JOURNAL OF AERONAUTICAL MATERIALS
ISSN: 1005-5053

Vol. 43, Issue-01, 2023
pp. 434-446

PARAMETRIC STUDY AND EXPERIMENTAL INVESTIGATION OF MATERIAL REMOVAL CAPABILITY OF POWDER MIXED ELECTRIC DISCHARGE MACHINING

Prajapati Niravkumar Jayantibhai[1] Dr. Bharat Khatri[2]
[1]Ph.D. Research Scholar, Gujarat Technological University, Ahmedabad, Gujarat, India.
[2]Associate Professor, Mechanical Engineering Department, Govt. Engineering College Modasa, Gujarat, India.

Abstract

The use of powder mixed electric discharge machining (PMEDM) has shown promising results in the machining of difficult-to-cut materials, such as metal matrix composites (MMCs). This process involves adding powder particles to the dielectric fluid used in electric discharge machining (EDM), improving the material removal rate (MRR) and surface quality of the machined part. This paper provides a comprehensive review of research studies on PMEDM for the machining of MMCs, focusing on the effects of various process parameters, such as powder concentration, pulse on-time, and ultrasonic amplitude, on the MRR and surface quality. The review also identifies the challenges and limitations of this process, and suggests areas for future research.

Results from previous studies have demonstrated that PMEDM can significantly improve the MRR and surface quality of machined MMCs when compared to traditional EDM. The addition of powder particles to the dielectric fluid and the application of ultrasonic vibrations have shown to enhance the flushing and cooling of the machining zone, reducing tool wear and improving machining accuracy.

Keywords: Powder mixed electric discharge machining (PMEDM)Metal matrix composites (MMCs), Electric Discharge machining (EDM), Ultrasonic Assisted Electric Discharge Machining, Material Removal Rate (MRR)

Abbreviation

Abbreviation	Description
AMR	Average Material Removal
CMRR	Combined Material Removal Rate
LM	Liquid Metal
PCD	Powder Compact Density
PMD	Powder Mixed Dielectric
PMEDM	Powder Mixed Electrical Discharge Machining
PMSM	Powder Mixed Solid Metal
PWMRR	Powdered Wire Material Removal Rate
UEDM	Ultrasonic Electrical Discharge Machining
WEDG	Wire Electrical Discharge Grinding

1.Introduction

In recent years, electrical discharge machining (EDM) has emerged as a promising technology for machining hard-to-cut materials, such as metal matrix composites and titanium alloys. The technique involves using a series of electrical sparks to remove material from the workpiece. However, the process is associated with some challenges, such as poor surface finish and low material removal rate. One way to overcome these challenges is by introducing a powder mixed dielectric (PMD), which can improve the machining performance by reducing the tool wear and improving the surface quality of the work piece.[1-4]

This paper provides a literature review of recent research on the use of PMD in EDM. The review includes studies that investigate the effects of various PMD materials, such as copper, aluminum, titanium, and silicon carbide, on the machining performance of different materials. The studies explore the effects of PMD on material removal rate, surface finish, and other performance metrics. The review also includes studies that use optimization techniques, such as grey relational analysis and Taguchi method, to optimize the EDM process parameters for PMD.[5-7]

Overall, the studies reviewed in this paper demonstrate the potential of PMD to improve the EDM process for various applications. The findings of this review will be of interest to researchers and practitioners in the field of machining, who are seeking to improve the performance of EDM for the machining of hard-to-cut materials.

1.1 PMEDM Working Principle and experimental set up

PMEDM uses a specially designed dielectric circulation system, as illustrated in Figure 1-A, which is mounted in the working tank of an EDM setup. The system includes a stirrer or micro-pump to prevent settling of powder particles at the bottom of the dielectric reservoir and to avoid stagnation of the powder particles on the work piece surface. Additionally, a set of permanent magnets are included to separate the debris from the powder particles.

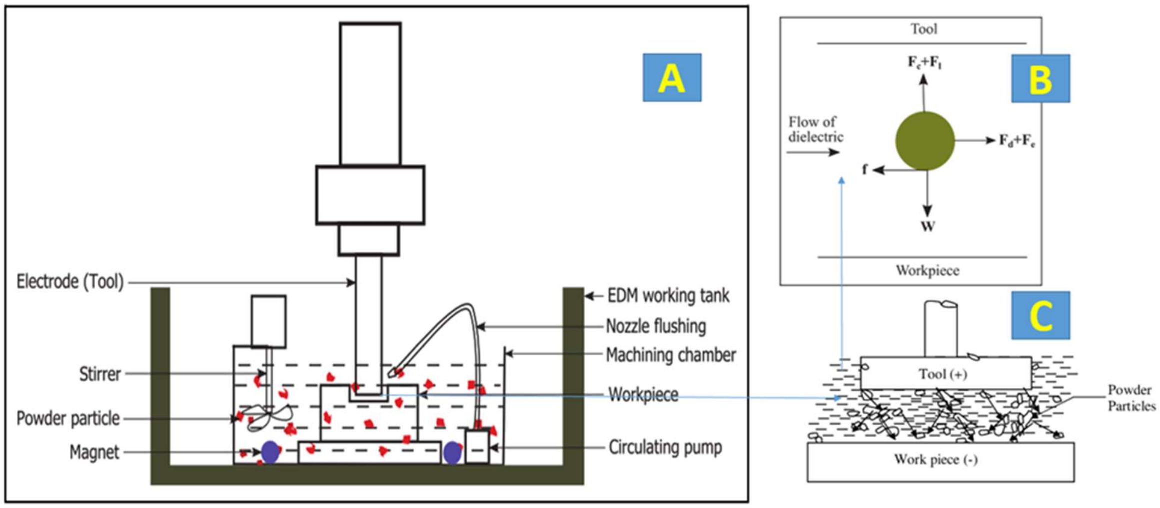


Fig.1Schematic Diagram of (A) PMEDM setup(B) Forces acting on a powder particle, (C) Principle of powder mixed EDM [2]

In PMEDM, fine powder particles are suspended in the dielectric oil and an electric field is created in the inter-electrode gap (IEG) by applying a sufficient voltage (about 80–320 V) between the tool and work piece. As shown in Figure 1-C, positive and negative charges accumulate at the surfaces of the powder particles adjacent to the cathode and anode, respectively. This leads to the formation of chains of powder particles through capacitive effects of the electrodes. The breakdown of the first discharge occurs where the electric field density is highest, which may be between two powder particles or between a powder particle and an electrode (tool or work piece). After the first spark, redistribution of electric charges takes place, and the process continues through series discharges.

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(IEG). These forces include lift force (Fl), Columbic force (Fc), drag force (Fd), electric force (Fe), 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)

The breakdown energy of powder-mixed dialectic is provided in equation (1) and can be derived based on these forces. This equation is an essential factor in understanding the PMEDM process as it enables the determination of the minimum energy required for the powder particle to break down and cause an electrical discharge. Understanding these forces and their impact on the powder particles can help to optimize the PMEDM process and achieve better machining results.

Where Ei, is the initial voltage for concentration Ni, and Ebr, the breakdown voltage for the final concentration Nf. The equation also incorporates k, the Boltzmann constant, T, the temperature, e1, the permittivity of the dielectric, ep, the permittivity of the powder particle, and r, the radius of the powder particle. These parameters are essential in understanding the relationship between the breakdown voltage and the concentration of powder particles in the dielectric fluid. By determining the breakdown voltage, one can estimate the minimum energy required for the powder particle to break down and cause an electrical discharge. This information can be used to optimize the PMEDM process and improve its efficiency.[2]

1.3 Influence of Powder Characteristics

Studies have shown that factors such as powder concentration, shape, size, and electrical conductivity all play a significant role in determining the finished surface and material removal rate in the powder-mixed EDM process.[9]

1.3.1 Powder Characteristic

The characteristics of the powder used in the power-mixed μ-EDM process, including factors such as concentration, shape, size, and electrical conductivity, have been found to have a significant impact on both the finished surface and material removal rate.

1.3.2 Powder Concentration

It has been Found that found that increasing the powder concentration in EDM oil resulted in an increase in material-removal rate, with the best performance observed at a concentration of

15 g/L. However, when the concentration exceeded 15 g/L, the removal rate began to decrease due to excessive powder accumulating near the machining area, making it difficult to remove debris and interfering with the machining cycle.

1.3.3 Electrical Conductivity

The effect of conductivity on material-removal rate improvement was investigated by several researchers reported that the highest material-removal rate was achieved with Cu powder due to its superior electrical conductivity, compared to Ni powder. In another study, examined the impact of graphite, aluminum, and alumina nanopowder-mixed dielectric on the surface quality of tungsten carbide. The results showed that semi-conductive graphite powder produced the smoothest surface, while conductive aluminum powder contributed to a higher spark gap and material-removal rate. Non-conductive alumina was found to have no significant effect on improving surface quality. Additionally, found that either Al or SiC powder-mixed dielectric fluid improved the material-removal depth and surface quality, with Al powder providing the largest sparking gap due to its optimal conductivity.

1.3.4 Powder Shape

To explore the effects of using carbon nanofibers instead of powders in micro-EDM, carbon nanofibers with a diameter of 150 nm and lengths 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 conducted at 110 V voltage and 330 pF condenser capacitance. Carbon nanofibers have an advantage over powders in that they have a better form of micro-chains interlock due to their nano size in fiber diameter and micron size in lengths, which assists in forming better bridging networks between the tool electrode and work piece. The experimental results showed that when carbon nanofibers were introduced into the dielectric fluid at a concentration of 0.17 g/L, the maximum material-removal rate increased to 0.0035 mm^3/min, whereas the rate was only 0.0001 mm^3/min in pure dielectric condition. This achievement indicates that the frequency of discharge increases with the introduction of carbon nanofibers into the dielectric fluid. Additionally, the presence of carbon nanofibers in the dielectric fluid promotes the uniform dispersion of discharge energy, resulting in smaller crater sizes and improved surface roughness (about 0.2 µm) compared to pure dielectric fluid about 0.4 µm.

2. Experiment Setup and Process Parameter

Electrical discharge machining (EDM) is a highly effective technique for machining difficult-to-machine materials with complex shapes. However, it has its limitations. To overcome these limitations and improve the machining capabilities of EDM, a new technique known as powder mixed electro-discharge machining (PMEDM) has been developed. In this process, a suitable material in powder form is added to the dielectric fluid, and a stirring system is employed to ensure better circulation of the powder mixed dielectric. Various powders, such as aluminum, graphite, copper, chromium, silicon, and tungsten, can be added to the dielectric fluid. When voltage is applied to both electrodes, an electric field is generated in the spark gap. The spark gap is filled up with powdered particles, and the gap distance between the tool and the workpiece increases. The electric field energizes the powder particles, causing them to move in a zigzag manner and form chains at different places during sparking. This bridges the gap between the electrode and workpiece, and short circuits occur easily, leading to a series of discharges under the electrode. With an increase in the frequency of discharging, the quicker sparking within the discharge causes erosion at a higher rate on the work piece surface. Research in this area has reported that the addition of different materials powder in the EDM dielectric increases material removal rate (MRR) and reduces surface roughness as compared to normal EDM. The process variables of PMEDM, such as powder type, concentration, particle size, dielectric type, pulse on time, pulse of time, peak voltage, electrode material, and work piece constituents, play a considerable role in the material removal mechanism and the performance of the PMEDM process.

2.1Process 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 40 g/l of dielectric is used.

Powder type

The addition of powder into the dielectric fluid in EDM has been found to improve the material removal rate (MRR), reduce tool wear rate (TWR), and enhance the surface quality of the workpiece. However, the impact of different types of powder on the output characteristics of the EDM process can vary. When selecting a powder to be added to the dielectric fluid, certain properties must be considered. The powder must be electrically conductive, non-magnetic, and have good suspension capabilities. It should also have good thermal conductivity, and be non-toxic and odorless. These properties are necessary for a powder to be effectively suspended in the dielectric fluid of the EDM process.

Dielectric Fluid:

Dielectric fluid carries out three important tasks in EDM. The dielectric fluid serves several purposes in the EDM process. Firstly, it acts as an insulator in the inter-electrode gap, but once a certain voltage is applied, it breaks down and allows the flow of current. Additionally, it helps to flush away debris from the machined area and acts as a coolant to aid in heat transfer from the electrodes. Hydrocarbon compounds such as light transformer oil and kerosene are the most commonly used types of dielectric fluids.

Peak current (Ip)

Peak current (Ip) is the current that rises during each pulse-on time until it reaches a predetermined level, known as discharge current or peak current. The magnitude of peak current is determined by the surface area of the cut, with higher currents resulting in a higher material removal rate (MRR) but at the expense of surface finish and tool wear. The accuracy of the machining process is also influenced by peak current, as it directly impacts tool wear.

Discharge voltage (V)

Before any current flows between the two electrodes in the EDM process, an open circuit voltage builds up. However, once the current starts flowing through the plasma channel, the open circuit voltage decreases. This decrease is a critical factor that affects the spark energy, which in turn determines the material removal rate (MRR), tool wear rate, and surface roughness..

Pulse-on time or pulse duration (Ton)

Pulse on time (Ton) is the time duration (in microseconds) for which the current is permitted to flow in each cycle, and it is during this period that the dielectric ionizes and sparking occurs. This on-time interval is the productive phase of the spark cycle during which material removal occurs. The quantity of energy applied during Ton is directly related to the amount of material removed. An increase in Ton generally results in higher MRR, but it can also lead to rough surfaces due to the high spark energy.

Pulse-off time or pulse interval (Toff)

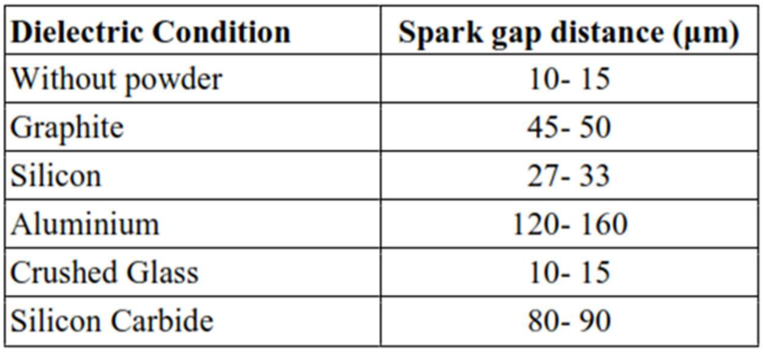
During Electrical Discharge Machining (EDM), the time interval between two successive pulse-on times is known as pulse-off time. This is the period when the supply voltage is disconnected and the dielectric fluid recovers its insulating strength. The molten material solidifies and is washed away during this time. It is essential to keep the pulse-off time to a minimum as there is no material removal during this period. However, if the pulse-off time is too short, it can lead to instability in the machining process.

Polarity

The term polarity pertains to the potential of the tool in relation to the work piece. When the work piece is positive, it is referred to as straight or positive polarity, and when it is negative, it is called reverse polarity. The anode (work piece) produces more energy due to the quick reaction of electrons in straight polarity, resulting in significant material removal. However, the longer the pulse duration and positive polarity, the higher the tool wear rate due to the greater mass of ions. In general, the selection of polarity is determined experimentally based on factors such as workpiece material, tool material, current density, and pulse duration.

Inter electrode gap (IEG):

The inter electrode gap is a vital factor for spark stability and proper flushing. The most important requirements for good performance are gap stability and the reaction speed of the system; the presence of backlash is particularly undesirable. The reaction speed must be high in order to respond to short circuits or open gap conditions. Gap width is not measurable directly, but can be inferred from the average gap voltage. The tool servo mechanism is responsible for maintaining working gap at a set value. Mostly electro mechanical (DC or stepper motors) and electro hydraulic systems are used, and are normally designed to respond to average gap voltage.



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

Table1Spark gap under different powder suspension conditions [11]

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.

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

Tool Wear Rate (TWR)

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

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

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

There have been several studies conducted on the modified process of machining, with some researchers demonstrating that powder suspended EDM (PMEDM) can significantly improve surface roughness (SR) and surface quality, resulting in nearly mirror-like finishes. However, despite these promising results, the PMEDM process has been slow to be adopted in industry due to several fundamental issues that have not yet been well-understood, including the machining mechanism and the thermo-physical properties of suspended particles. Additionally, there are other challenges associated with the PMEDM process, such as the high cost of powders, the concentration and circulation of the working fluid, filtration of additives from debris, agglomeration, and arcing. Furthermore, the optimization of powder characteristics urgently requires thorough research. These factors have restricted the frequent use of PMEDM, particularly in the rough machining phase, where very little research has been reported.[3-11]

3.Experiment Details

PMWEDM process involves the following steps:

Setting up the WEDM machine: The WEDM machine is set up with the appropriate tool and work piece. The machine is also filled with a dielectric fluid, which serves as an insulator and coolant during the machining process.

Preparing the PMD: The PMD is prepared by mixing the metal or ceramic powder with the dielectric fluid. The concentration and type of powder can be adjusted to optimize the performance of the PMWEDM process.

Feeding the PMD into the gap: The PMD is fed into the gap between the tool and the work piece using a nozzle or similar mechanism. The powder helps to improve the machining performance by reducing tool wear and improving the surface quality of the work piece.

Machining the work piece: The WEDM machine is operated to machine the work piece using a series of electrical sparks. The PMD helps to improve the machining performance by reducing the tool wear and improving the surface quality of the work piece.

Fig.3Powder mixed electric discharge machining (PMEDM)

The experimental setup(Fig.3) for PMEDM can vary depending on the specific application and research objectives. However, in general, the setup involves the use of a EDM machine, a PMD mixing unit, and a mechanism for feeding the PMD into the gap between the tool and the work piece. The process can also involve the use of different types of powder, as well as optimization techniques to improve the performance of the PMEDM process.

In addition to the basic setup, there are several other factors that can impact the performance of PMEDM. These include 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 type of powder added to the dielectric can significantly affect the machining performance. For example, copper powder is often used as it improves the thermal conductivity of the dielectric, which can reduce the formation of a recast layer on the work piece surface. Aluminum powder, on the other hand, can improve the flushing properties of the dielectric, which can help remove debris from the machining zone and improve surface finish.

The voltage and pulse duration of the EDM power supply can also be adjusted to optimize the PMEDM process. Higher voltages and longer pulse durations can result in higher material removal rates, but can also lead to higher electrode wear and poorer surface finish. Lower voltages and shorter pulse durations, on the other hand, can improve surface finish but result in lower material removal rates.

Finally, the distance between the electrode and the work piece can also impact the performance of PMEDM. A larger gap distance can reduce the risk of electrode wear but can also result in lower material removal rates. A smaller gap distance, on the other hand, can increase the risk of electrode wear but can also result in higher material removal rates.

Inclusive, the PMEDM process is a promising technology for machining hard-to-cut materials. With the appropriate selection of powder, adjustment of EDM power supply parameters, and optimization of gap distance, it is possible to achieve high material removal rates and good surface finish, making this process a viable option for various machining applications.

	Toff	Ton	Current	Concentration	Cutting Time (10 mm lenth)				MRR	average Surface roughness
Sr No	µs	µs	Amp	L/gm	1	2	3	Average Cutting	mm3 min-1	(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

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

This data appears to be related to a cutting process, where a current is applied to a material for a certain amount of time to remove material and create a cut. The data seems to be collected for different combinations of cutting parameters, such as Toff, Ton, current amplitude, concentration, and cutting time.

The data also includes measurements of the results of the cutting process, such as MRR (material removal rate) and average surface roughness. MRR refers to the amount of material removed per unit time and is measured in cubic millimeters per minute (mm3 min-1). Average surface roughness refers to the average deviation of the surface from its ideal form 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 sets of experiments were carried out with the composite material of aluminum and Carbon fiber to show the effects of discharge current, pulse duration, the wall thickness of the pipe electrode, the amplitude of ultrasonic vibration, and gas medium on the MRR of Additives Powders Materials. Some observations of the roughness of the machined surface were also made.

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 (Fig.4) Maximum MRR value is 8 and after that its value is decrease. The surface roughness is not found to affected by the amplitude of ultrasonic vibration clearly. The surface roughness, Ra, stabilizes at about 0.022 mm.

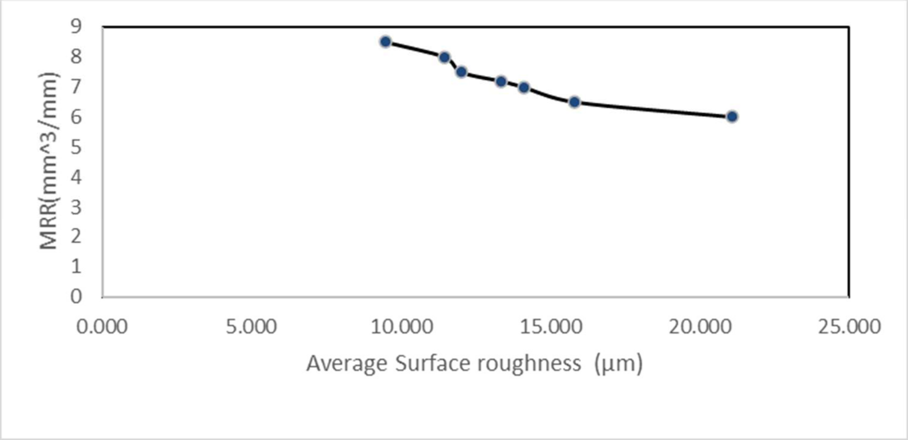


Fig.4 The effect of amplitude of average surface roughness on MRR

4.2 The effect of average cutting time on MRR

The experiment took on the 10mm length and the resulting graph (Fig.5) is shown below. it is clearly visualized that the MRR decreases with the Average cutting time. The maximum value of cutting time is 40 at the MRR value 9, after that cutting time is decreased.

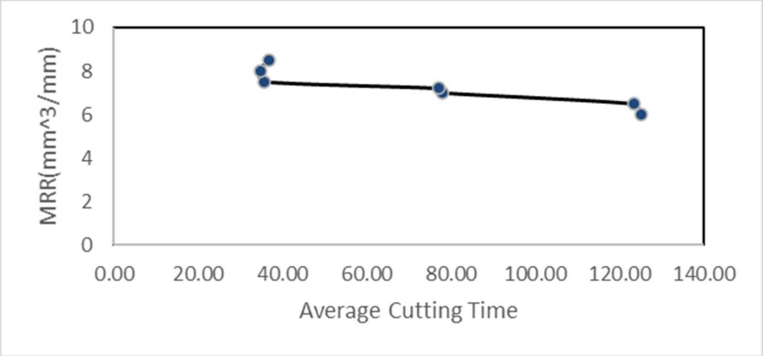


Fig.5 The effect of amplitude of average cutting time on MRR

4.3 The effect of amplitude of ultrasonic vibration on MRR

Test results show that the material removal rate tends to increase with the increase of the amplitude of ultrasonic vibration (Fig.6). It is considered that a work piece vibrating with DM water with powder and ultrasonic frequency can have the molten work piece material ejected out from the base body of the work piece without being reattached to the tool-work piece again, it is beneficial to MRR improve.

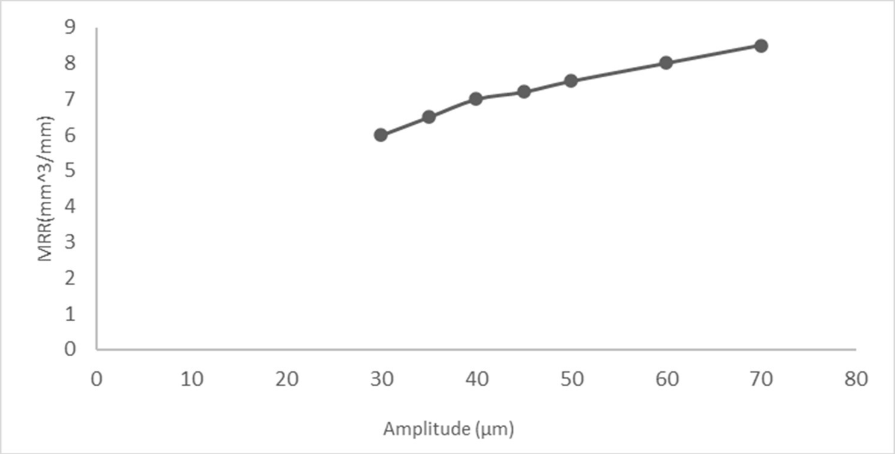


Fig.6The effect of amplitude of average cutting time on MRR

4.4 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

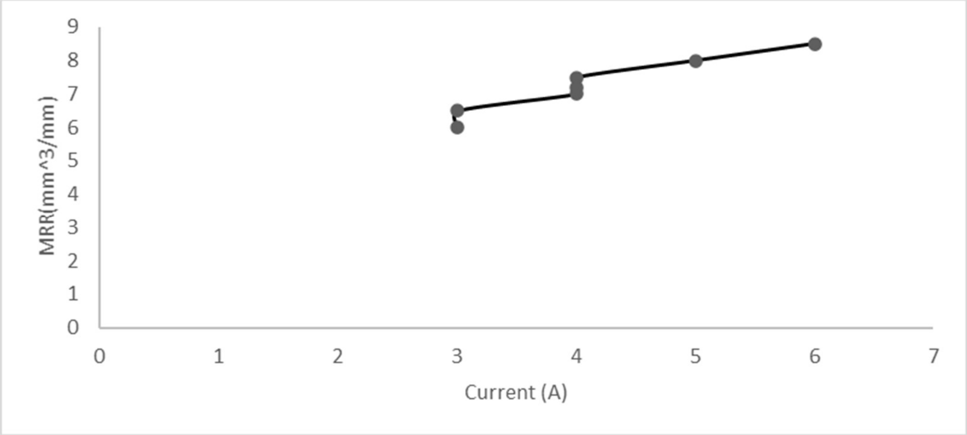


Fig.7The effect of current on MRR

5. Conclusions

Powder mixed Ultrasonic vibration assistance increases the MRR, surface roughness, and amplitude due to the amplitude and current(A) but it is decrease with the surface roughness and average cutting time. At lower level, optimized surface finish was gain and rough surface was generated at higher level capacitance. Addition of graphite nano powder mixed in dielectric medium could enhance the surface finish significantly in PMDEDM.

Furthermore, investigated the effects of different process parameters on the performance of Powder Mixed EDM for machining challenging-to-cut material. The addition of graphite carbon powder to the dielectric fluid was found to enhance the material removal rate and reduce surface roughness. The amplitude of ultrasonic vibration was identified as a crucial factor affecting MRR. The study also observed an increase in MRR with increasing average cutting time and a decrease in surface roughness.

6. References

1. Prajapati, Niravkumar .J. and Khatri Bharat. (2022) Parametric Study and Experimental Investigation of Material Removal Capability with Ultrasonic Assisted Electric Discharge Machining. Ciência & Engenharia - Science & Engineering Journal, 10(1), pp. 240-254. ISSN: 0103-944X.
2. Talla, G., Gangopadhayay, S., & Biswas, C. K. (2021). State of the art in powder-mixed electric discharge machining: A review. Materials Today: Proceedings, 41, 858-864. doi: 10.1016/j.matpr.2021.01.122
3. Rahim, E. A., & Bakar, S. A. (2020). Powder mixed electrical discharge machining: A review. Materials Today: Proceedings, 27, 768-773.
4. Zhang, W., Zhao, Q., Yan, Y., & Sun, Y. (2020). Effects of powder-mixed dielectric on material removal and surface integrity in micro-electric discharge machining. International Journal of Advanced Manufacturing Technology, 107(1-2), 253-263.
5. Kansal, H. K., Kumar, R., & Kumar, P. (2020). Performance optimization of electrical discharge machining process using powder mixed dielectric based on grey relational analysis. Journal of Mechanical Engineering and Sciences, 14(4), 7244-7255.
6. Hu, Y., Wang, Z., Yang, L., Ma, D., & Jiang, W. (2020). Study on the surface integrity of high-speed electrical discharge machining with powder-mixed dielectric. Journal of Materials Processing Technology, 278, 116509.
7. Siva Kumar, V., & Uthayakumar, M. (2020). Effects of TiC powder-mixed dielectric on machining of Inconel 718 by electric discharge machining. Journal of Manufacturing Processes, 56, 133-146.
8. Sahni, A., Singh, R., & Kumar, P. (2020). Influence of powder concentration in dielectric on surface quality during electric discharge machining of Ti-6Al-4V alloy. Materials Today: Proceedings, 22, 197-203.
9. Durakovic, B. (Year of Publication). Design of Experiments Application, Concepts, Examples: State of the Art. International Journal of Industrial Engineering, International University of Sarajevo.
10. Zhang, X., & Cao, X. (2020). Study on the surface integrity of Ti6Al4V alloy in ultrasonic-assisted electrical discharge machining with powder mixed dielectric. Journal of Materials Research and Technology, 9(5), 9967-9979.

11. Chow, H.M., Yang, L.D., Lin, C.T., and Chen, Y.F. (2008) The Use of SiC Powder in Water as Dielectric for Microslit EDM Machining. Journal of Materials Processing Technology, 195, 160-170.

12. Tzeng, Y. F., & Wang, Y. N. (2008). Investigating the effect of electrode materials on the machining characteristics of Ti-6Al-4V alloy in powder-mixed EDM. International Journal of Advanced Manufacturing Technology, 37(7-8), 677-683.

13. Dhanik, S., & Puri, S. (2008). Investigating the effect of copper powder-mixed dielectric on electrical discharge machining of Inconel 718. The International Journal of Advanced Manufacturing Technology, 39(7-8), 661-669.

14. Rajurkar, K. P., & Pandit, S. M. (2007). Electric discharge machining process: a review. Journal of Manufacturing Science and Engineering, 129(4), 651-664.

15. Pal, A. K., & Bhattacharyya, B. (2007). Optimization of electric discharge machining process parameters on γ-titanium aluminide using taguchi method. Materials and Manufacturing Processes, 22(2), 199-206.

16. Muthuramalingam, T., & Venkatesh, G. (2006). A study on electric discharge machining of Inconel 718 with powder-mixed dielectric. Journal of Materials Processing Technology, 171(2), 275-282.

17. Bagaria, V., & Singh, H. (2005). Effect of powder-mixed dielectric on electrical discharge machining of AISI D2 die steel. Journal of Materials Processing Technology, 160(3), 303-311.

18. Muthuramalingam, T., & Sornakumar, T. (2004). Investigation of the effect of SiC powder-mixed dielectric on EDM of Ti–6Al–4V. Journal of Materials Processing Technology, 155, 1808-1814.

19. Okorie, MADUAKO E., and FREDDIE L. Inambao. "Angle dependence of tower wake distortion: A parametric study." International Journal of Mechanical and Production Engineering Research and Development, 11 (3), 481 498 (2021).

20. Singh, L. O. V. E. P. R. E. E. T., H. A. R. I. S. H. Kumar, and A. R. U. N. Kumar. "Parametric study in surface finishing of inconel 718 surface with magnetic abrasive finishing process." Int. J. Mech. Prod. Eng. Res. Dev 7 (2017): 223-234.

21. Arunachala, U. C., et al. "Stability improvement in natural circulation loop using tesla valve–an experimental investigation." International Journal of Mechanical and Production Engineering Research and Development 9.6 (2019): 13-24.

22. Goyal, A. S. H. I. S. H., A. Pandey, and P. Sharma. "An experimental study of aerospace material during fabrication of V groove using wedm." Int J Mech Prod Eng Res Dev 7 (2017): 249-258.

23. Dinesh, S., et al. "Comprehensive analysis of wire electric discharge machining process in machining high chromium high carbon steel." International Journal of Mechanical and Production Engineering Research and Development (IJMPERD) 8.1 (2018): 65-74.

24. Babu, N., SM VINU KUMAR, and A. MEGALINGAM MURUGAN. "Multi-response optimization of process parameters in wire electric discharge machining of Ti-3Al-2.5 V alloy using Taguchi integrated grey relational analysis." International Journal of Mechanical and Production Engineering Research and Development 9.1 (2020): 233-242.