Stagnation Phenomenon of Spark in the PMEDM Medium: A Review

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ABSTRACT

New electrically conductive materials with desirable mechanical qualities and thermal characteristics have become available thanks to developments in materials science. It is difficult to machine these materials with standard machining techniques. In order to produce hard materials with geometrically complex geometries, a well-established machining technology called electrical discharge machining (EDM) is utilised. Electrical discharge machining (EDM) is a thermo-electric method that erodes material by repeated sparks between an electrode and a workpiece that are not in touch. Due to the lack of physical contact between the electrodes in EDM, typical machining flaws such as mechanical strains, clattering, and vibration are avoided. Despite its benefits, the method has found little application in industry due to its unsatisfactory surface polish and low volumetric material removal. Mixing the metallic powder in the dielectric fluid improves its conductive strength and extends the spark gap between the tool and the workpiece, mitigating these shortcomings. Powder Mixed Electrical Discharge Machining is the name of the cutting technique that has recently evolved (PMEDM). The EDM process's efficiency is drastically altered by the additional powder. The purpose of this review is to help researchers better grasp the PMEDM idea, and to analyse the process parameters in more depth for the purpose of making improvements to the process and so achieving higher quality levels.

Keywords: Powder mixed EDM (PMEDM), EDM, Material removal rate, Dielectric, Powder additives

1. Introduction

Adding fine powders like silicon and aluminium to the conventional kerosene-based working fluid enhances the discharge condition, improving the surface quality and finishing effectiveness. This new processing technology is known as powder-mixed EDM. As well as improving the surface qualities of the workpiece, it may effectively reduce the unloading area and surface quality variance. For completing broad areas of die cavities, powder-mixed EDM technology is advantageous. Industries like aerospace, automotive, healthcare, nuclear energy, and precision machinery are receiving much more attention. [1]. According to the findings of the experiments, mixing insulating liquid with EDM powder can raise the EDM spark gap, improve curing time, enhance MRR, decrease SR, and improve surface quality. The insulating liquid does, however, have the following issues. The powder has lifted the workpiece's surface during the operation, causing a build-up that results in a mild spark. The PMEDM process's an increased peak current value, pulse duration, and powder concentration adversely affect the machine's capacity in this environment. Figure 1 shows a model of the PM-EDM technique [2], [3].

These experimental results show that the sputtered MRR performs poorly, as evidenced by the high rise of peak current, pulse duration, and powder concentration in PMEDM. The high degree of allowable hardness and average surface roughness of the -Titanium alloy, 784.71 HV and 1.31 m, respectively, serve as proof in this situation. These reactions happened when tungsten powder was applied at its highest concentration (t = 100 s; PC = 6 g/L; IP = 5 A). Even though the electric current and temporal pulse-related parameters of PMEDM are decreased during the electro-corrosion of D2 steel, an increase in silicon powder above five g/L decreases the MRR to 12.280 mm^3/min. [4]. These experimental results illustrate the poor performance of the sputtered MRR since they show a high increase in peak current, pulse duration, and powder concentration in PMEDM. The high degree of acceptable hardness and average surface roughness of 784.71 HV and 1.31 m in the -Titanium alloy support this claim. These reactions occurred when tungsten powder was applied at its highest concentration over time (t = 100 s; PC = 6 g/L; IP = 5 A). Even though the electric current and temporal pulse-related parameters of PMEDM are decreased during the electro-corrosion of D2 steel, an increase in silicon powder above five g/L reduces the MRR to 12.280 mm3/min. [5]–[9]. As seen in Figure 2, this debris eventually combines with the remaining powder particles and carbon particles produced by the breakdown of the insulating liquid, causing spark breakage and short circuits and adversely reducing automation performance.

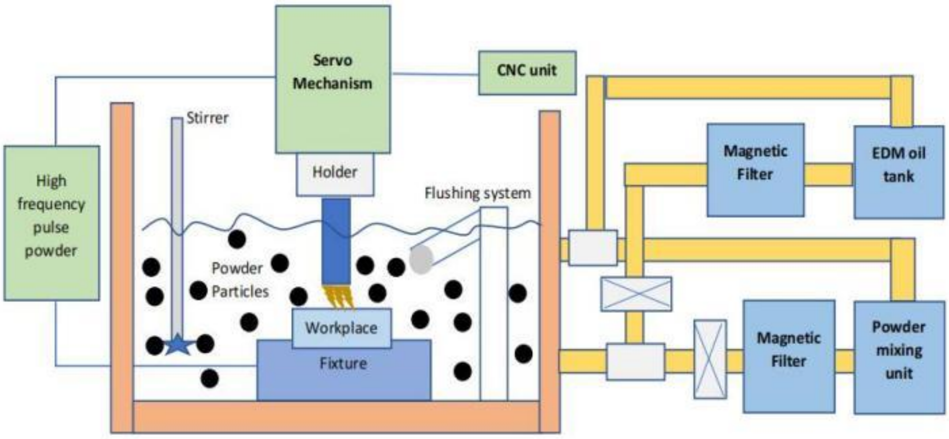


Figure 1. The Schematic diagram of the PMEDM technique [3]

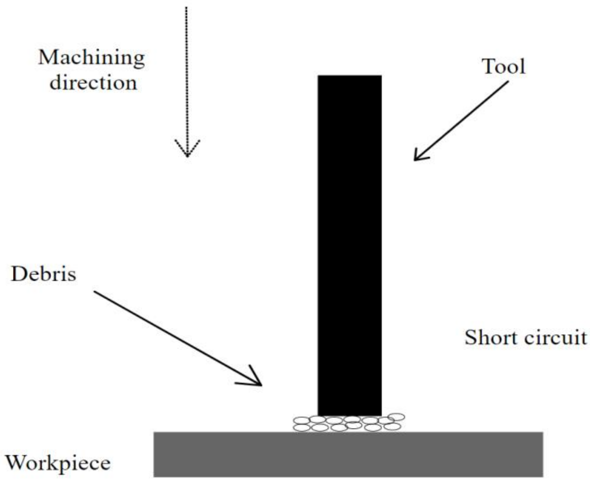


Figure 2. This Schematic of short-circuiting phenomena on PMEDM [5]

The accumulation phenomenon in the PMEDM environment leads to a short circuit by adding the powder to the EDM environment as an external factor to enhance it. This pattern is supported by every explanation provided by prior studies in PMEDM. The workpiece, electrode tool, and an insulating liquid all produce dust and carbon particles, which are related to internal aggregation in the opposite direction because they represent a pure EDM environment. This trend does not coincide with the prior shift regarding parameter behaviors [10], [11]. Hence, technological improvements are enthusiastically requested by manufacturing industries to improve surface finish, reduce short circuit and enhance material removal rate. In this review paper, the detailed report on the short-circuit phenomenon and spark breakdowns that occur during the PM - EDM process when processing various work materials, adding various powders to the insulating liquid and using a composite electrode, the reasons for its occurrence and ways to reduce it are discussed.

2. Aggregation in pure EDM

Due to various innovations in the area of materials and the potential of machines that can make them difficult, the need for solid materials is constantly rising in the fields such as engineering [12], [13]. A well-liked method for producing parts with intricate features with great accuracy is electric discharge machining (EDM). Because conventional techniques are expensive and have a high tool wear rate, EDM is preferred for cutting hard and brittle materials [14]–[16]. Discrete electrical sparks generated by electrical energy remove material from the surface during EDM milling [17]. A dielectric liquid is kept around the tool and workpiece during this operation. When cutting using an EDM machine, the tool and workpiece are slightly separated and submerged in a dielectric fluid. The material on the workpiece exterior reaches very high temperatures and is burned due to the spark's discharge energy [18], [19]. The residue is then flushed away by the dielectric medium. The parameters affecting EDM outcomes include the pulse current, servo voltage, pulse on time, pulse off time, dielectric medium, and electrode material. [20]–[22]. Figure 3 depicts a typical EDM configuration.

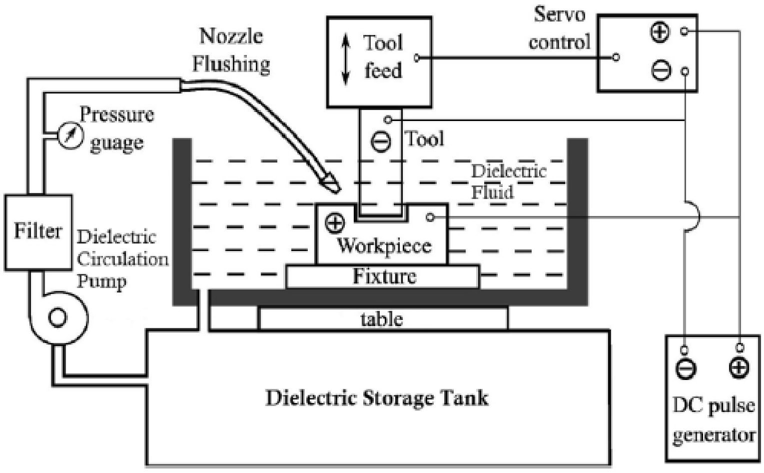


Figure 3. EDM Setup [22]

The EDM process for removing material is shown in Figure 4. The combustion phase involves the application of a significant voltage differential between two non-contacting electrodes (Figure 4(ii)). When the electrode gets closer to the workpiece, the inter-electrode gap's electric field intensifies until the dielectric breakdown voltage is attained. The tool's discharge happens at the area of the workpiece that is closest to it. If there are contaminants or particles in the gap, as mentioned, the location can shift. A phase of the plasma: When the fluid channel begins to take shape, currents flow across it, and the voltage drops due to the ionization of the dielectric material (Figure 4(iii)). During the discharge phase, the constant bombardment of ions and electrons on the electrodes results in significant workpiece heating. Due to the continuous discharge current raising the temperature, a small pool of fluid steel formed on the electrode surfaces. The molten metal instantly loses some of its moisture. The plasma route widens during this phase, making the molten metal pool more noticeable (Figure 4(iv)). A small hole appears on the surface of the workpiece during the ejection phase because the plasma channel collapses due to the neighboring dielectric applying pressure and the voltage being turned off during the plasma channel's collapse (Figure 4(v)).

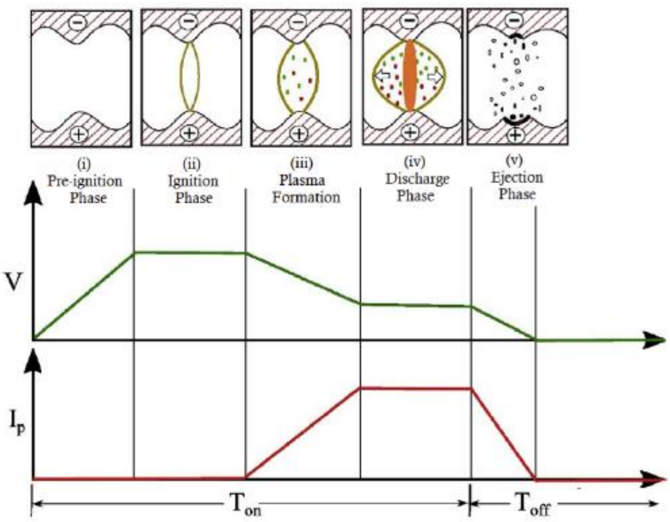


Figure 4. The Material removal process in EDM

Little amounts of workpiece material are removed as molten metal, where they harden and produce debris. Dielectric flushing through the inter-electrode gap removes this debris from the discharge zone; as the hole grows, the spark moves to the nearest electrodes. In the earlier example, a replica of the opposite nature is created on the workpiece surface to thousands of these electric discharges occurring in various places. The liquid metal resolidifies due to the high heat and quick cooling, creating a recast layer on the machined surface. [23]. Microcracks in this layer reduce its capacity to withstand corrosion, wear, and fatigue. Surface integrity must be restored through post-machining processes. [24]. The EDM method can manufacture any electrically conductive material, but it is not widely used in industry because of its poor surface quality, low surface integrity, and low productivity. Researchers developed fresh and better iterations of the EDM technique to boost process performance. Some of the methods used in EDM are Rotary EDM (REDM), Ultrasonic EDM (UTEDM), Powder-Mixed EDM (PMEDM), Near Dry EDM, and Magnetic Assist EDM (MAEDM) [25]–[27]. Past studies have examined how different electrode materials affect several different characteristics, including the rate of mass transfer and electrode wear. The authors of [28] studied the EDM of SKD61 die steel using input parameters including voltage, pulse current, and pulse-on-time and found the ideal level for maximum MRR, low surface roughness, and decreased white layer thickness. [29] analyzed boron alloy steels and found that as the discharge current and stroking period keep increasing, so do MRR and surface roughness. As per studies in [30], The impact of adhesive layer separation on CFRP laminates with various time-pulse scenarios increases. The cause of the delamination is the MRR decreases because the dielectric fluid does not thoroughly wash off the molten material.

We found that with a high power level setting, the pulse time is longer, and the pulse off time is shorter [31] by studying a wire EDM based on biodegradable AZ91 Mg alloy. Thus, higher roughness is created on the machined surface leading to broader and deeper craters and increased energy discharge in the machining area. Numerous attempts were made to identify an appropriate composite material for the electrode to improve the performance of an EDM throughout machining [32], [33]. Researchers recommend powder metallurgy to prepare composite electrodes because it is impossible to create composites with high variation in densities using other techniques. The different approach is stir casting because during the melting, owing to the increased fluctuation in thicknesses, the reinforcement floats or sits at the bottom until poured into the mild.[34], [35]. Powder metallurgy produces components by combining powders and pushing them in a die to interact with them to form the desired shape mechanically and heating them to the appropriate temperature to bond them metallurgically. Researchers examined the properties of Al-TiO2-Mg composites and discovered that, while the hardness of the composite falls as the sintering temperature is raised, the density of the specimen increases [36].

3. Aggregation in pure PMEDM

Figure 5 depicts a usual dielectric flow system used during PMEDM [37]—designed system installed in an EDM setup's working chamber. Powder particles are kept from collecting at the bottom of the dielectric basin by a mixer or a micro pump. Moreover, it prevents powder particle stagnation on the surface of the workpiece. A permanent magnet is available to separate the trash from the powder particles. The workpiece must be magnetic for this approach to be practical; the powder material must not be magnetic. Particle aggregation is one of the most efficient and cost-effective techniques for increasing electrostatic material's high collection efficiency. Particle aggregation is the process by which sub-micron particles clump together to form a larger particle that can be observed and removed [38]. Typically, a chemical is introduced into the gas stream to promote sub-micron particle surface aggregation. Natural convection requires a tremendous amount to encourage sub-micron particles' aggregation surface. Dust particles suspended in the gas are agitated by sound, increasing impingement and aggregation. Charged particles impede the disturbance of the AC or DC electric field [39].

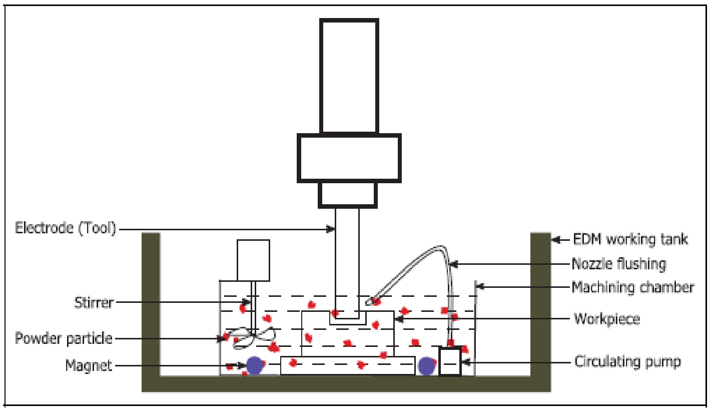


Figure 5. PMEDM Setup [37]

In PMEDM, an applied voltage of 80–320 V creates a field intensity of 105–107 V/m, which causes positive and negative charges to collect at the top and bottom of the powder particles, respectively [40]. An emission gap forms in the region of the field density where it is best (between 'a' and 'b' in Figure 6). This fragmentation might occur between powder particles or between powder particles and an electrode on a blade or workpiece [41], [42]. Electric charges relocate and gather at sites 'c' and 'd' after the first discharge. A sequence of sparks keeps happening depending on the field density. A series is produced by connecting several powder particles, which enables rapid short-circuiting and an initial bombardment in the gap. [43]. Combining particle interconnection and suspended additive particles alters the plasma channel, lowering discharge power density and pulse explosive gas pressure.

The powder particles' physical and electrical properties primarily influence the discharge gap's dimensions. At high temperatures, free electrons in powder particles decrease dielectric resistance. As a result, sparks can be created from a more extended range, effectively increasing the discharge gap [44], [45]. Authors in [38] used ultrasound to improve particle aggregation with one micrometer or fewer diameters. However, the cost of implementing this technique on a large scale was prohibitively high. In [46] investigated the effect of bipolar charging on a parallel plate aggregator's small particle aggregation efficiency and discovered that the decrease in the number concentration of 0.1 micrometer-sized particles was between 17 and 19 %. Corona charging is used in experiments to detect the various charge-to-mass ratios of particles. It was discovered that when particle concentration rose, the charging mechanism lost some of its effectiveness. Similarly, a Non-thermal Plasma aggregation is offered as a sample method for reducing the concentrations of sub-micron particles in an acrylic duct equipped with a saw-tooth electrode and an electrostatic precipitator with wire plates (ESP). Operator parameters such as pulse voltages, pulse frequencies, dust loadings, and gas velocities controlled the particle aggregations generated by pulse energized ESP. Gas velocity was increased to 1 m/s at 45 kVp and 20 kHz, which increased efficiency. At all particle sizes and a gas velocity of 1 m s-1, the sub-micron particle number reduction efficiency in ESP was greater than 90% [39].

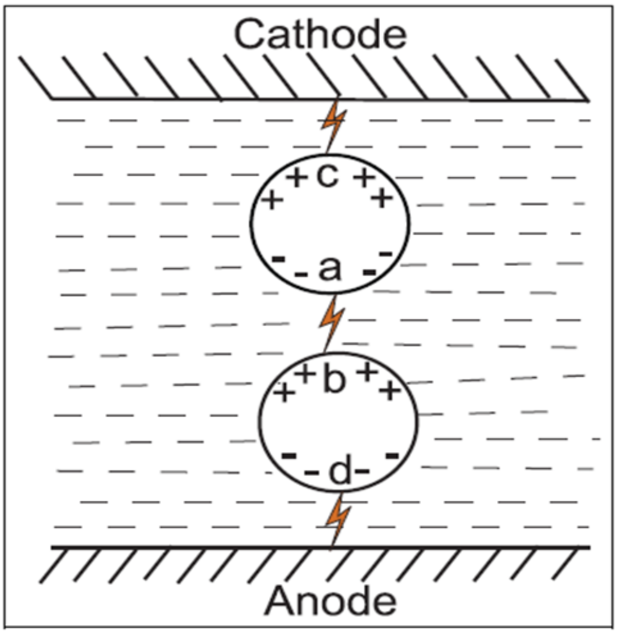
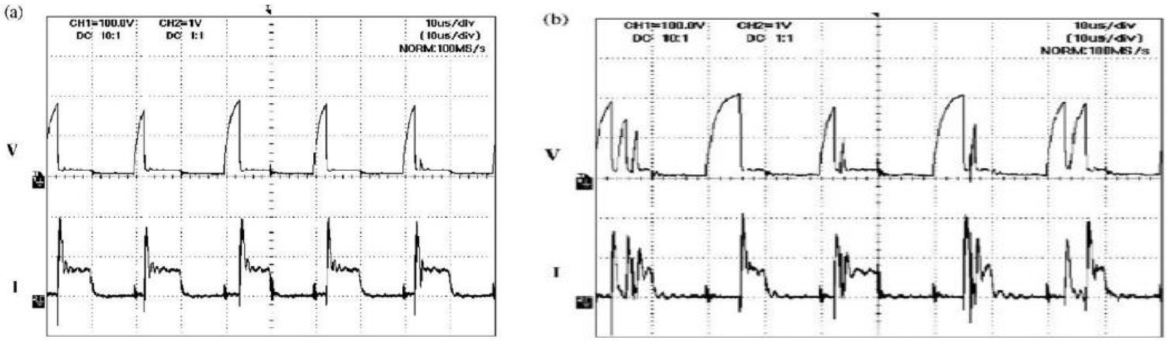


Figure 6. The Series discharging in PMEDM [41]

The first discharge is followed by the powder particles becoming electrified and moving quickly with ions and electrons. These powder particles produce more electrons and ions than typical EDM when they hit dielectric molecules, leading to more oversized electric charges. Research on using powder-mixed EDM for rough machining suggests that doing so will reduce the hydrostatic pressure on the plasma channel [47]. When positive polarity and short pulse duration were used, Meng et al. [48] a hypothesis was made that the workpiece's discharge passage's diameter was significantly more significant than the tool electrodes'. As ions must accelerate more slowly due to their higher mass than electrons, the carriers at the finish machining condition (positive polarity, small peak current, and brief pulse length) are primarily electrons. A cone-shaped passage will occur from the electron avalanche. Kojima et al. [49] used spectroscopy to determine the diameter of the arc plasma. It has been confirmed that as the gap width increased, so did the diameter of the arc plasma.

The uniform energy distribution brought about by the fast Zigzag motion of the particles leads to the development of many pieces in a single pulse. The voltage fluctuates significantly within a single pulse period due to several shoots

[44]. Figure 7 depicts a typical current and voltage waveform (a) for conventional EDM - Pure water Dielectric and (b) for PMEDM - Pure water added with SiC powder [50]. Chow et al. [51] discovered were created from a single input pulse. A single input pulse can therefore result in many discharging regions. This conclusion is supported by reports from Han et al. [52] and Kung et al. [53]. Similar behavior of powder particles across the dielectric is made possible by the lower density of powder particles' ability to better balance against surface forces. [54], [55]. Low density also lessens the number of powder particles that collect at the tank's bottom, which minimizes the amount of needed powder. On molten steel, lighter particles also have a little progressive effect [56]. The discharge waveforms changed from those without the powders when different powders were added. There were several discharging effects produced from a single input pulse.



(a) (b)

Figure 7. Voltage and current waveforms (a) conventional EDM, (b) PMEDM - pure water with SiC powder added [59]

4. Influential parameters in the aggregation of PMEDM

The productivity of machining is influenced by adjustable input components called procedure factors. [58]–[60]. Performance parameters, used to evaluate process performance under specified parameters, are one of the two primary types of PMEDM parameters. The parametric analysis of the PMEDM process is displayed in Figure 8.

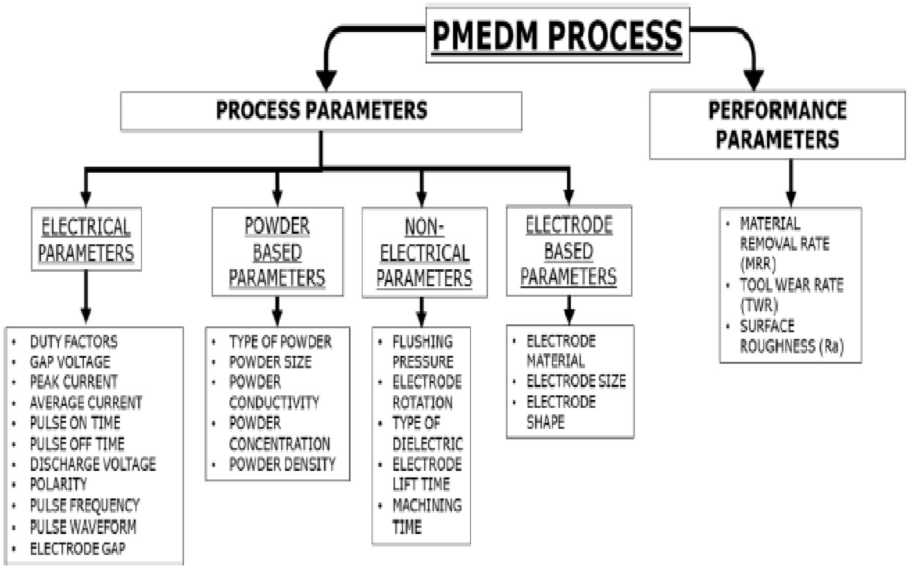


Figure 8. Parametric analysis of PMEDM process [3]

4.1 Dielectric

PMEDM Dielectric is characterized by its high dielectric strength, efficient quenching, speedy post-breakdown recovery, flushing capability, and good fluidity. Some of the crucial dielectric qualities employed in PMEDM are listed in Table 1. Debris in the inter-electrode gap decreases process efficiency and can spark arcing, which degrades both dimensional precision and surface integrity, making efficient flushing a need [61], [62]. Differences in MRR, TWR, crack density, and recast layer thickness can be attributed to differences in dielectric type and flushing method. There are many methods of flushing available, including side flushing, suction via the electrode, pressure through the electrode, jet flushing, hoover flushing, and injection flushing [63]. Using a servo-controlled cyclic reciprocation or vibrating tool electrode helps remove chips from the inter-electrode gap by creating a hydraulic pumping motion. The material removal rate, surface quality, and tool wear rate can all be improved by using powdered dielectric [64]–[67]. The performance of a process might be improved or hindered depending on the type of powder used. Electric conductivity, Suspension capabilities, Thermal conductivity, and Non-magnetic nature are some of the particle qualities that affect performance. While inorganic oxide particles can be added to a dielectric, their poor dispersion throughout the material means they won't help the performance characteristics at all [68]–[71].

Table 1. Properties of typical dielectrics used in PMEDM [80]

Dielectric Name	Specific heat (J/kg-K)	Thermal conductivity (W/m K)	Breakdown strength (kV/mm)	Flashpoint (^{0}C)
Deionized Water	4200	0.623	65–70	NA
Kerosene	2100	0.14	24	37–65
Mineral oil	1860	0.13	10–15	160
Silicon oil	1510	0.15	10–15	300

Table 2 provides an overview of the characteristics of common powdered substances. Krypton fuel and deionized in PMEDM, water frequently use in addition to commercial EDM oils. Pure water has a cooling effect advantageous because of its higher thermal conductivity and specific heat. [72]–[74]. Water produces oxidation on the machined surface, whereas kerosene develops carbides. More thermal energy is needed to melt carbides than oxides[75], [76]. Hence, compared to kerosene, deionized water produced higher MRR and lower tool wear rate (TWR). Kerosene, however, results in a smoother surface finish. [77]–[79]. employed emulsified water as the dielectric (Water + Emulsifier + Machine Oil), which had better surface performance and a higher MRR than pure kerosene. The ionization of the water-soluble anionic chemical emulsifier present in the emulsified oil is the origin of the increase in the dielectric's overall electrical conductivity attributed to kerosene.

Table 2. Properties of various additives powders [54]

Material	Density (gcm^{-3})	Thermal conductivity ($Wcm^{-1}C^{-1}$)	Electrical conductivity ($\mu\ \Omega\ cm^{-1}$)	Melting Point(^{0}C)	Specific heat (cal $g^{-1}C^{-1}$)	Remarks
Aluminium (Al)	2.70	2.38	2.45	660	0.215	Decreases TWR enhances the form of the machined profile and produces surfaces with a mirror quality.
Chromium (Cr)	7.16	0.67	12.7	1875	0.11	Increased the machining efficiency, and the electrode wear ratio tended to decline.
Silicon Carbide (SiC)	3.21	1-5	1×10^9	2975	0.18	Rises in MRR, TWR, and surface quality
Silicon (Si)	2.33	1.5	1×10^5	1410	0.17	Surface roughness of the dielectric decrease by adding Si powder.
Tungsten (W)	19.3	1.673	5.6	3410	0.031	An increase in surface microhardness lengthens part of life
Titanium (Ti)	4.72	0.22	55	1668	0.125	Surface microcracks are less noticeable when surface hardness rises.
Molybdenum	5.06	0.138	106	1185	0.07	Enhanced are MRR, profile depth, and machined quality characteristics.

Disulphide (MoS_2)						
Boron Carbide (B_4C)	2.52	2.79	5.5×10^4	2763		The powder's effective discharge distribution properties significantly increase MRR and machining effectiveness.
Graphite (Gr/C)	1.95	4.70	3000	4550	0.20	Graphite powder improves electrical conductivity and offers lubricity, which lowers TWR and improves MRR.
Molybdenum (Mo)	10.2	1.39	5.27	2610	0.06	Molybdenum is used to make EDM wires because of its muscular tensile strength and good conductivity.
Alumina (Al_2O_3)	3.98	0.251	103	2072	0.17	The use of nanosized alumina powder has increased surface quality and topography.
Carbon nanotubes (CNTs)	2	4	50	2900		Surface roughness, the length and width of surface fractures, and the depth of the recast layer are all reduced with the inclusion of CNV particles.

4.2 Polarity

The movement of ions and electrons produces the discharge current. At brief pulse-on times, the discharge current is predominantly caused by the electron current. When the thump-on time prolonged, a tremendous amount of ion current is present in the discharge. The positive polarity (workpiece +ve) to a short pulse-on time should be sought MRR and decreased TWR. Negative polarity, on the other hand, can be utilized for a long enough period (workpiece -ve) [81]. Samples of craters developed during the EDM of a titanium component using SiC additive in the dielectric [82] are shown in Figure 9. The crater's center bulged due to a piece of the molten metal crystallizing there due to the positive polarity. Moreover, additional powder material accumulated on the workpiece [83]. Furthermore, negative polarity was used to find depth holes with large crests, which may allow for high MRR but a rougher surface [84], [85].

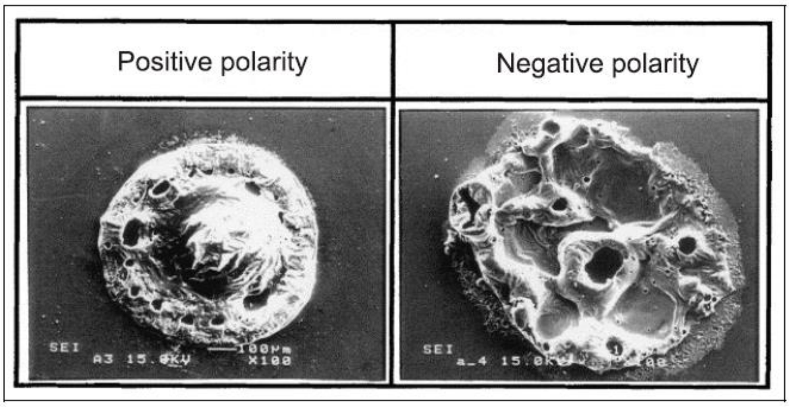


Figure 9. Influence of polarity in PMEDM [82]

4.3 Peak Current

MRR improves with peak current as discharge rises [86]–[88]. Peak current raises the volume and density of electrons and ions, raising the plasma channel's pressure. As a result, the particular sharp point's impulsive force per unit area rises, causing the flow of molten material to be more efficacious [89], [90]. As more particles touch the surface, tool wear and pulse current increase. Nonetheless, pulse energy prevails at large pulse currents, and tool wear is decreased [91], [92]. A decline in surface quality results from increased peak wind speed because more material removes per discharge due to higher discharge energy [93]. At powerful pulse currents, large and deep craters have been discovered[94]. The amount of material that melts and resolidifies increases the thickness of the recast layer [95]. Together with transferring material, rapid heating and quenching at high pulse currents improve the workpiece's ability to withstand fracture [96]. Using a Ti-suspended dielectric with a concentration of 3 g/L and a pulse-on time of 30 ms, The exact metallurgical changes that occurred in the recast layer throughout Ti machining. Figure 10(a) displays cubic-shaped crystalline grains identified as the TiO phase. The identical TiO phase is depicted in Figure 10(b). Due to the quick heat transfer to the outside at a low peak current and brief pulse-on period, no titanium (TiO2) is found.

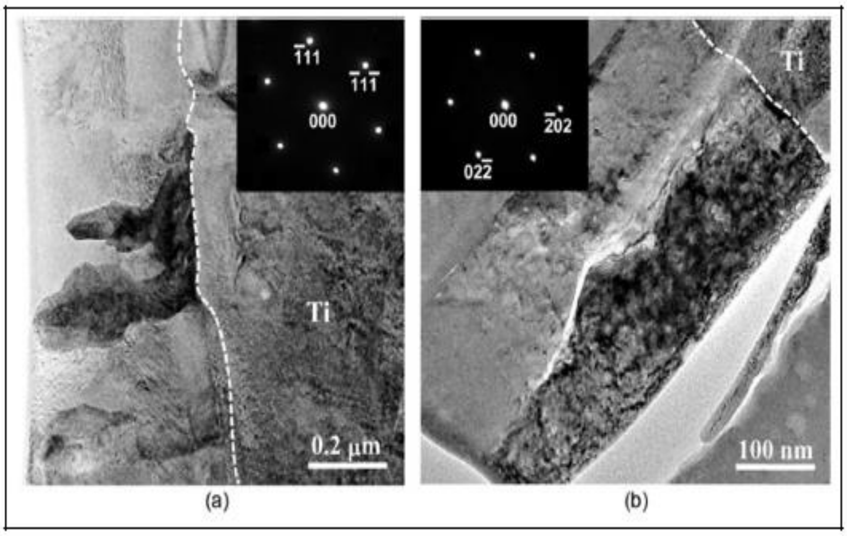


Figure 10. This is a TEM image of the cross-section from foil typical:
(a) (110) at 0.1 A and (b) (111) at 0.3 A [97]

4.4 Pulse on time

It describes how long a current can flow through a system in a single cycle. Microseconds are generally used for transmission. This time frame is when dielectric ionization occurs. The amount of material removed is a function of the power level generated during the pulse on time [92]. A more expansive crater, a more noticeable recast layer, and a deeper heat-affected zone are possible outcomes of a lengthier pulse on time because of more power concentration on the workpiece. The timing of pulses is crucial because machine completes the pulse on time. With sufficient machining time, dust continues to develop and stick to the machined surface as the pulse time increases. The recast layer's thickness is increased by TEM [76], [95]. Due to material transfer, the microhardness of the machined surface initially drops and subsequently increases as the pulse-on duration increases. [96]. Due to the time available for heat transfer from the molten crater to the electrode body, TWR decreases with pulse duration. Due to the deposited carbon, the electrode's high wear resistance causes TWR to grow [98]. High pulse-on time caused further overcut because of the substantial amount of material removed from every spark (OC) [85].

4.5 Duty cycle

It measures how much of the cycle's time is spent on the pulse. The longer the spark energy delivery time during the beating, the higher the duty cycle result and the greater the MRR. Unsatisfactory discharge results in an unbalanced process when the duty cycle is long. [92], [99]. MRR increases with the duty cycle as a result of increased spark energy. The process falls out of balance when the duty cycle is too long, and arcing may occur due to unfavorable flushing circumstances. [99], [100]. The lowest SR is acquired with a low-duty cycle for the same reasons. Longer duty cycles will likely reduce tool wear because they prevent gas and accumulated debris from escaping [101].

4.6 Gap voltage

MRR decreases when the spark gap increases because it takes longer for electrons and ions to link to the inter-electrode gap. [102]. The greater the space voltage, the improved the surface finish [82]. As the spark gap widens, the thickness of the recast layer increases, allowing additional power to apply to it. The recast layer thickness drops, and the discharge column diverges as the gap voltage rises. [103]. According to Kumar et al., the TWR decrease when a cryogenically treated copper electrode is used during the EDM of Inconel 718 with a dielectric embedded in natural graphite[104]. The coated carbide tool's increased electrical and thermal conductivities due to coarsening connection to TWR. Wong et al. [105] used Al-suspended dielectric to accomplish an accurate result on SKH-54 tool steel but not on AISI-01, emphasizing the importance of workpiece composition in the PMEDM process. Pecas and Henriques found that the surface quality improved over time as AISI H13 mold steel was machined with Si-impregnated dielectric.

Nevertheless, excessive dielectric flow caused surface quality to be compromised because of the instability in the machining zone [106] [51]. The dielectric's turbulent flow increases tool wear as well [54].

5. Minimizing challenges of aggregation in PMEDM

Authors, [107] To accelerate the machining process, studies with Ti powder suspended EDM is conducted. TiC deposition was feasible at powder densities of 5 J under and below. They discovered that a more significant discharge current and a smaller range of pulse on time promote carbide production. It was possible to create a TiC layer with a 2000 Hv hardness. Similarly, [99] studied the effect of surfactant in mold steel PMEDM (SKD61). Surfactant molecules coat the surface of waste and carbon dregs, preventing particle build-up. Surfactant is added to the PMEDM process, which reduces surface roughness and increases MRR by 40%. In 2010, experiments with manganese powder suspended in dielectric were carried out, and the amount of material eliminated was measured [87]. The study found that the fluid-migrated material's surface characteristics had changed. The findings demonstrated that hardness values increased when manganese and carbon percentages rose to 95 and 1.03, respectively. Surface alloying is favored by the short pulse on-time and low peak current. In [108] investigated, the performance of Al powder-based PMEDM with reverse polarity. It has been demonstrated that powder qualities have a considerable influence on machining characteristics. With increasing Al powder absorption and element size variation, surface integrity improves.

Similarly, [109] When cutting EN8-Carbon steel using a chromium powder-suspended dielectric, the material removal and tool wear rates were examined**.** The studies' findings show that while increasing tool diameter reduces tool wear, increasing tool diameter increases MRR. Authors in [110] Using graphite-suspended dielectric PMEDM and cold-treated copper electrodes, the machining performance concerning TWR studied. The results showed that cold-treated electrodes reduce tool wear with other graphite powders. The material removal rate and surface roughness were measured to mill a W300 die steel workpiece utilizing an electrolytic copper electrode and an Al powder and distilled water dielectric [111]. The experimental findings suggest negative polarity is chosen for a superior surface polish, while positive polarity is recommended for higher MRR. Authors in [112] investigated ASID3/HCHCR - Cold Work Steel with High Carbon and Chromium Contents for machining using PMEDM based on graphite and Cr powder. The results show that MRR increases as powder concentration rises and is influenced mainly by Peak current. The MRR also grows as tool lift time increases.

This study examined the impact of a mixed dielectric made of graphite powder, silicon carbide, and Inconel 718 [113]. MRR and TWR are measured to examine machining characteristics. A current of 18 A, an 85% duty cycle, and a tonne of 5s a dielectric with additional graphite powder was used to achieve the highest MRR. TWR was lowest for a current of 12 A, a duty cycle of 90%, and a tonne of 20 s with silicon carbide powder added as a dielectric. In [114], They looked at three types of metal matrix composites (MMCs): 65% SiC/A356, 10% SiC-50% quartz/Al, and 30% SiC/A359 for surface alteration. They used a mixed EDM technique with graphite powder. Microhardness rises as the density of the reinforcing particles grows. [115] studied how adding carbon nanotubes (CNTs) to PMEDM may produce a mirror-like finish on AISI-D2 steel. The surface topography of a workpiece was studied through experiments to determine the effects of peak current, pulse duration, and CNTs powder concentration.

The outcomes demonstrated that a true proposition's MRR and surface quality are improved by the addition of CNTs. The peak current and CNT concentration have a significant impact on MRR. [115] Using the Taguchi parameter design approach, the powder concentration effect in graphite powder mixed PMEDM for machining Ti-6Al-4V alloy was investigated. The SR and MRR are calculated to assess the impact of changes in various process parameters. The experimental results revealed that as peak current increases, so do SR and MRR. According to [116], Hydroxyapatite (HA) powder suspension in deionized water is used to mill Ti6Al4V alloys. According to SEM examination, an HA-rich layer forms on the workpiece as powder particles migrate from the dielectric. When high temperatures are reached with a very high pulse current and a brief pulse on time, a decomposed layer forms on the surface. Authors in [117] studied the impact of PMEDM with Si powder addition on Ti6Al4V machining. Response surface modeling was employed to simulate the tests, and the effects of changing different parameters on MRR and surface roughness were investigated (Ra). The SR and MRR are both enhanced by using silicon powder. Peak current that is high and powder concentration that is high combined improve MRR while lowering SR. EDM was combined with magnetic stirring and SiC abrasive in the examined titanium alloy. The chemical makeup and structural traits were discussed using SEM and X-ray diffraction (XRD) methods. The outcomes demonstrated the formation of a Sic layer with increased hardness. The layer quality and strength increased with an increase in pulse width. The TOPSIS (Technique for an order of preference by similarity to ideal solution) and GRA (Gray Relational Analysis) techniques were used to evaluate the efficacy of different process parameters while milling H-11 die steel using a copper electrode and mixed chromium powder EDM. The experiment results demonstrate that the surface finish can be improved by adding the proper size particles at the appropriate concentration [118].

The authors in [119] employed the PMEDM technology to add a new biomimetic nano-porous layer to the phase Ti alloy, improving the bio-mechanical anchoring of the implant. The surface created by the process enhances osteoblastic cells' adherence and proliferation (MG-63). Authors in [120] investigated the impact of process factors on the micro-hardness of workpieces made of H-11 die steel while utilizing EDM with mixed chromium powder to determine the impact on micro-hardness; process variables such as duty cycle, peak current, and pulse on time were changed. They calculated the material that traveled from the tool to the workpiece, involving SEM and EDS techniques. Experiments were conducted in [121] using a copper-tungsten electrode to machine a Ti6Al4V workpiece using nano aluminum powder mixed EDM. Using nano aluminium powder minimizes microcracks and crates, according to the investigation results, which improves the surface finish.

The homogeneous distribution of aluminum particles and the resulting carbide-enriched surface layer impacts transfer element alloying, enhancing surface osseointegration. [122] In the PMEDM of Ti-6Al-4V-ELI material, the effect of SiC powder concentration on particle deposition, subsurface structures, and surface topography was studied. The findings demonstrated that low pulse currents and higher suspended particle concentrations enhanced the material transfer mechanism. The current material transfer mechanism is depleted at very high pulses due to the scarcity of secondary discharges. [123] We examined the effects of combining micro powder aluminum oxide (Al2O3) for Inconel 825 workpieces. MRR, SR, and surface integrity were measured concerning how the process parameters changed. According to the experimental results, peak current, pulse on time, and gap voltage are improved by powder surface roughness as the primary parameters impacting SR and MRR. A brass electrode and aluminum powder addition EDM for cutting EN-19 grade steel was studied in [124]. According to the experimental findings, MRR is drastically impacted by Space voltage and Point current.

6. Minimizing challenges of aggregation in PMEDM

EDM, is one of the most popular non-traditional manufacturing techniques used to machine electrically conductive materials that are high strength and high hardness. PMEDM is an upgraded approach that solves the disadvantages of the standard EDM process and carries with it a great deal of hope for the future. Several researchers have conducted experiments with a wide variety of powder materials and different dielectrics in a variety of combinations. The purpose of this paper is to provide a concise synopsis of previously published research work that is based on the experimental investigation of PMEDM.

According to the current literature, adding the powder to a solvent in EDM improves MRR and surface quality and can help produce a smooth surface that resembles a mirror. Because the machining process is still poorly understood, PMEDM technology is widely utilized in the industry due to significant advantages over conventional EDM. More research is required due to the thermo-physical characteristics of the other powder particles. Due to PMEDM's high power consumption, the cost of purchasing dielectric fluid, and environmental constraints, its industrial application has also been constrained. Below are a few issues and challenges that will be addressed.

- The inter-electrode gap must be properly pumped, and the dielectric must be chosen appropriately for the powder particles to move without obstruction.
- PMEDM is more expensive than conventional procedures since it requires a substantial amount of powder to provide the surface treatment.
- It can be challenging to separate powder particles and trash when the suspended powder is non-magnetic.
- Powder particle aggregation and settlement issues at the tank bottom
- PMEDM is less environmentally friendly than traditional EDM due to the discharge of many harmful solid, liquid, and gaseous wastes.

Table 3. Summary of previous works

Ref. No.	Machining method	Inputs process parameter	Quality criteria	Multi response optimization technique	Method of determining weight	Optimization process parameters			Determination of optimal parameters of authors
						Ranking index	Ranking index of S/N	Compare results	
[125]	PMEDM	Cp, I, Ton, Tau, U	MRR SR, WLT and HV	GRA	Simple average formula	Cp =3gm/l, I = 6A, Ton = 150 ms, Tau =80%,U = 40V	Cp = 6gm/l, I= 3A, Ton = 150 ms, Tau = 90%, U = 50V	Different	Ranking index
[126]	PMEDM	Ton, Tof, I, powder	SR and HV	GRA	Simple average formula	Ton = 100 ms, Tof = 50 ms, I = 9A, Powder = graphite	Ton = 100 ms, Tof = 10 ms, I= 3A, Powder = graphite	Different	Ranking index
[127]	PMEDM	Cp, I, Ton, DC, U	MRR, TWR, SR and EWR	TOPSIS	Simple average formula	Cp = 6 g/l, I = 6A, Ton = 100 ms, DC = 90%, U = 50 V	Cp = 6 g/l, I = 3A, Ton = 150 ms, DC = 70%, U = 30 V	Different	Ranking index
[128]	EDM	I, Ton, TW, Tup	WLT, SR, SCD and OC	RSMTOPSIS	Fuzzy technique	I = 1A, Ton = 10 ms, TW = 0.2 s, Tup = 1.5 s	I = 5A, Ton = 150 ms, TW = 0.6 s, Tup = 0.0 s	Different	Ranking index of S/N
[129]	EDM	I, Ton, Tau	MRR, SR, and ROC	TOPSIS and GRA	Simple average formula	I = 2A, Ton = 150 ms, Tau = 70	I = 8A, Ton = 50 ms, Tau = 90	Different	Ranking index of S/N
[130]	EDM	Wt, Ton, Tof, WF, S	MRR and TWR, SR CS, MRR, SR, and DD	DENG'S	AHP	Zinc coated, Ton = 32 ms, Tof = 6 ms, WF = 60 mm/min, S = 4 mm/min	Zinc coated, Ton = 32 ms, Tof = 6 ms, WF = 60 mm/min, S = 4 mm/min	Similar	Ranking index

Figure 11 summarizes the causes of the powder aggregation problem in the PMEDM environment. Precipitated powder particles, accumulated debris, and dissolved particles from the dielectric liquid are the main idea of outer and inner aggregation in PMEDM. The study's results showed the effect of the aggregation phenomenon on the performance of the PMEDM machine, represented by spark breakdown and a decrease in the material removal rate [131].

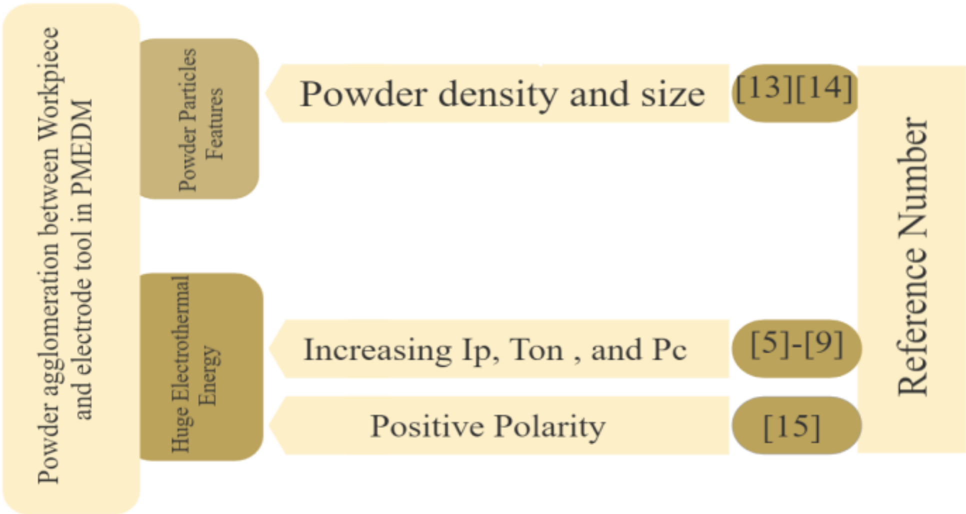


Figure 11. Schematic summary illustrating the cause of powder aggregation in PMEDM

Hence, manufacturing industries enthusiastically request technological improvements to improve surface finish, reduce short circuits and enhance material removal rate. This review paper is a detailed report on the short-circuit phenomenon and sparks breakdowns. During the PM - EDM process, when processing various work materials, adding different powders to the insulating liquid, and using a composite electrode, the reasons for its occurrence and ways to reduce it are discussed.

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