A Comprehensive Investigation into the Material Removal Capability of Powder Mixed Wire Electric Discharge Machining

[1]Prajapati Niravkumar Jayantibhai [2]Dr. Bharat Khatri

[1]Ph.D. Research Scholar, Gujarat Technological University, Ahmedabad, Gujarat, India.
[2]Associate Professor, Mechanical Engineering Department, Govt. Engineering College Modasa, Gujarat, India.

E-mail: [1]niravlcit153@gmail.com, [2]khatribharat752@yahoo.com

Abstract: The powder mixed electric discharge machining (PMEDM) has demonstrated promising results in the machining of difficult-to-cut materials including metal matrix composites (MMCs). Adding powder particles to the dielectric fluid used in electric discharge machining (EDM) improves material removal rate (MRR) and surface quality of the machined item. This study presents a thorough overview of research works on PMEDM for the machining of MMCs, concentrating on the impacts of different process parameters on the MRR and surface quality, such as powder concentration, pulse on-time, and Pulse off-time. The study also notes the process's obstacles and limits, as well as opportunities for further research.
Previous research has shown that PMEDM can greatly increase the MRR and surface quality of machined MMCs when compared to regular EDM. The addition of powder particles to the dielectric fluid has been found to improve machining zone cleansing and cooling, decreasing tool wear and enhancing machining precision.
Keywords: Powder mixed electric discharge machining (PMEDM), Metal matrix composites (MMCs), Electric Discharge machining (EDM), Material Removal Rate (MRR)

1. Introduction

Electrical discharge machining (EDM) has developed as a potential method for machining difficult-to-cut materials such as metal matrix composites and titanium alloys in recent years. To remove material from the workpiece, a sequence of electrical sparks is used. However, the method has several drawbacks, such as a tool wear and a low material removal rate. One approach to overcoming these issues is to use a powder mixed dielectric (PMD), which can increase machining performance by minimizing tool wear and enhancing work piece surface quality. [1-4]

This study presents an overview of recent studies on the use of PMD in EDM. The review contains research that study the impact of several PMD materials, such as copper, aluminum, titanium, and silicon carbide, on the machining performance of diverse materials. The investigations investigate the impact of PMD on material removal rate, surface quality, and other performance measures. The study also contains research that employ optimization approaches, such as grey relational analysis and the Taguchi method, to improve the EDM process parameters for PMD..[5-7]

Overall, the experiments examined in this paper show that PMD has the potential to improve the EDM process for a variety of applications. The conclusions of this study will be of interest to machining researchers and practitioners who are looking to improve the performance of EDM for the machining of difficult-to-cut materials.

1.1 PMEDM Working Principle and experimental set up

PMEDM utilizes a dielectric circulator, as shown in Fig. 1-A, mounted in the EDM working tank. PMEDM circulators include a stirrer (or micro-pump) to prevent powder settling at the bottom of dielectric reservoir. PMEDMs also use permanent magnets to separate debris from powder particles. PMEDMs use permanent magnets to avoid stagnation of powder particles on work piece surface.

When PMEDM is loaded with fine powder particles suspended in the Dielectric oil, an electrical field is generated in the IEG (Inter-Electrode Gap) by the application of a sufficiently high voltage (80-320 V) from the tool to the work piece. As illustrated in Fig. 1-C positive and negative charge are deposited at the surface of powder particles near the cathode (Cathode) and anode (Anode) of PMEDM. The formation of powder particle chains is caused by capacitive effects on the electrodes. The first discharge of PMEDM is broken where the electrical field density is the highest. This may be between powder particles or powder particle and electrode (tool/work piece) after the first spark. The process continues with series discharges.

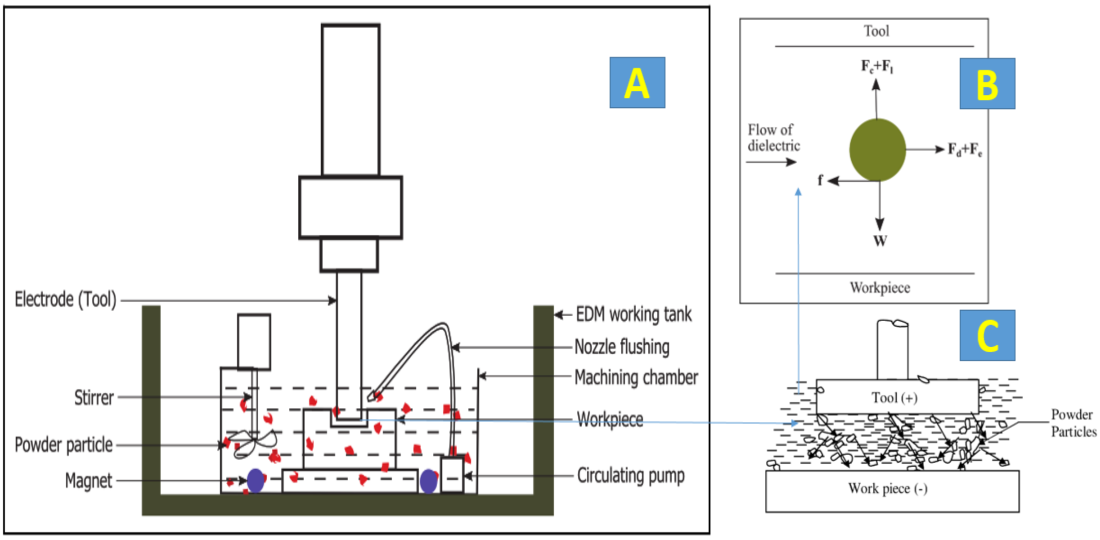

Fig. 1: Schematic Diagram of (A) PMEDM setup (B) Forces acting on a powder particle, (C) Principle of powder mixed EDM [2]

1.2 Different forces acting on a powder particle

Figure 1-B depicts a schematic representation of the various forces exerted on a powder particle in the inter electrode-gap(I_{EG}). These forces include lift force (F_l), Columbic force (F_c), drag force (F_d), electric force (F_e), and friction force (f) acting in different directions. Additionally, the self-weight of the particle is denoted by W.

$$E_{br}^2 = E_i^2 - 2kT\frac{1}{\varepsilon_1}\left(\frac{\varepsilon_p + 2\varepsilon_1}{\varepsilon_p - \varepsilon_1}\right)\left[\frac{1}{r^3}\left(\ln\frac{N_f}{N_i}\right)\right]$$

…………......Equation… 1)

Equation (1) provides the breaking energy of powder dialectics, which may be obtained from these forces. This equation may be used to calculate the lowest energy needed to shatter the powder particles and produce an electrical discharge, which makes it crucial to understanding the PMEDM process. Better machining outcomes may be attained by optimizing the PMEDM process and being aware of these forces and how they affect powder particles.

Where E_i, is the initial voltage for concentration N_i, and E_{br}, the breakdown voltage for the final concentration N_f. The equation also incorporates k, the Boltzmann constant, T, the temperature, e_1, the permittivity of the dielectric, e_p, the permittivity of the powder particle, and r, the radius of the powder particle. Understanding the connection between the breakdown voltage and the amount of powder particles in the dielectric fluid requires an understanding of these factors. The breakdown voltage may be used to calculate the lowest energy needed for a powder particle to degrade and result in an electrical discharge. The PMEDM process may be made more efficient and effective with the usage of this information. [2]

1.3 Influence of Powder Characteristics

Powder concentration, shape, size, and electrical conductivity have all been proven in studies to have a substantial impact in defining the completed surface and material removal rate in the powder-mixed EDM process. [9]

1.3.1 Electrical Conductivity

The effect of conductivity on the improvement of material removal rate has been investigated by several researchers who reported that the highest material removal rate was achieved with Cu powder due to its better electrical conductivity compared to Ni powder. Another study investigated the effect of a mixed dielectric of graphite, aluminum, and alumina nano-powder on the surface quality of tungsten carbide. The results showed that the semiconducting graphite powder produced a smoother surface, while the conductive aluminum powder increased the spark and material removal. Non-conductive alumina was found to have no significant effect on improving surface quality. In addition, dielectric liquid mixed with either Al or SiC powder was found to improve the depth of material removal and surface quality, with the Al powder providing the greatest spark gap due to optimal conductivity.

1.3.2 Powder Characteristic

The parameters of the powder utilized in the power-mixed -EDM process, such as concentration, shape, size, and electrical conductivity, have been discovered to have a substantial influence on both the completed surface and material removal rate.

1.3.3 Powder Shape

To investigate the effect of using carbon nanofibers instead of powders in micro-EDM, carbon nanofibers with a diameter of 150 nm and a length of 6-8 µm. They used reaction-bonded silicon carbide (RB-SiC) as the workpiece material and a tungsten rod as the tool electrode. The micro-EDM process was performed with a voltage of 110 V and a capacitor capacitance of 330 pF. The advantage of carbon nanofibers over powders is that they have microcircuits that are better formed in relation to each other due to the fiber diameter and microscale length, which helps to form better bridging networks between the tool electrode and the workpiece. The experimental results showed that when carbon nanofibers were added to the dielectric liquid at a concentration of 0.17 g/l, the maximum material removal rate increased to 0.0035 mm^3/min, while the rate in the pure dielectric state was only 0 ,0001 mm^3/min. This achievement shows that the discharge density increases when carbon nanofibers are added to the dielectric fluid. In addition, the presence of carbon nanofibers in the dielectric liquid promotes uniform dissipation of the discharge energy, resulting in smaller crater sizes and better surface roughness (about 0.2 µm) compared to pure dielectric liquid, which is about 0.4 µm in size.

1.3.4 Powder Concentration

The best result was achieved at a concentration of 15 g/l. It was found that increasing the powder content in the EDM oil increased the material removal rate. However, the removal rate began to decrease when the concentration exceeded 15 g/L because too much powder accumulated near the treatment area, making it difficult to remove the debris and hindering the treatment cycle.

2. Experiment Setup and Process Parameter

Complex-shaped, hard-to-machine materials may be effectively machined using Electrical Discharge Machining (EDM) technology. But it's not without limitations. Powder mixed electrical discharge machining (PMEDM) is a novel technology that was created to get around these restrictions and enhance the machining capabilities of EDM. This procedure involves adding an appropriate substance in powder form to the insulating liquid and using a mixing mechanism to improve the powder mixture's circulation. The insulating fluid can be mixed with a variety of particles, including silicon, tungsten, copper, graphite, aluminum, and chromium. The spark produces an electric field when a voltage is supplied to both electrodes. Particles of powder fill the spark, and the gap between the tool and the workpiece. Particles in powder fill the spark gap and the space between the tool and the workpiece gets bigger. When sparking occurs, the powder particles are energized by the electric field and travel in a zigzag pattern, forming chains at various locations. This fills the space between the workpiece and electrode, making it simple for short circuits to happen and a sequence of discharges beneath the electrode. The faster sparking inside the discharge produces erosion on the work piece surface at a greater rate as the discharge frequency increases. Studies in this field have shown that, in comparison to standard EDM, adding powdered materials to the EDM dielectric boosts material removal rate (MRR) and decreases surface roughness. The powder type, concentration, particle size, dielectric type, pulse on time, pulse of time, peak voltage, electrode material, and work piece components are some of the process factors of PMEDM that have a significant impact on the process's performance and the mechanism of material removal.

2.1 Process Parameter of PMEDM

Subsequent are the process parameters which are taken into consideration.

1. Powder Size
2. Peak current
3. Inter electrode gap (IEG)
4. Powder Concentration
5. Powder Material
6. Pulse on time
7. Dielectric type
8. Polarity
9. Peak Voltage
10. Pulse off time

Powder concentration: Generally, Powder concentration of about 1g/l to 10 g/l of dielectric is used.

Powder type: The incorporation of powder into the dielectric fluid in EDM has been discovered to enhance the material removal rate (MRR), decrease the tool wear rate (TWR), and improve the surface quality of the workpiece. However, the influence of various types of powder on the output characteristics of the EDM process can differ. When choosing a powder to be added to the dielectric fluid, specific attributes must be considered. The powder must possess electrical conductivity, be non-magnetic, and exhibit good suspension capabilities. Additionally, it should have commendable thermal conductivity, as well as being non-toxic and odorless. These properties are essential for a powder to be effectively suspended in the dielectric fluid of the EDM process.

Dielectric Fluid: In EDM, dielectric fluid performs three crucial functions. Throughout the EDM process, the dielectric fluid performs many functions. In the inter-electrode gap, it first functions as an insulator, but when a specific voltage is applied, it degrades and permits current to pass. It also functions as a coolant to facilitate heat flow from the electrodes and helps remove debris from the machined region. Dielectric fluids that are hydrocarbon-based, including kerosene and light transformer oil, are the most often utilized kind.

Peak current (I_p): The peak current (Ip) is the current that increases during each pulse-on time until it reaches a predetermined level called the discharge current or peak current. The size of the peak flow is determined by the cutting surface. Higher flows result in higher material removal rates (MRR), but at the expense of surface finish and tool wear. The precision of the machining process is also affected by the peak current, because it directly affects the wear of the tool.

Discharge voltage (V): Prior to the flow of current between the two electrodes in the EDM process, an open circuit voltage is established. Nevertheless, as soon as the current begins to pass through the plasma channel, the open circuit voltage diminishes. This reduction plays a crucial role in influencing the spark energy, which subsequently determines the material removal rate (MRR), tool wear rate, and surface roughness.

Pulse-on time or pulse duration (T_{on}): During each cycle, the pulse on time (T_{on}) refers to the duration (in microseconds) in which the current is allowed to flow. It is within this timeframe that the dielectric ionizes and sparking takes place. This on-time interval is crucial as it is the productive phase of the spark cycle, where material removal occurs. The energy applied during Ton is directly proportional to the amount of material that is removed. While an increase in Ton typically leads to a higher material removal rate (MRR), it can also result in rough surfaces due to the elevated spark energy.

Pulse-off time or pulse interval (T_{off}) : The period of time between two consecutive pulse-on times in Electrical Discharge Machining (EDM) is referred to as the pulse-off time. This is the time when the dielectric fluid regains its insulating strength after the supply voltage is cut off. During this time, the molten material solidifies and is removed by washing. Since no material is removed during the pulse-off time, it is imperative to keep it as short as possible. On the other hand, an excessively short pulse-off time may cause instability during the machining process.

Polarity : The term polarity refers to the relative charge between the tool and workpiece. When the workpiece has a positive charge compared to the tool, it is called straight or positive polarity. When the workpiece has a negative charge, it is reverse polarity. In straight polarity, the anode (workpiece) generates more power because electrons react quickly, removing more material. However, longer pulse times and positive polarity lead to faster tool wear. This is because more positively charged ions hit the tool. In general, polarity selection depends on tests with different workpiece and tool materials, current density, and pulse length.

Inter electrode gap (I $_{EG}$): : The stability of the spark and the effectiveness of the flushing process depend greatly on the inter electrode gap. To ensure optimal performance, it is crucial to maintain a stable gap and a fast reaction speed within the system. The presence of any backlash is highly undesirable. The system must be able to respond quickly to short circuits or open gap conditions, which requires a high reaction speed. Although the gap width cannot be directly measured, it can be estimated based on the average gap voltage. The tool servo mechanism is responsible for keeping the working gap at a predetermined value. Typically, electro mechanical (DC or stepper motors) and electro hydraulic systems are utilized, and they are designed to respond to the average gap voltage.

Table 1 Spark gap under different powder suspension conditions [11]

Dielectric Condition	Spark gap distance (μm)
Without powder	10- 15
Graphite	45- 50
Silicon	27- 33
Aluminium	120- 160
Crushed Glass	10- 15
Silicon Carbide	80- 90

2.2 Performance Parameters

Performance of PMEDM can be measured by following parameters [11]

1. Material Removal Rate (MRR)
2. Tool Wear Rate (TWR)
3. Wear Ratio (WR)
4. Surface Roughness (SR)

Material Removal Rate (MRR)

The MRR is expressed as the weight of material removed from work piece over a period of machining time in minutes.

$$\text{MRR (mm}^3\text{/min)} = \frac{\text{Workpiece weight loss (g)} \times 1000}{\text{Density (g/cm}^3\text{)} \times \text{machining time (min)}}$$

Tool Wear Rate (TWR)

The TWR is calculated by using the weight loss from the tool divided by the time of machining.

$$\text{TWR (mm}^3\text{/min)} = \frac{\text{Tool weight loss (g)} \times 1000}{\text{Density (g/cm}^3\text{)} \times \text{machining time (min)}}$$

Wear Ratio (WR)

The performance of tool work piece material combinations can be measured using a ratio called WR, which is calculated by dividing TWR by MRR. Since different material combinations have varying TWR and

MRR values, WR is useful in quantifying the effectiveness of each combination. A material combination with a lower WR is considered to have the optimal conditions for both TWR and MRR.

Surface Roughness (SR)

The surface roughness (SR) of a workpiece can be measured using various methods, such as average peak-to-valley height (RZ) or peak roughness (RP), among others. However, the most common way to measure SR is through the arithmetic average roughness (Ra) method, as defined by ISO 4987:1999. Ra is calculated by determining the average roughness deviation from the central line of the surface profile and is measured in micrometers (µm). A high Ra value indicates a rough surface, while a low value suggests a smooth surface. To measure Ra, a Portable style type profilometer is typically used.

2.3 Literature gap and current problem in PMEDM

Multiple studies have examined the modified machining method, with some researchers finding that suspended powder electrical discharge machining (PMEDM) can significantly increase surface roughness (SR) and surface quality, resulting in nearly mirror-like surfaces. However, despite these promising results, industry has been slow to adopt the PMEDM process due to several fundamental issues that are still not well understood, including the machining mechanism and thermo-physical properties of the suspended particles. There are also other challenges with PMEDM, such as the high cost of powders, concentration and circulation of the working fluid, removing additives from debris, clumping, and arcing. Furthermore, optimizing powder characteristics requires thorough research. These factors have limited the frequent use of PMEDM, especially in rough machining where very little research exists.[3-11]

3. Experiment Details

PMWEDM process involves the following steps:

Setting up the WEDM machine: The WEDM machine has been prepared with the suitable tool and workpiece. Additionally, a dielectric fluid has been added to the machine, serving as both an insulator and coolant throughout the machining procedure.

Preparing the PMD: Blending the dielectric fluid with either metal or graphite powder results in the creation of the PMD. The performance of the PMWEDM process can be optimized by varying the concentration and type of powder utilized.

Fig. 3: Powder mixed electric discharge machining (PMEDM)

Feeding the PMD into the gap: The PMD is introduced into the space between the tool and the work piece through a nozzle or a similar mechanism. The powder aids in enhancing the machining performance by minimizing tool wear and enhancing the surface quality of the work piece.

Machining the work piece: Utilizing a sequence of electrical sparks, the WEDM apparatus is employed to fabricate the work piece. The PMD plays a crucial role in enhancing the machining efficiency by diminishing tool wear and refining the surface finish of the work piece.

The configuration of the experimental setup for PMEDM (Fig.3) can vary depending on the specific application and research objectives. However, in general, it involves utilizing an EDM machine, a PMD mixing unit, and a mechanism for introducing the PMD into the gap between the tool and the work piece. The PMEDM process may also incorporate different types of powder and optimization techniques to enhance its performance. Apart from the fundamental setup, there are several other factors that can influence the performance of PMEDM. These factors encompass the type and concentration of the powder added to the dielectric, the voltage and pulse duration of the EDM power supply, and the distance between the electrode and the work piece.

The PMEDM process can be optimized by adjusting the voltage and pulse duration of the EDM power supply. Increasing the voltage and pulse duration can enhance the material removal rates, but it may also cause increased electrode wear and a decrease in surface finish quality. Conversely, decreasing the voltage and pulse duration can improve the surface finish, but it may result in lower material removal rates.

Different types of powder can have a significant impact on the performance of the dielectric in machining. One commonly used powder is copper, which enhances the thermal conductivity of the dielectric. This, in turn, reduces the likelihood of a recast layer forming on the surface of the workpiece. On the other hand, aluminum powder can improve the flushing properties of the dielectric, aiding in the removal of debris from the machining zone and resulting in an improved surface finish.

Finally, the performance of PMEDM can be influenced by the distance between the electrode and the work piece. Increasing the gap distance can minimize electrode wear, but it may lead to lower material removal rates. Conversely, decreasing the gap distance can heighten the risk of electrode wear, while potentially increasing material removal rates.

Inclusive, the PMEDM process shows great potential as a technology for machining difficult-to-cut materials. By carefully selecting the appropriate powder, adjusting the EDM power supply parameters, and optimizing the gap distance, it is possible to achieve high rates of material removal and excellent surface finishes. As a result, this process is a viable option for a wide range of machining applications.

Table 2: Test results for model parameters and Measurement of Surface Roughness in micro meter (µm)

Sr No	Toff µs	Ton µs	Current Amp	Concentration L/gm	Cutting Time (10 mm lenth) 1	2	3	Average Cutting	MRR mm3 min-1	average Surface roughness (µm)
1	7	16	4	5	139	94	142	125.00	6	65.500
2	7	25	4	5	128	118	---	123.00	6.5	64.750
3	7	34	4	5	102	121	176	78.00	7	14.100
4	7	43	4	5	---	80	75	77.50	7.2	42.350
5	7	52	4	5	63	66	68	33.75	7.5	20.625
6	3	34	4	5	66	67	67	31.50	8	19.750
7	5	34	4	5	69	69	67	32.50	8.5	9.500
8	9	34	4	5	94	80	94	41.00	9.1	25.050
9	11	34	4	5	80	69	72	35.50	9.2	22.350
10	7	34	2	5	153	151	160	65.25	9.3	37.275
11	7	34	3	5	68	201	150	59.88	9.3	34.588
12	7	34	5	5	131	133	140	58.38	9.5	33.938
13	7	34	6	5	141	138	136	60.00	9.6	34.800
14	7	34	4	1	132	133	131	57.00	9.7	33.350
15	7	34	4	3	133	132	133	57.63	9.7	33.663
16	7	34	4	7	128	135	137	58.50	9.8	34.150
17	7	34	4	9	136	135	127	58.63	10	34.313

It appears that this data pertains to a process involving the application of an electric current to a material for a specific duration in order to remove material and create a cut. The data seems to have been gathered for various combinations of cutting parameters, including Toff, Ton, current amplitude, concentration, and cutting time.

Additionally, the data includes measurements of the outcomes of the cutting process, such as the material removal rate (MRR) and the average surface roughness. MRR refers to the quantity of material removed per unit of time and is expressed in cubic millimeters per minute (mm^3 min^{-1}). On the other hand, average surface roughness refers to the average deviation of the surface from its ideal shape and is measured in micrometers (µm).

For example, represents the current (in Amperes) used during the machining process. From the given data, it can be observed that the current is constant at 4 A for all experiments except for experiments 10 to 17, where the current value is varied between 2 A and 9 A. It is interesting to note that as the current is increased from 2 A to 9 A, the average cutting time (column 9) decreases from 65.25 s to 58.63 s. This suggests that higher currents may result in faster cutting times. However, it should be noted that the effects of other parameters such as Toff, Ton, and concentration of the dielectric fluid may also play a role in determining the cutting time, and further analysis is required to confirm the influence of current on the cutting time.

4. Research and discussion

Five tests were performed on the composite material of aluminum and carbon fiber to demonstrate the effects of discharge current, pulse duration, tube electrode wall thickness, ultrasonic vibration amplitude and gas environment on the MRR of additive powders. Materials. Some observations were also made about the roughness of the machined surface.

4.1 The effect of amplitude of average surface roughness on MRR

The test result shows that the material removal rate decreases with the average surface roughness (Figure 4). The maximum MRR value is 8 and after that the value decreases. The amplitude of ultrasonic vibration does not clearly affect the surface roughness. The surface roughness Ra stabilizes at a value of approximately 0.022 mm.

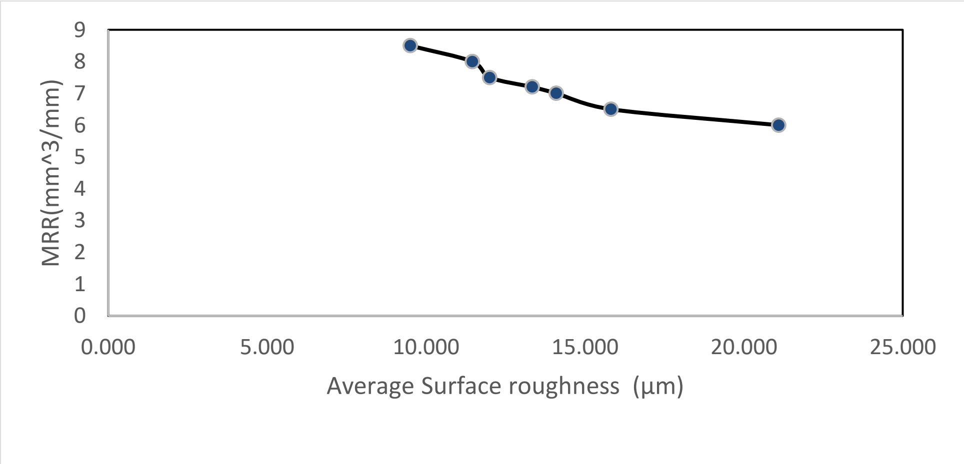

Fig.4: The effect of amplitude of average surface roughness on MRR

4.2 The effect of average cutting time on MRR

The MRR reduction with increasing Average cutting time is apparent in the graph (Fig.5) obtained from the 10mm length experiment. The cutting time reaches its highest value of 40 at an MRR value of 9, after which it decreases.

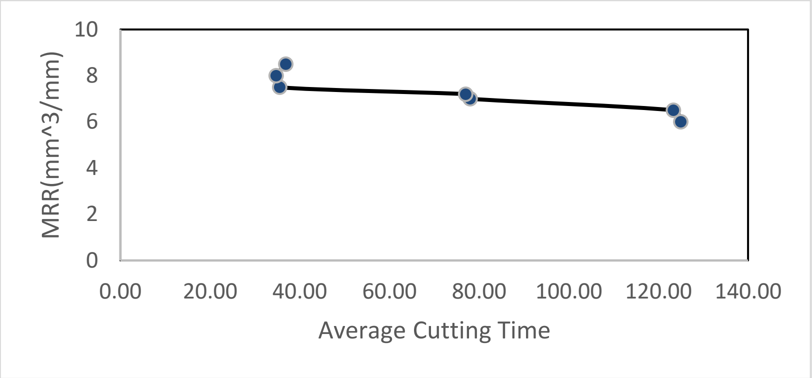

Fig.5: The effect of amplitude of average cutting time on MRR

4.3 The effect of current on MRR

The test result shows that current rate increase with the MRR (Fig.7) Maximum MRR value is 6 and after that its value is increase. The current(A) maximum value is 6

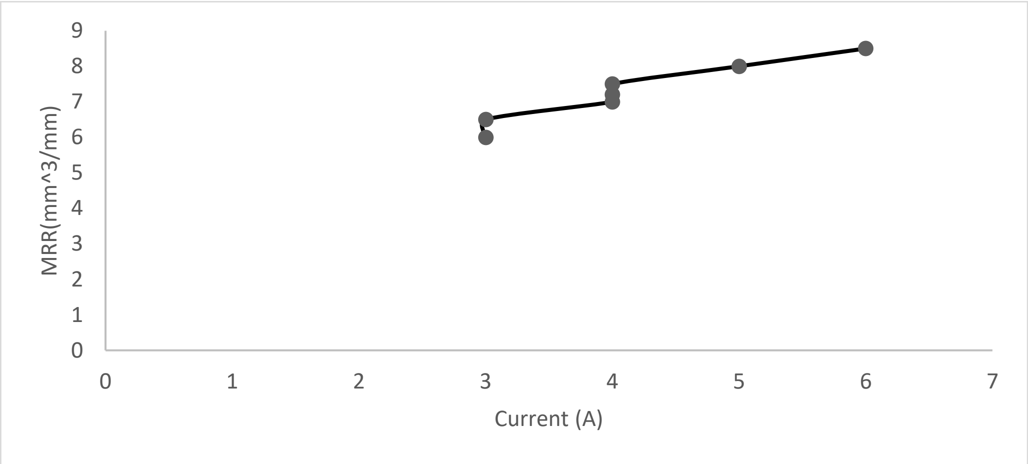

Fig.7: The effect of current on MRR

4.4 The effect of Current & Pulse Off on Cutting time & Surface Roughness

According to the test's results and the graph that is displayed below (fig. 8). Cutting time increases and surface roughness progressively reduces as pulse off time increases. Additionally, cutting time decreases and surface roughness rises as current increases.

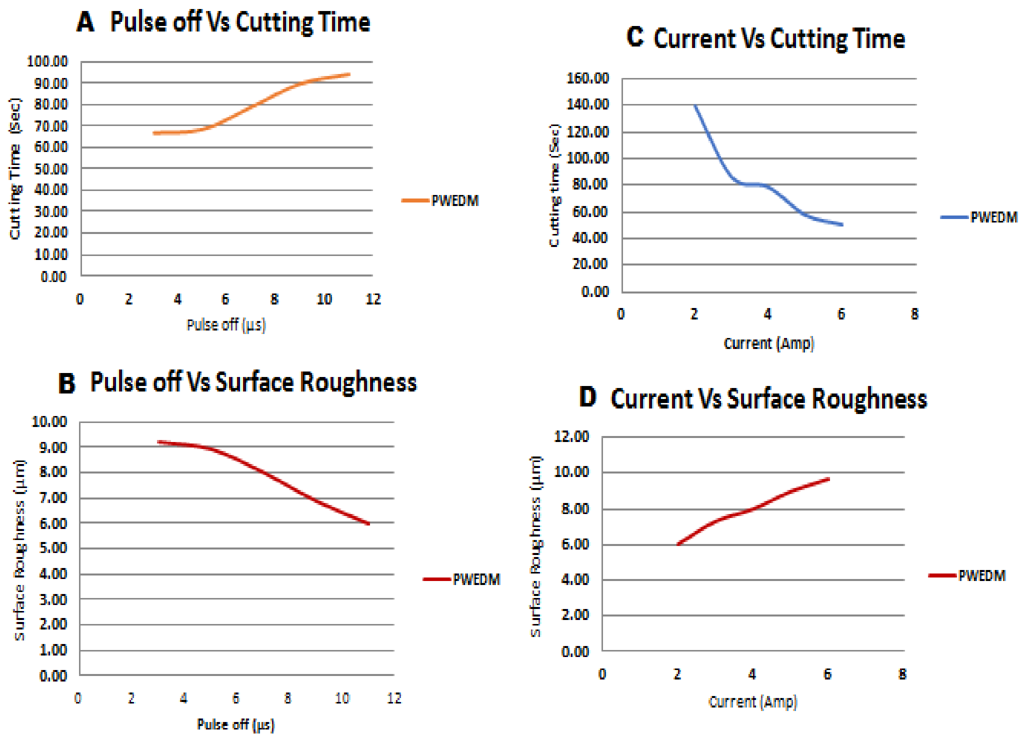

Fig.8: (A) The effect of Pulse off on Cutting Time (B) The effect of Pulse off on Surface Roughness (C) The effect of Current on Cutting Time (D) The effect of Current on Surface Roughness

5. Conclusions

The utilization of powder mixed in the EDM process has shown positive effects on various aspects. When powder is mixed, it leads to an increase in the material removal rate (MRR), surface roughness, and amplitude. However, the surface roughness and average cutting time have an inverse relationship with the powder mixture. At lower levels, the surface finish is optimized, while at higher levels of capacitance, a rough surface is generated. The addition of graphite nano powder to the dielectric medium in PMDEDM has been found to significantly enhance the surface finish.

Additionally, the study also investigated the impact of different process parameters on the performance of Powder Mixed EDM for machining difficult-to-cut materials. The inclusion of graphite carbon powder in the dielectric fluid resulted in an increase in the rate of material removal and a decrease in surface roughness. The amplitude of ultrasonic vibration was identified as a crucial factor influencing the MRR. Furthermore, the study revealed that as the average cutting time increased, the MRR also increased, while the surface roughness decreased.

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