved highest MRR however their specific energy is poor than maglev EDM. This condition is observed since they have applied excessive voltage and 14 mm diameter copper tool with EDM oil which producing excessive carbide layer and high plasma energy density. Additionally, pulse on time is very low therefore excess amount of arcs are produced than discharge pulses, which has increased the wastage of input power. Duty cycle during Nair et al. experiment is lowest (3 %) which enhanced the wastage of input power. Moreover, they have applied brass tool similar to maglev EDM experiment that has low electrical conductivity than copper tool.

From above discussion it can be determined that the maglev EDM setup has high specific energy than two experimental setup and has low specific energy than three setup. In published articles during experiments CNC EDM machines were applied while newly developed maglev EDM has no CNC control. By comparing experimental parameters used during both experiment, the key reason of low specific energy are detected plasma energy density (tool electrode diameter), continuous flow of dielectric medium with pressure and copper electrode. Hence, it can be concluded that the less costly novel maglev EDM setup can achieve better results than many high costly conventional EDM setup, if similar parameter of tool and dielectric medium has been selected, since it can work at higher duty cycle without short circuit throughout the longer period of time.

5 Conclusion

A novel maglev EDM mechanism is developed to assist and drive the tool electrode to maintain the optimum electrode gap. Maglev EDM control mechanism could reduce the possibility of irregular electric discharge, therefore; the machining efficiency has been enhanced impressively. In this investigation, the stability of the maglev EDM is observed by the analysis of discharge waveforms, and the machining characteristics such as MRR and surface roughness parameters. The mathematical modelling is achieved with different experimental setup results to diminish the effect of similar servo mechanism. This study can be concluded as following-

- The experimental results of discharge waveform, surface morphology and MRR are validating that the novel maglev EDM mechanism is capable to do stable EDM process. As the controlled spark between electrodes are producing optimum amount of discharge energy to remove the material.
- From discharge waveform results it is observed that short circuit is not existing in maglev EDM mechanism, although still dielectric was used. Therefore, higher duty cycle and continuous discharges are achieved than conventional EDM process.
- Prediction error of MRR is higher than the prediction error in R_a since high plasma energy density is achieved during maglev EDM. Higher experimental result than prediction result of MRR is showing that maglev EDM produces better result than expected result without ample increment in R_a of Ti-6Al-4V alloy.
- It is observed from machined surface that during maglev EDM process the increase in pulse-on time causes enhancement in number of craters and its size, resultantly; MRR and R_a are increased.
- It is established from mathematical modelling prediction results that MRR and R_a has no direct relation with each other. There are certain other factors such as amount of plasma energy density, tool material and dielectric medium; which have equivalent impact as discharge energy and workpiece material have on MRR and R_a .
- It is detected that static dielectric medium placed micro-debris on machined surface and macro-debris were removed by controlled oscillation of tool electrode.

- From the surface roughness parameters R_a , R_q , R_{Sk} and R_{ku} ; it is concluded that that maglev EDM control mechanism is forming the craters and removing asperities which were existent on surface before the machining.
- Specific energy of material removal results have concluded that the novel maglev EDM is generating excellent result as compared to various conventional EDM mechanism. Therefore, novel maglev EDM control mechanism can work as low cost sustainable manufacturing substitute to high costly conventional EDM machine.

Future scope:

The developed technology and the prototype are in very early stage. Hard metals such as nimonic alloy, titanium alloys, inconel with different tool materials, and dielectric media (hydrocarbons and gases) are under investigation. The results are in line with the current work. Improvements have been observed and the work will be reported in the subsequent publications. It is expected that the developed technology may be a replacement for the existing servo mechanism and the power supply due to its simplicity, low cost, low maintenance, sustainability and availability of the components.

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