Feasibility Analysis of Novel Maglev EDM by Comparing with Conventional Micro EDM

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Research Article

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Feasibility analysis of Novel Maglev EDM by comparing with conventional micro EDM

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Abstract: The Micro EDM is the most suitable machining process in the miniaturization of products at present era. The attainment of close precision is the primary obligation in miniaturization or micromachining. Especially in machining of hard-to-cut materials like titanium alloy. Such alloys are applied in several **cutting-edge** high-**quit** applications due to extraordinary properties. Current work presents an exploratory analysis of novel Maglev EDM while machining of commercially used pure titanium alloy (CP-TI). The work outlook is to establish the viability of novel Maglev EDM by comparing the with similar range of micro EDM. The pure DC power is employed with the conjunction of Maglev lucidity to refine the shortcomings of the conventional micro EDM. The novel technology deals with prime concerns of conventional micro EDM and cracked deficiencies like delay response of mechanical actuator and a servo mechanism. The Novel technology uses the logical arrangement of permanent and electromagnet to dealt with inadequacies like short-circuiting and arcing. The results of state of art novel technology proclaimed the improved Material removal rate (MRR), which are lying in the average range of 76.6 µgm/min, whereas the specific energy and surface roughness are observed 33.4 Joule/ microgram and 4.3 µm respectively.

Keywords: Commercially Pure Titanium Alloys (CP-TI), Maglev EDM, Material Removal Rate (MRR), Tool Wear Rate (TWR), Surface Roughness (SR), Specific Energy (SE).

1. Introduction

An electrical discharge machine (EDM) is the most popular and appropriate technique to process the hard to cut materials like titanium alloys. Since the applications of such alloying elements have become essential to mitigate the quality index and customer expectations. These materials are having extraordinary chemical, mechanical, and thermal properties. Such characteristics of materials make suitable applications where no margin of error in quality and strength are required like the aviation industry, electronics industry, and medical sector. However, in contrast, these strange properties of the advanced materials make them difficult to cut. So, the processing of such materials by conventional machining method is about to impossible or not worthwhile economically. Hence, the applications of non-conventional or advanced machining methods like EDM have become popular. Owing to the practicality of EDM, the process has extended up to micro-level i.e., Micro-EDM. The micro EDM has become a handy technique in emerging the miniaturization industries. It is applicable to produce the micro feature in hard materials. The micro EDM differs from conventional EDM in terms of size of tool electrode, less amplitude of energy pulse, with high resolution for fine finishing. In micro EDM very short pulse is generated by the pulse generator for a few microseconds or Nanoseconds. Subsequently, a small volume of work material is removed ranges ∼0.05–500 μm3 because of low energy ranges ∼10−9 –10−5 J. Though the machining of difficult to cut materials such as titanium alloys through micro EDM exhibit the issues like lower material removal rate (MRR), high tool wear, generation of recast layer, and improper flushing of debris [1].

In actuality, the material removal rate (MRR) of the micro-EDM lies in the range of 0.6 mm3 /h to 6.0 mm3 /h depending on the process parameters [2]. Practically such a low material removal rate is not worthwhile economically. Hence, the research scope is to improve the performance by thorough investigation of Micro-EDM. Even though the EDM is an established machining technique, but the performance enhancements are still dubious. The dependability on a large number of input parameters makes the process stochastic [3]. In past several attempts have been made to improve the MRR through various techniques. Some researchers used magnetic assistance to improve the MRR by transport out the debris using a magnetic force. The researcher compared machining characteristics by developing magnetic assistance techniques. In a study, the effect of magnetic force assistance is analyzed by observing waveforms of current and voltage and found that magnetic force is helpful to increase the capability of current EDM compared to conventional EDM [4]. The magnetic field assistance further enhanced by employing additional flushing methodology results in higher MRR in conventional EDM. However, it is reported that the size limitation and fragile tool material restrict the peripheral flushing in micro EDM. It is also observed that the magnetic assistance is favorable for higher MRR only, with no significant effect on the surface roughness. On the other hand, magnetic assistance increase tool wear rate by increasing the distortion [5]. The literature review shows that the MRR is not only the single process output of EDM, parameters like tool wear rate (TWR) and surface roughness (SR) also pronounce the capability of micro-EDM. Like the conventional EDM, the performance of the micro EDM can also be evaluated on the output response which mainly associates with the input process parameters.

The input parameters include the discharge current, discharge voltage, pulse on time, and pulse off time, duty factors, dielectric medium, and electrodes gap between tool and workpiece. The researcher studied the effect of various input parameters and identify that discharge current is the most influencing factor which affects the process efficiency overall. In EDM the pulse energy is the function of potential difference produced using the pulse generator equipment and gap across the electrodes. In the early stage of EDM, the relaxation type pulse generator was in use with capacitor discharge. The applications of relaxation types of pulse generators are common in wire EDM (WEDM). Such type of pulse generator provides a high peak current for a very short time which is a favorable condition for higher MRR [6]. Later the relaxation type generator was replaced by the transistor type generator with improvement in power transistors. Transistor-type generators are applicable where a large amount of current with a high response is required. However, the relaxation-type generators are still in use in micro EDM and WEDM. The relaxation type generators are capable to generate the short pulse with constant energy pulse, but the time taken in capacitance recharging is the drawback of the relaxation generator. Along the time factual pulse generation apparatus and tools have been developed by the inventors but none of them give the adequate efficiency of the process. Since it has been observed that the increase in pulse duration improve the MRR up so some extend but longer pulse lower down the MRR due to reduction in plasma strength [7]. Hence, moderate pulse generation is essential for optimum results. Overall, the stable discharge is essential via utilization of each energy pulse for higher MRR, low tool wear, and high-quality surface. Further, it has been evident through research that precise apparatus is required to provide appropriate gap conditions between electrodes which ensure effectual spark for erosion [8].

To execute the toned gap, condition the study of the existing feed mechanism is required. In the present work, the authors have gone through the available literature and drawn succeeding inferences. The study emphasizes that the electrode gap known as the actual spark gap is maintained using a servo control mechanism in conventional EDM. The spark gap plays an important role and is solemnly responsible for efficient machining in terms of higher MRR and surface roughness (SR) with minimum tool wear rate (TWR). It is well known that the actual processing in EDM is carried out in narrow space (usually in microns) between two electrodes one cutting tool and another is a workpiece. The adequate gap between the electrodes neither more nor less is essential to maintain for efficient machining in EDM. The higher enter electrodes gap reduces the plasma strength. Whereas the smaller electrode gap hinders, the effective deionization at the time of pulse rest. The improper deionization leads the harmful effect like short-circuiting which affect the surface quality of the ground part. Particularly in micro EDM, the metal is eroded in the form of micro and nano-size derbies and eventually accumulates in a narrow space between the electrodes. The accumulation of eroded material particles in narrow space increases the chance of inefficient discharge energy; ultimately reduce the efficiency of micro EDM. Referring to the above importance of process and to maintain the electrodes gap using servo mechanism is required to maintain or optimize. Since the use of conventional motor and ball screw in servo mechanism reduce the capability of micro EDM by their slower response. The efforts have been made by the researcher to improve the meticulous electrodes gap using magnetic actuators. Every pulse is important for speed up the machining by keeping the appropriate electrodes gap but the conventional servo mechanism is not capable to regulate the proper gap [9].

Previous research has been made to improve the efficiency of micro EDM by incorporating two-stage fuzzy logic controllers. In this system first stage is used for the detection of the discharge state and the second stage for servo feed speed [10]. Even though comprehensive attempts have been made to improve the functionality of the servo mechanism over time, but several questions regarding effective meticulous gap of electrodes is not yet confined appropriately by any method. Various reasons may be there, like the delay response of motor and mechanism, dependability on actuator material and response, or controlling error. The poor performance results in a long ignition delay which limits the machining speed and accuracy [11]. It also leads to harmful short-circuiting and arcing due to improper positioning of electrodes. Furthermore, the pulse power circuit and servo mechanism increase the intricacy of the system which leads to high upkeep cost and energy in EDM. The present study is conducted to; conquer the above prominent issues, by developing novel Maglev EDM technology. In novel EDM the complex pulse power supply is replaced through the Direct current (DC). The tool electrode movement is confined by a floating magnetic environment instead of a conventional servo controller mechanism. The substitutions of power supply and servomechanism itself resolved above issues in the present Maglev micro EDM. To validate the results and feasibility of the system series of experiments have been performed. The experimental results state the improved performance of Maglev micro EDM significantly over the existing EDM technology. The Characterization of MRR, TWR, and SR pointed out the capabilities of Novel Maglev EDM. The detailed explanation and comparison are reported in the following sections.

2. EDM Working Principle: EDM is based on the generation of potential differences between the two electrodes namely the cutting tool and workpiece. In EDM workpiece material eroded by the sequential reoccurring of electric spark between the two electrodes, usually cutting tool acts as cathode and workpiece as anode[12]. The dielectric medium kerosene or deionized water of high thermal conductivity is used for proper flushing of eroded nanoparticles (debris) and to avoid thermal stresses via extremely high temperature [13]. During the process, an appropriate range of voltage is supplied to electrodes. The narrow gap usually 0.005 to 0.05 mm between tool and workpiece is maintained by the servomechanism. Owing to the establishment of an electrical arena in the narrow gap between electrodes, the free electrons are subjected to electrostatic force and start to move from the cathode (tool) to anode (workpiece) via the dielectric medium. As these free electrons gain energy and strike with the molecule of dielectric fluids. Such impact results in the ionization of dielectric fluid. When the ionization is on pick a sharp plasma channel is generated, which is having very less amount of electrical resistance. Consequently, large number of electrons collides with positive ions. This phenomenon is produced a large amount of local intense heat. Thus, through the intense local heat, the material is started to vaporize and melt from the workpiece as well from the tool. Accordingly, the negative impression of the cutting tool is produced in the form of the cavity on the workpiece without physical contact between the tool and work. Since in EDM there are contact-free metal removals from the workpiece, so the process is considered one of the vibrational, chatters, and mechanical stress-free machining techniques [14]. In the EDM process, the temperature between the tool and workpiece is mainly the function of the power supply and the narrow gap between the electrodes. So, the performance of EDM primarily depends on these important factors. The influencing parameters in EDM may be categorized in two ways, first are electrical parameters like discharge current, discharge voltage, pulse on-time, etc. whereas the second kind is non-electrical parameters like electrode gap, flushing medium, and tool life [15]. The researcher investigated EDM in all aspects and specified to manage all influencing parameters to improve the machining efficiency [16]. They suggested various techniques like ultrasonic vibration, dry EDM, Powder EDM, etc. In conventional EDM each process parameter is precisely control for the optimum response output. In EDM the pulse generation and duration is continued by the power regulatory devices. Each energy pulse can be categorized in three subsequent zones as ionization, discharge, and short circuit zone as shown in Fig.1. During the machining process, the first ionization of dialectic fluid is carried out which helps to increase discharge energy, consequently, a high required spark is produced in the second discharge zone for material removal. The third short circuit is an unwanted zone and needs to be avoided in machining by interrupting the power supply for a small time and again switch on for another stable spark [6]. The short-circuiting phenomena is harmful for the quality EDM surface hence, it has been eliminated in present work up to great extent by employing the Novel EDM technology. The proficiency of Novel machine is presented in following sections.

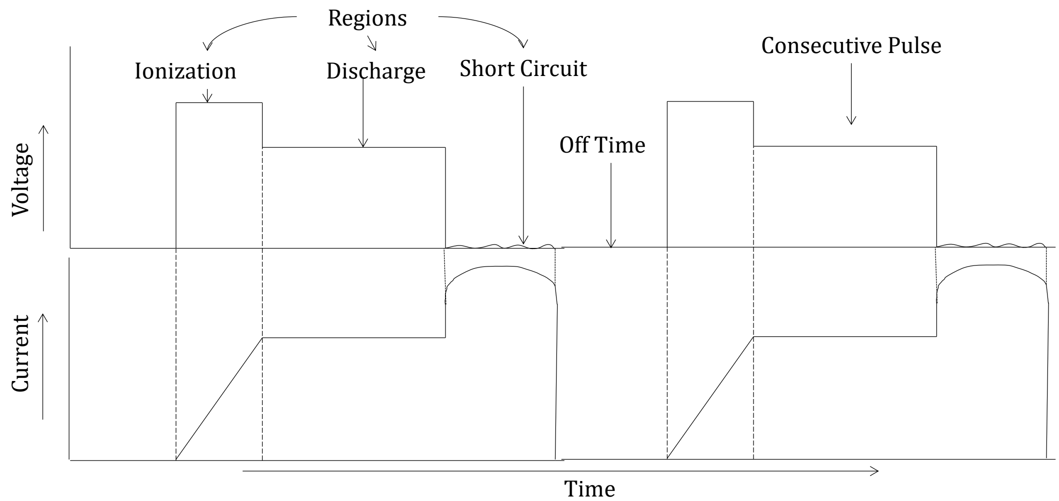

Fig. 1 Voltage and current graph of conventional EDM process[17]

3. Experimental Method

3.1 Experimental setup and procedure

In the present work, a newly developed EDM technology is used to perform all the experiments. The maglev mechanism is applied to maintain the required gap between the tool (cathode) and the workpiece (anode). The maglev concept is based on the electromagnetic repulsive force and a restoring magnetic force. The true scaled working prototype is presented in Fig.2. In current technology the DC power is supplied across the electrodes using the positive polarity i.e., cutting tool (cathode) connects with the negative and workpiece (anode) with the positive terminal. The workpiece is properly clamped and submerged in deionized water. The tool electrode is free to move up and down under precise control using a maglev mechanism. The movement of the tool electrode is accomplished by placing a permanent magnet on the cathode and one electric magnet is mounted above the permanent magnet to produce the magnetic repulsive force. Another steady permanent magnet is attached below the moving magnet to secure and avoid collision with the workpiece.

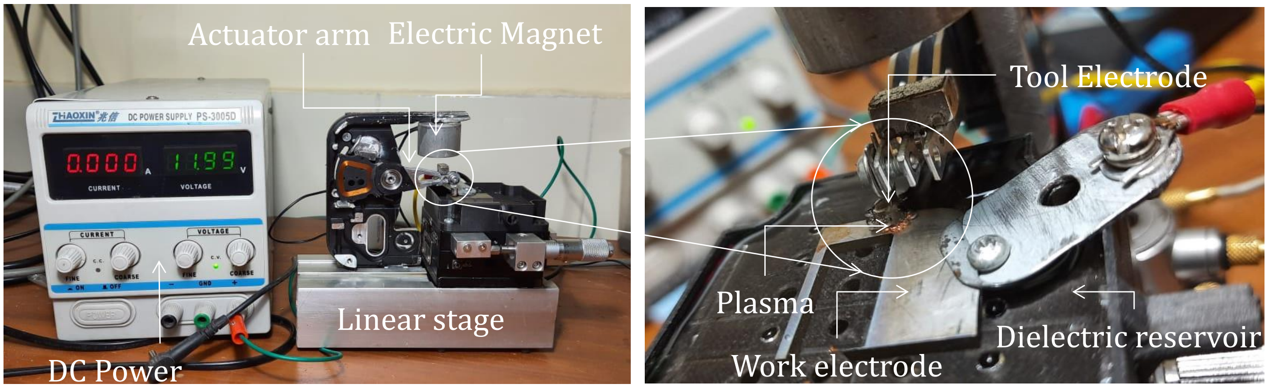

Fig.2 True Scale working prototype Maglev EDM

The generation of the magnetic field by the electric magnet is accomplished through the same DC power supply in parallel. This magnetic field produces the repulsive force on the movable permanent magnet which results in the movement of the tool electrode towards the workpiece electrode. Thus, two electrical loops formed precisely, one loop between the DC power and electrodes and another between the DC power and electric magnet. Precisely, the concept is based on Kirchhoff's voltage law to maintain the gap between the electrodes.

The variability in the potential difference of power supply affects the voltage applied to an electric magnet; consequently, the magnetic strength of the electric magnet is changed invariably. A detailed illustration of tool movement and gap control is mentioned in Fig.3. In the figure, there are three labeled curves which are as follows

Curve – I: voltage between the electrodes which is the same as voltage applied to the electric magnet.

Curve- II: the repulsive force by the electric magnet, the repulsive force pusses the tool towards the workpiece

Curve-III: the restoring force between two permanent magnets, the restoring force impulses the tool away from the workpiece

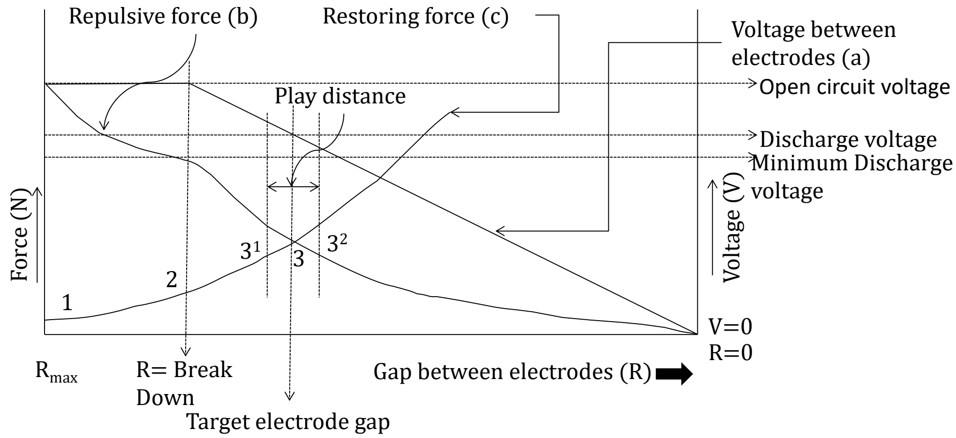

Fig.3 Graphical representation of tool movement in Maglev EDM

At the start of the process when the tool electrode is at home position i.e., the extreme gap between tool and workpiece. At this phase potential difference or gap, the voltage will be equal to the open-circuit voltage consequently no load will be applied. During this period, the electric magnet will be at its full strength. Later, the tool electrode starts to move in the downward direction, which increases the distance between the repulsive magnets. The repulsive magnetic force is represented mathematically by the following relation as

Force α m1xm2/r2 ………………. (i)

In the above relation, the m1 and m2 are the strength of the magnets and r is the distance between the magnets. According to the relation, the magnetic force is inversely proportional to the distance between the magnets. The repulsive magnetic force is responsible to reduce the gap between the electrodes and the movement of the tool electrode towards the workpiece. This reduction of electrode gap, results in the breakdown of the dielectric strength of fluid. Consequently, the ionization and discharge phenomena occur at this moment which results in the dropping of applied voltage. Further, this drop of voltage reduces the magnetic strength of the electric magnet, and the rate of reduction of the repulsive force increases from point 02 in Fig. 03. In the meantime, the gap between the permanent magnet decreases and restoring force increases along curve III in Fig.3. In graphical image point, 3 is the location where the repulsive force and restoring force are supposed to equal ideally where the tool electrode stays and deliver the constantly required discharge for machining. However, the tool oscillates near point 3 results of its inertia and permanent magnet which results in an unbalanced condition in repulsive force and restoring force. In the figure, the oscillation path is shown by the play distance. In the current work, the electrode gap and movement of the tool electrode are maintained precisely to generate optimum spark using maglev lucidity.

3.2 Workpiece and tool material

In present work the experiments have been performed on commercially pure titanium alloy CP-TI. The initial dimension of work sample was 25×25×10 mm with surface polished to ensure parallelism on stage. The CP-TI is the most used material to make non-structural applications, such as water channels, ducts, and piping owing to special characteristics of corrosive resistance and good deformability. The brass tool electrode of 2mm diameters is used with deionized water as a dielectric medium. Both the electrodes connect to direct current (DC) power supply in such a manner that cutting tool with negative (cathode) and workpiece with (anode). The specific resistance of work is decreasing in positive polarity which helps to enhance MRR[18]. In the present work, the open-circuit voltage of 12V, pure DC, and the peak current was 2A. The Tektronix oscilloscope was used to assess the waveforms of discharge voltage and current during the EDM.

The real-time current is measured by the current probe of 100X. The workpiece material is eroded in circular pocket shapes of 2mm diameter in four different experiments. The experiments are performed at two different periods, to ensure the minimum undesirable errors of environment and conditions. The digital weighing pan of least count 10 micrograms is used for the measurement of MRR. The tool wear rate also measures in the same manner. The Mitutoyo SJ-210 make surface roughness tester is utilized to observe stochastically at the various location on the EDM surface.

4. Results and discussion

The experimentations have been carried out systemically and all the observations were noted sensibly. In the following sections, the explanation and science behind the occurrences of all response outputs have been discussed. The entire process itself adequately explained and validates micro EDM. In the process, metal is removing from the harder workpiece (CP-TI) without the physical contact of the tool (brass) which is a comparatively soft material. The following sections provide insights into the capabilities and proficiency of the Novel Maglev EDM.

4.1 Discharge voltage current characteristics

The discharge voltage and current characteristics play a crucial role in the formation of the required appropriate spark between the electrodes. In general, during EDM there may be five different stages as shown in Fig.4. These all are based on the input process variables. The first stage open discharge voltage is the condition where the voltage will be maximum, and the current will be very weak. This is the ideal condition where there is no removal of work material due to low current. The next stage spark or normal spark condition has the sufficient capability to perform the proper machining utilizing high current amplitude between electrodes.

The normal spark provides the proper delay for breakdown and recovery of the dielectric strength of the liquid medium for the next pulse. The transition arc or stable arc is a common phenomenon except the stable arc has no high-frequency component as in transition arc. Whereas the stable arc differs from the normal discharge and has a very weak high-frequency signal in contrast with normal discharge. In the last possible phenomena short-circuiting state in which it has been observed that the gap voltage is very low and current amplitude is very high. The short-circuiting may occur due to various reasons typically includes very low gap voltage for resistor and capacitance circuit [19]. It affects the process stability as well as leads to lower MRR.

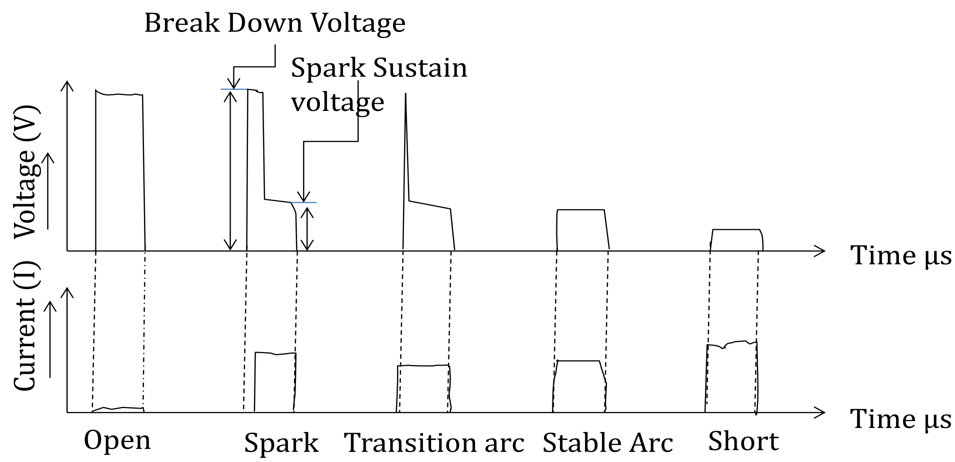

Fig. 4 Shows the different five possible conditions in EDM[20]

Further investigation on voltage-current waveform found that arcing is another harmful phenomenon for the quality surface in micro EDM. The arcing is the result of the uncontrolled transformation of thermal energy during the process. Arcing is the successful discharge of current before attaining the open-circuit voltage this results in repetitive discharge at the same location [21]. During the arcing, the current is flowing in the same plasma without recharging the capacitor and recovering of dielectric strength of the previous discharge [22]. In Fig.5 arcing, short-circuiting, Phenomena which are abnormal nature of waves has been shown. Such waves of the voltage and current lead to the inefficiency of micro EDM.

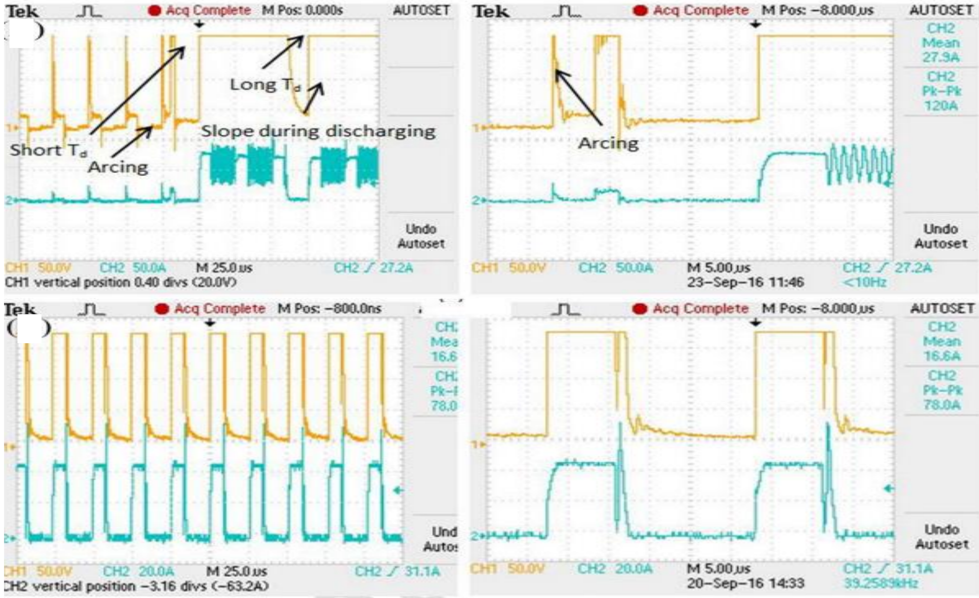

Fig. 5 shows the waveform of conventional EDM[23] [24]

In the study of waveforms, it is observed that the ignition delay occurred usually because when the potential difference is applied to the electrodes and the dielectric does not break down immediately it takes a little static time lag. The researcher investigated the spreading of ignition delay and define that discharge occurred after the activation time [25]. To attain the stable spark the discharge interval should be sufficiently long so that proper plasma and dielectric strength would be generated and recovered respectively. However, it has been reported that too long interval leads the low MRR [6]. Hence, the precise controlling of electrode movement is the most essential especially in micro EDM.

In addition of the discharge interval, plugging of debris in electrodes gap, electrodes geometry, and inappropriate input parameters also affect the machining because of arcing and most undesirable short-circuiting. Since the steady discharge energy is the prime requirement for micro EDM. Hence, the attention and consideration of voltage-current waveform are the most important in the process. In current work, a digital storage oscilloscope (DSO) is utilized to observe the waveform of discharge voltage and current. Fig.6 illustrates the discharge voltage and current waveforms of Maglev EDM. The waveforms clearly express that discharge is stable all along the process. The voltage is dropping during the ionization of dielectric fluid and the breakdown of dielectric strength. The breakdown of dielectric strength is a desirable phenomenon to produce the required spark. The proper discharge without short-circuiting ensures higher MRR in Maglev EDM.

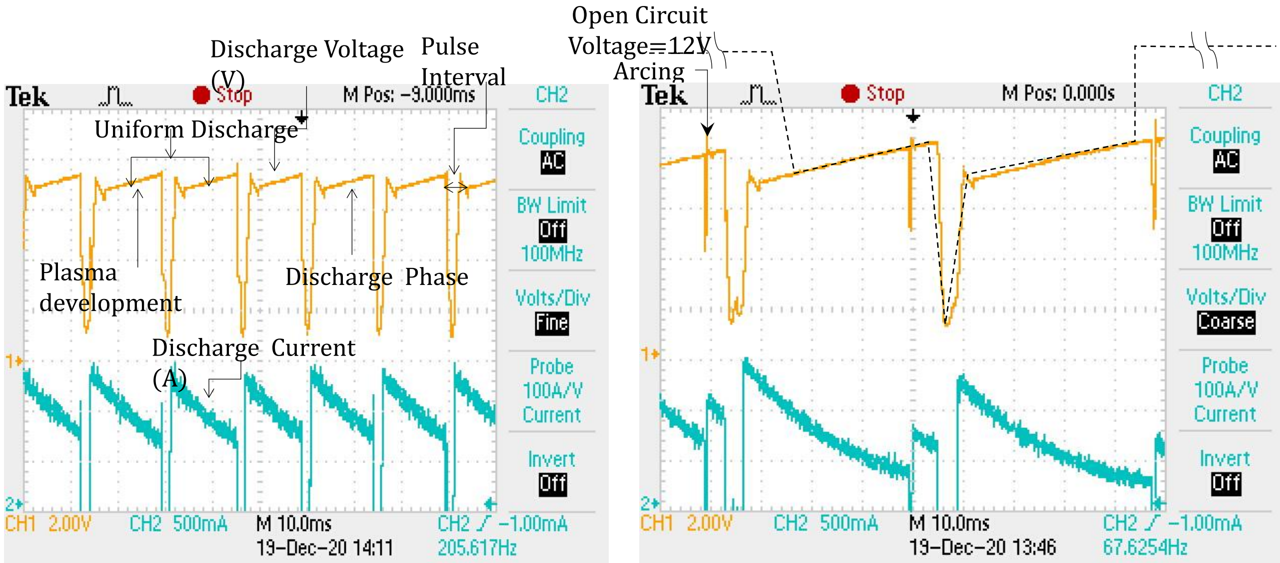

Fig.6 Actual discharge voltage and current wave form in Maglev EDM

Overall, the Maglev EDM is going on continuously without any abruption as occurred in conventional EDM, this indicates the proficiency of Maglev EDM. The result of Maglev EDM revealed a higher material removal rate, good quality surface, and low tool wear rate over conventional micro EDM. Further, the pulse of time is very less in Maglev EDM which is another significant reason for higher MRR than conventional micro EDM.

4.2 Material removal rate (MRR) and Tool wear rate (TWR)

The MRR and TWR are the most significant factors in the machining process. These factors are merely affecting the productivity of manufacturing firms along the time. The MRR is the weight difference of the workpiece before and after machining, divided by machining time.

Mathematically,

$$MRR= [Ww\ (before\ Machine) - Ww(after\ machining)]/\ T \ldots\ldots\ldots\ldots\ldots\ (i)$$

Where, Ww is the weight of the workpiece before and after machining, usually in µgram and T is the machine time in minutes.

Similarly, TWR is the difference in weight of tool before and after machining and divided by machining time.

$$TWR= [T_{w\ (before\ Machine)} - T_{w(after\ machining)}]/\ T \ldots\ldots\ldots\ldots\ldots(ii)$$

Here, Tw is the weight of the cutting tool before and after machining, usually in µgram and T is the machine time in minutes.

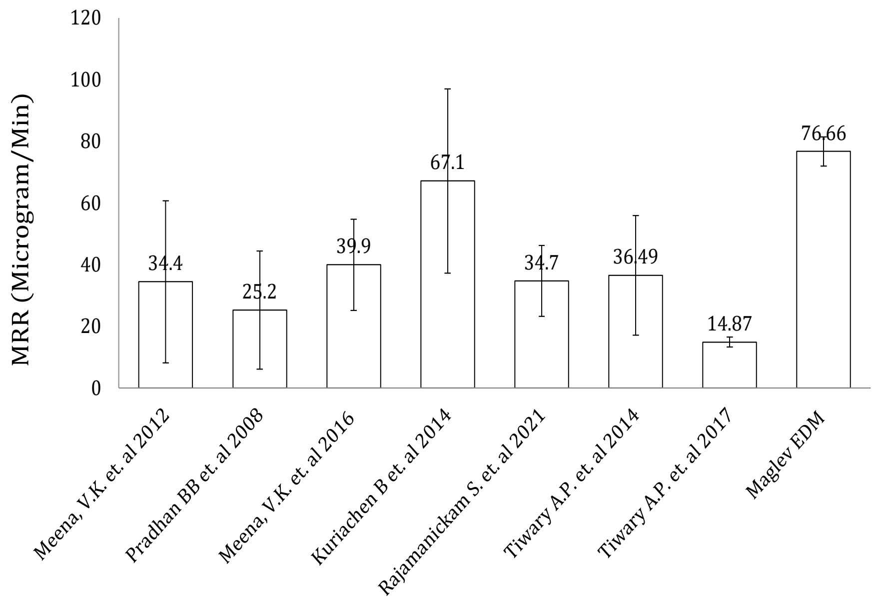

Fig.7 Show the comparison of MRR

The MRR is the key component to be considered as per the economic point of view of any machining operation. Similarly in the field of EDM especially in the machining of hard-to-cut materials, the MRR is always a prime concern for the researcher. From the inspection to the present era the research continues to optimize this machining response. As per Fig. 7, many researchers have suggested the tools and techniques enhance the EDM from time to time. The Meena, V.K. et.al [26] calculated the MRR in the average of 34.4 µg/min and concluded that the voltage is the most influencing parameter among all parameters. The MRR is observed by the Pradhan BB et.al [27] was in the range of 25.2 µg/min. They produced the micro holes in titanium alloy and observed that the machining on time is the most significant factor in MRR and peak current mainly affects the tool wear rate in micro EDM. They attributed the peak current for higher MRR and high tool wear due to the increase of high energy density monotonically. Later the Meena, V.K. et. al [27] confirmed that the current is the most promising factor among all parameters of micro EDM for higher MRR. They observed the MRR in the average range of 39.9µg/min while machining commercially pure titanium. The MRR is measured by the Kuriachen B et.al [28] was in the average range of 67.1 µg/min during the multi-response optimization technique. They used multi-objective particle swarm optimization and considered that the gap voltage influences the MRR in micro EDM. The Rajamanickam S. et.al [29] calculated the MRR in the average range of 34.7 µg/min. They used tap water as a dielectric medium with and without additives for the comparison of conductive and non-conductive additives. Tiwary A.P. et.al [30] observed the MRR in the range of 36.49 µg/min and concluded that the pulse on time, peak current, and gap voltage affect the range of MRR. It is evident that material removal rate is measured in the average range of 76.6µgm/min which is significant, higher and tool wear is assessed as low compared to other conventional micro-EDM for a similar range of discharge energy. In the current work, the maximum tool wear rate was observed at 8.5µg/min and the minimum tool wear rate was noted at 2µg/min. The accumulation of eroded material on the tool electrode and abruptly detached with high electrical shocks, because of the absence of pressure flushing may be the one cause of variation in tool wear rate. The above results proclaimed higher performance of Maglev EDM due to the availability of continuous discharge energy with very low pulse off time as compared to conventional micro EDM. In the current work, the value of MRR and TWR is observed at the natural flushing. It can additionally enhance by employing the artificial flushing system. Fig.7 is showing the comparison of MRR attained by conventional EDM and compared with Maglev EDM. The MRR is higher showing the capability of Maglev over the other EDM. The Maglev EDM showing higher MRR because of superior control of inter-electrode gap (IEG) which almost removes the harmful effects like short-circuiting and acing.

4.3 Specific energy in EDM

The proper IEG leads the efficient specific energy (SE) by utilizing each power pulse for spark generation. The specific energy is termed as the energy required removing the unit amount of material from the work. In current work, the specific energy is varying from 35.21 to 30.765 J/microgram along the increase in MRR which is evident of EDM. Specific energy is another crucial factor to define the machining productivity of any manufacturing firm. The specific energy (SE) is termed as it is the ratio of mandatory energy to the volume of material removed. It is denoted by SE and refers to EDM as similar as in other machining processes. In EDM the SE is the define as follows

$$SE = \text{Energy (E)} / MRR \quad \text{.................} \quad (iii)$$

Further, here Energy (E) can be evaluated in EDM as a product of discharge voltage and Current.

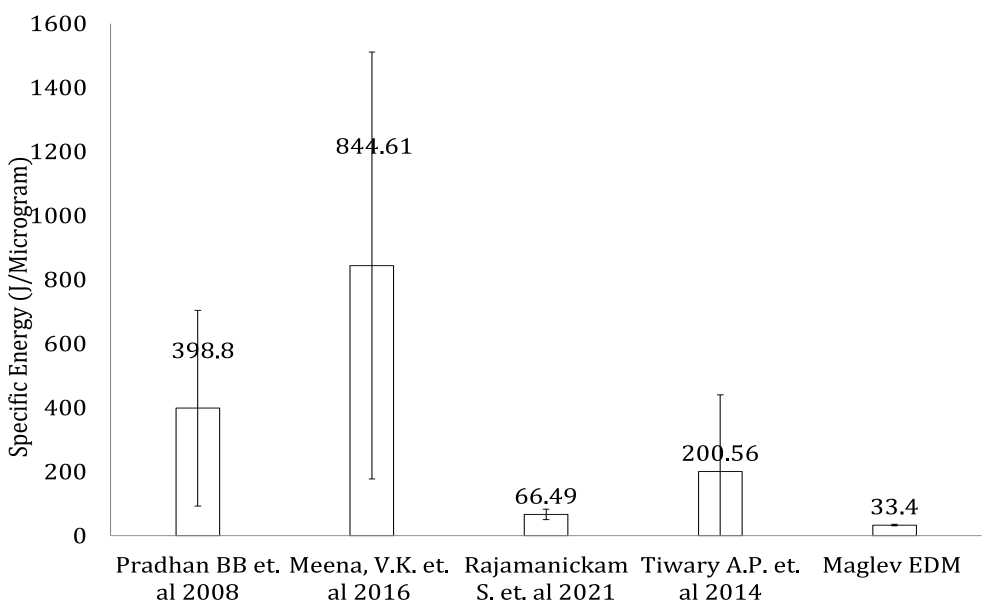

Fig.8 Show the comparison of Specific energy

During the Maglev EDM maximum, maximum MRR is obtained around 82 Microgram/min and the minimum specific energy (SE) has been calculated using the equation (iii). The SE is ranging around 30.76 to 35.21J/Microgram as shown in Fig.8. The average MRR during the various experiments is observed 76.6 Microgram/min which is significantly higher than the other conventional micro EDM. The specific energy of past reported work has been studied and presented in Fig. 8. From the comparison, the specific energy is lowest in Maglev EDM for the same range of MRR as compared to the work carried out till date. This indicates that the current Maglev EDM is utilizing low energy to erode the significant material which pronounces the proficient of current Maglev EDM over conventional EDM.

4.4 Surface Morphology and Surface roughness

The surface characteristics of EDM components lie on the arbitrary range of craters and hills associated with discrete discharge pulse. The machining parameters significantly affect the level of surface roughness by resulting in overlapping craters and hills. The excessive level of surface roughness is undesirable in engineering applications like Moulds and dies manufacturing industries [31]. It has been noticed that the recast layer is one of the downsides of EDM and a prime issue to be considered in the enhancement of surface quality [32]. The recast layer produces by the lack of appropriate elimination of melted material and re-solidification again, similar to quenching phenomena [33]. The recast layer is closely associating with the pulse duration. The long pulse duration can reduce the thickness of the recast layer up to great extent. Furthermore, the thickness of the recast layer depends on the type of dielectric as the study reported that kerosene dialectic form the thinner layer comparative to other dielectric media [34]. The long pulse releases a higher amount of energy to enhance the effect of dielectric force and reduce the thickness of the layer further [35]. It has been seen that the surface roughness values of the machined component are increased at the higher current as well the longer pulse duration [36]. Since the discharge energy associate with the melting and vaporization mainly depends on the discharge current along with the plasma and the time duration for the single pulse. So, with high discharge energy larger craters produce on the work surface this sometimes deteriorates the quality of the surface. Sometimes the process further prolongs undesirably due to the movement of the tool electrode towards the work. This extended movement of the tool results in short-circuit during machining. This short circuit and acing intensify the discharge energy at a great level. This high energy deteriorates the surface quality through uneven erosion of work material as well as tool wear [37]. In the present Maglev EDM, the material is removed from the workpiece in the form of circular cavities as shown in Fig. 9. During the current EDM, one more common issue that arises in conventional micro EDM and current Maglev EDM, which is extended undesirable heating of machining surface. Under the recast layer, the heat penetrates prolong to the machining surface and a heated zone is generated called heat-affected zone (HAZ). Here, the surface morphology is detected by the OLYMPUS BX51M optical microscope. From the obtained images, the presence of the HAZ is evident as shows in Fig.9.

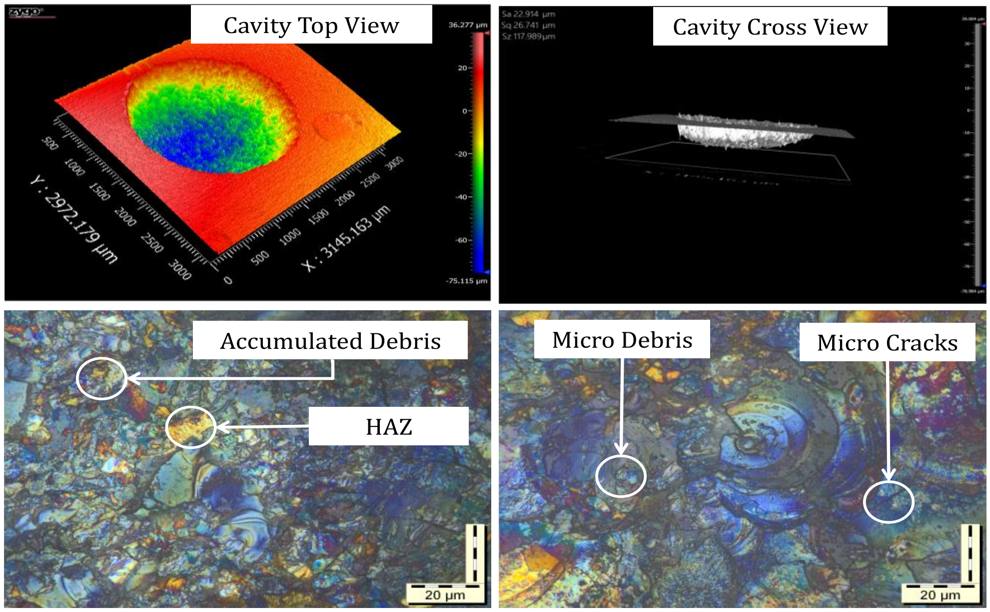

Fig.9 Optical microscope and Profilometer images of surface morphology

During the EDM process the temperature of HAZ does not reach the melting point or vaporization stage; hence, the heated material does not detach from the location, but the properties of the microstructure changed. Since the produced discharge energy is shared by each element of process namely Workpiece, dielectric medium, and tool hence HAZ is formed in both the electrodes [38]. The obtained Maglev EDM surface was further analysed by optical profilometer Zygo new view 9000. The refine machined surface by profilometer gives the more accurate results and showing the HAZ clearly during the formation of the desired cavity of 2mm. The images are divided into six different slices to recognize the peaks and valleys which lead the surface portrayal, especially in micro EDM. Moreover, since in present investigations the natural flushing technique is used so the accumulation of unwanted debris seeing with continuous EDM. Debris can be washed out or minimized using artificial pressure flushing and by employing fresh dielectric medium. During the present EDM some micro crakes are often seen in EDM due to thermal shocks and quenching of newly machined surface.

The characterization of surface morphology is more volatile due to the specific energy density which is primarily affected by the current-voltage characteristics and gap condition of the electrodes. In the present Maglev EDM, the waveforms and gap condition are maintained to ensure a high surface finish with minimum loss of pulse discharge energy. In the current work, the primary value of surface roughness is varying from 3.08 µm to 5.17 µm while EDM and the average surface roughness is 4.085 µm obtained. In Fig.10 average Surface roughness of Maglev EDM is presented and compared with other same range of micro EDM process. It has been observed that the range of average surface roughness is lower in Maglev

EDM comparatively other conventional EDM. The average surface roughness in current work is in the range of 4.3 µm which is a little higher than surface roughness obtained by Ahmed N et.al [7] was 3.67 µm. They employed an artificial flushing technique to carry out the derbies and eroded metal particles whereas in the case of current Maglev EDM the natural flushing is used which can be further improved by employing an artificial flushing arrangement to lower the surface roughness index. However, the other researchers find out the various ranges of surface roughness like Kumar S et.al [39] obtained the average surface roughness in the range of 5.95 µm. They used the hybrid Taguchi-artificial neural network approach to predict the surface roughness in different conditions.

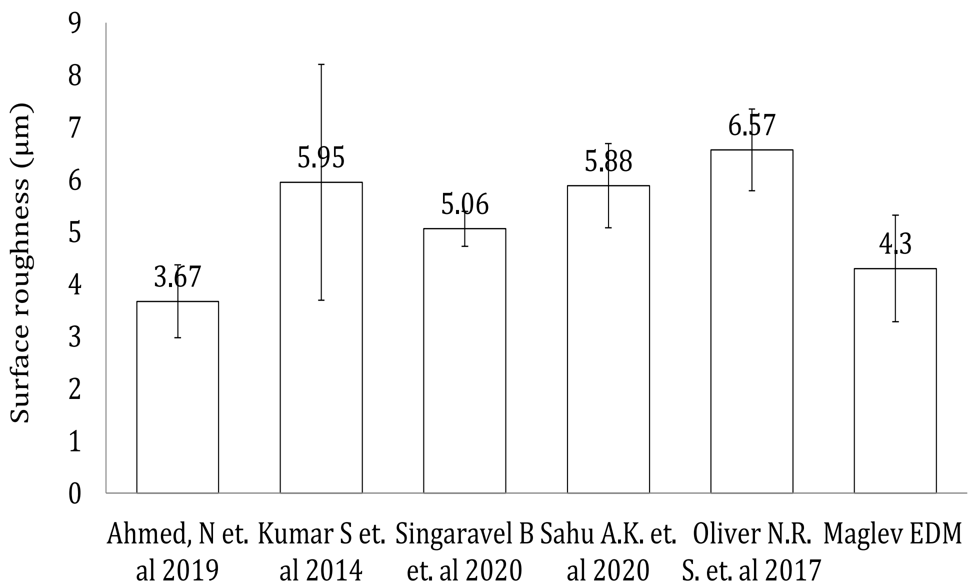

Fig.10 Comparison of Surface roughness

The average surface roughness observed by the Singaravel B et.al [40] was in the average range of 5.06 µm. They tested and concluded that the vegetable oil does not function as the dielectric medium in few cases and enhances the surface roughness comparative to the connectional dielectric medium. Sahu A.K. et.al [41] observed the average surface roughness in the range of 5.88 µm during the comparative experiments of various kinds of tools. The average surface roughness observed by the Oliver N.R. S. et.al [42] was in the range of 6.57 µm. They proposed the optimum process parameters to attend the lower surface roughness index. The research contributed to the field of EDM of hard-to-cut material pointed out that the peak current is the most significant parameter and leads the unwanted material removal during EDM. The pulse on time is the second factor that affects the surface roughness. Both the parameters ultimately increase the specific energy density while machining and affect the mechanism of material removal principally. The current Maglev EDM surface roughness is analysed at various indexes as shown in Fig. 11.

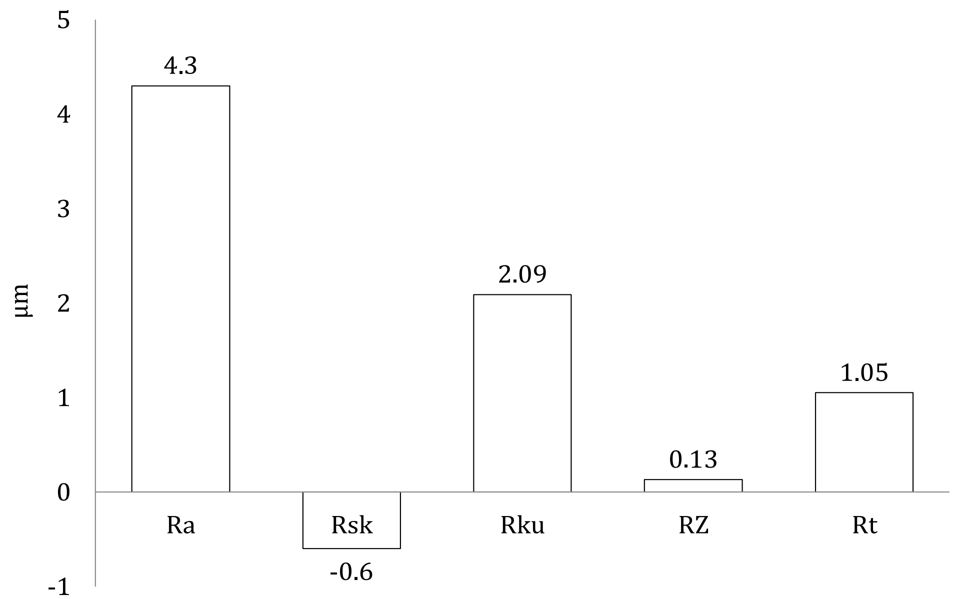

Fig.11 Comparison of Surface roughness parameters

In addition to the average surface parameter Ra the other surface indexes are also observed like Skewness (Rsk), Kurtosis (Rku), mean roughness depth Rz, and the total height of the roughness profile Rt. The surface parameters of Maglev EDM are in the acceptable range with the agreement of higher MRR in comparison to other same rages of conventional micro EDM process.

5. Conclusion

The Novel Maglev EDM is explored in the above sections by experimentations on the commercially available titanium alloy workpiece using the comparatively soft brass electrode. The results are revealed that the proficiency of the Maglev EDM is higher than the conventional EDM. In experiments, the MRR, and SR are considered as output responses of the process compared and represented here. The conclusive remarks are as follows:

1. MRR is higher in Maglev EDM as compared to conventional micro EDM because of low Pulse off time or longer machining time; subsequently, increase the desire available discharge energy for a longer time.
2. The IEG is precisely controlling and regulates as per the requirement in Maglev EDM. The spark gap is accurately executed by the logical arrangement of Magnets using Maglev lucidity by replacing the conventional servomechanism. The short circuit is the prime concern in conventional micro EDM which deteriorates the surface quality and increases tool wear rate. At present Maglev EDM, such issues have been resolved to a great extent.

3. Maglev EDM consumes less specific energy as compared to conventional micro EDM by replacing the conventional interacting power supply and effective utilization of maximum pulse.

Owing to the above exploration of EDM it reveals that the novel Maglev EDM is more proficient and feasible as compared to the conventional micro EDM which are using traditional power supply and servomechanism. Moreover, the present Novel Maglev EDM is in the toddler stage, and it is expected that improvement in the current machine will enhance the process outputs tremendously.

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Author Contribution:

1. **Mangal Singh Sisodiya: Preparing the manuscript, performing the series of experiments, analysis of the results, and critically discussed based on the relevant literature work carried out to date.**
2. **Shashank Shukla: Design the experiments based on the comprehensive assessment of the literature and arrange the required particular for experiments.**
3. **Dr. Vivek Bajpai: Supervise the work carried out in the present research and suggested valuable remarks.**