



Review article

A systematic review on powder mixed electrical discharge machining

Ayanesh Y. Joshi^{a,*}, Anand Y. Joshi^b^a Mechanical Engineering Department, A. D. Patel Institute of Technology, New V. V. Nagar, Karamsad, Gujarat, India^b Mechatronics Engineering Department, G. H. Patel College of Engineering & Technology, V. V. Nagar, Gujarat, India

ARTICLE INFO

Keywords:

Electrical engineering
Industrial engineering
Mechanical engineering
Nanotechnology
Metallurgical process
Powder additives
Process parameters
Dielectric
Powder mixed EDM (PMEDM)
Material removal rate
Surface Roughness

ABSTRACT

The advancement in the field of material science has gifted us new electrically conductive materials having good mechanical properties and thermal characteristics. Machining these materials using conventional machining process is a challenging task. Electrical discharge machining (EDM) is a well-established machining process used to manufacture process hard materials having geometrically complex shapes, that are extremely difficult to machine traditionally. EDM is a thermo-electric process in which material is eroded by rapidly recurring sparks between the non-contacted electrode and workpiece. As there is no direct contact between the electrodes in EDM, machining defects like mechanical stresses, clattering & vibration do not create problems during machining. In spite of the advantages of the process, its use in industry is limited owing to poor surface finish and low volumetric material removal. To overcome these drawbacks, the metallic powder is mixed in the dielectric fluid, which increases its conductive strength and increases the spark gap distance between the tool and workpiece. This new evolved material removal process is called Powder Mixed Electrical Discharge Machining (PMEDM). The added powder significantly affects the performance of the EDM process. The objective of this review is to benefit the researchers to understand the PMEDM concept precisely and study the process parameters furthermore in particulars to get enhancements in the process to achieve better quality levels.

1. Introduction

In recent years, an emerging drift of using compact, light-weighted and slim components (mechanical) in aerospace, automobile, medical and nuclear reactor industries have led to the development of the hard materials having properties like high strength and temperature resistant for numerous applications. These materials are not only harder, tougher, less heat sensitive and more resistant to corrosion but also more difficult-to-machine [1]. Conventional Machining of complex shapes with high surface finish and low tolerances at economic cutting speeds is extremely challenging, which demands new technologies, traditional or Non-traditional to machine these 'difficult-to-machine' materials with precision and ease [2]. Electrical discharge machining (EDM) is extensively used to machine such a 'difficult-to-machine' and high strength and temperature resistant (HSTR) alloys. These materials are generally used in the die and mold making industries [3]. In 1770, physicist, Joseph Priestly discovered the erosive effect of electrical discharges on metals. Later EDM process was conceived by Russian scientists, Dr. N.I. Lazarenko and Dr. B.R. Lazarenko in 1943. Erosion of material was observed by intermittent arcing in the air between electrodes which were

connected to DC power source. The accuracy of the process was very less due to the overheating of the machining region [4, 5]. In the early days' resistance-capacitance (R-C) type of power supply also known as the Lazarenko, the circuit was used as a spark generator for EDM machines. In the era of 1960s difficulties with weak electrode got reduced by the inventions of orbiting systems and the use of pulse and solid-state generators. Number of electrodes used to make cavity reduced in the 1970s because of the development. In the 1980s the first generation of computer numerical controlled (CNC) EDM was introduced in the United States of America which raised the efficiency of EDM extraordinarily. CNC control system made smoother finishing cut possible because of Unattended and Self-regulated machining.

Electrical discharge machining (EDM) is a non-traditional thermo-electric machining process in which material is removed by series of electric sparks that are generated between tool and work when the electrodes are held at a small distance from each other in a dielectric medium and a high potential difference is applied across them [6, 7]. Due to these sparks, localized regions of high temperatures are formed causing melting and vaporization of workpiece material. The first spark occurs where the inter-electrode gap is smallest. Inter electrode gap

* Corresponding author.

E-mail address: ayjoshi@adit.ac.in (A.Y. Joshi).

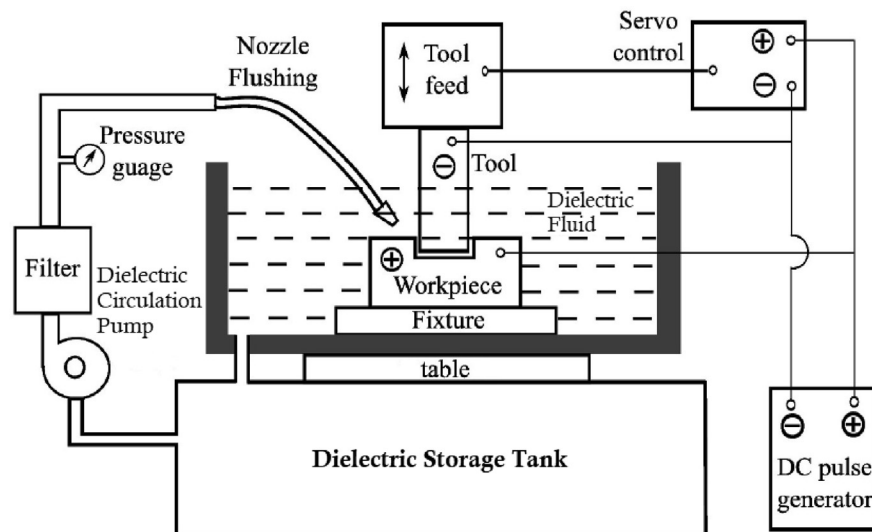


Figure 1. EDM setup.

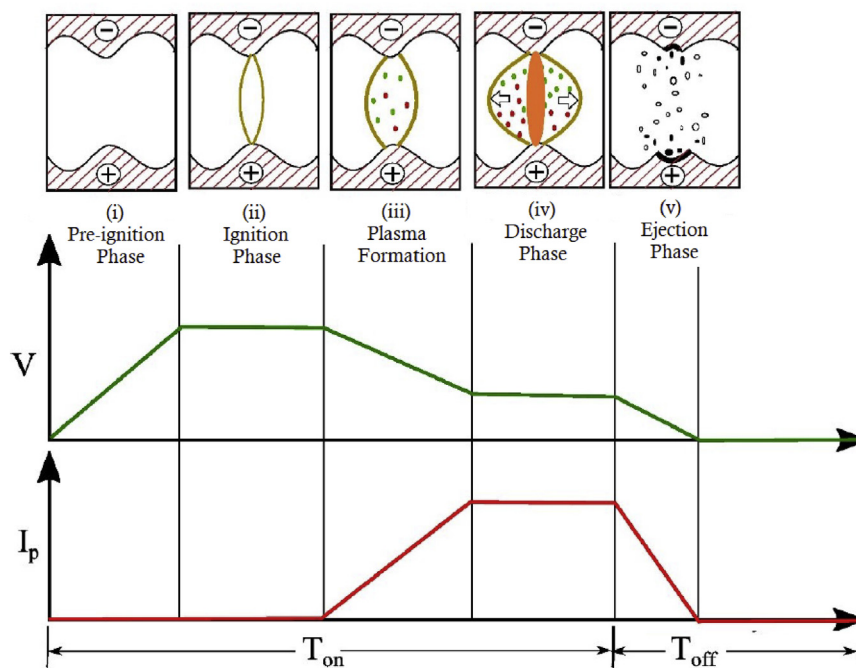


Figure 2. Mechanism of Material removal in EDM.

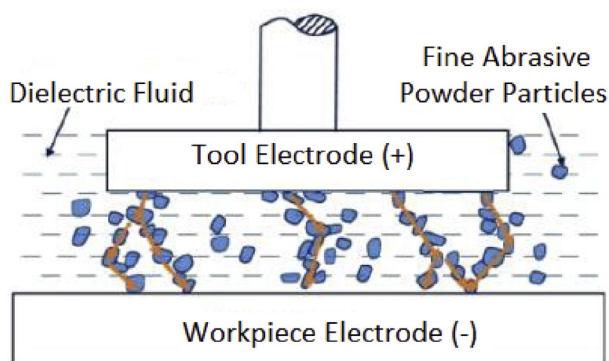


Figure 3. Principle of PMEDM.

increases because of material removal and hence the successive spark location shifts to another point. Likewise, a series of sparks occur at different locations on the workpiece analogous to the electrode gap. This process enables machining of any material, which is electrically conductive, irrespective of its hardness, shape or strength [8, 9]. Nevertheless, EDM is used to easily machine complex shapes, the process has certain limitations like poor surface finish, high tool wear ratio (TWR) and low material removal rate (MRR) [10, 11]. Hence, technological improvements are enthusiastically sought after by the manufacturing industries to improve the surface finish and the machining efficiency of EDM.

2. EDM process

The material removal mechanism of EDM is not absolutely identified and is still argumentative, it is the most accepted and

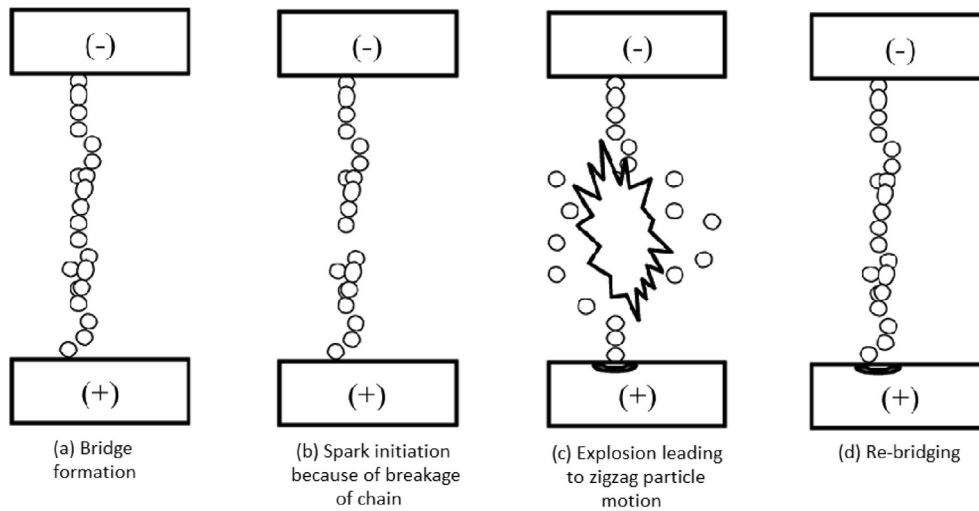


Figure 4. Mechanism of PMEDM.

established material erosion mechanism. The working principle is based on a thermo-electric model wherein electrical energy is transformed into thermal energy through numerous discrete electrical discharges befalling between two electrodes that are tool and

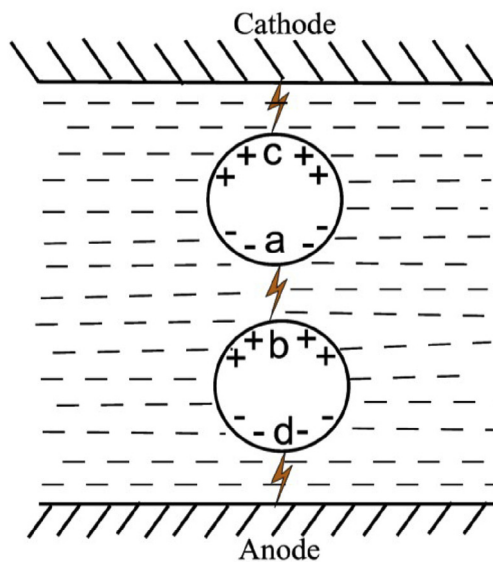


Figure 5. Series discharging in PMEDM.

workpiece which are immersed in dielectric fluid upon generation of suitable electrical potential difference [12]. Electrons are emitted from cathode because of the potential difference. These emitted electrons from cathode rush towards the anode and collide with the dielectric fluid, breaking them into electrons and positive ions. A narrow column of ionized dielectric fluid molecules is established between the electrodes causes a spark. The formed plasma channel raises the temperature in the range of 8000 °C to 20000 °C, because of which melting and evaporation of both electrode and workpiece take place creating a crater on the surface of the workpiece. The plasma channel breaks down when the pulse is turned off and circulating dielectric fluid flushes out machined material in the form of microscopic debris from the inter-electrode gap. Likewise, a series of craters are produced on the workpiece surface resulting into a rough machined surface [13, 14]. Figure 1 shows a typical EDM setup.

3. Mechanism of Material removal in EDM

The material removal process in EDM is explained with the help of Figure 2. Ignition Phase: high potential difference is applied between two non-contacting electrodes (Figure 2 (ii)). The electric field enhances in the inter-electrode gap as the electrode moves towards the workpiece until the dielectric breakdown voltage is reached. Normally the discharge occurs between the closest point on the Tool and Workpiece. The location might change if debris or impurities are present in the aforesaid gap. Plasma Phase: Once the plasma channel forms the currents start flowing through the channel and the Voltage drops as the dielectric ionization take place (Figure 2(iii)). Discharge Phase: Workpiece receives

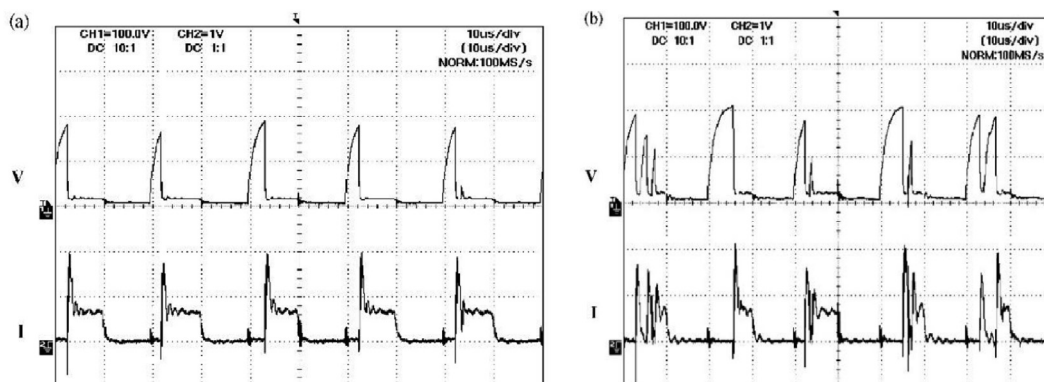


Figure 6. –Voltage and Current waveform (a) conventional EDM – Pure water Dielectric, (b) PMEDM – Pure Water added with SiC powder [23].

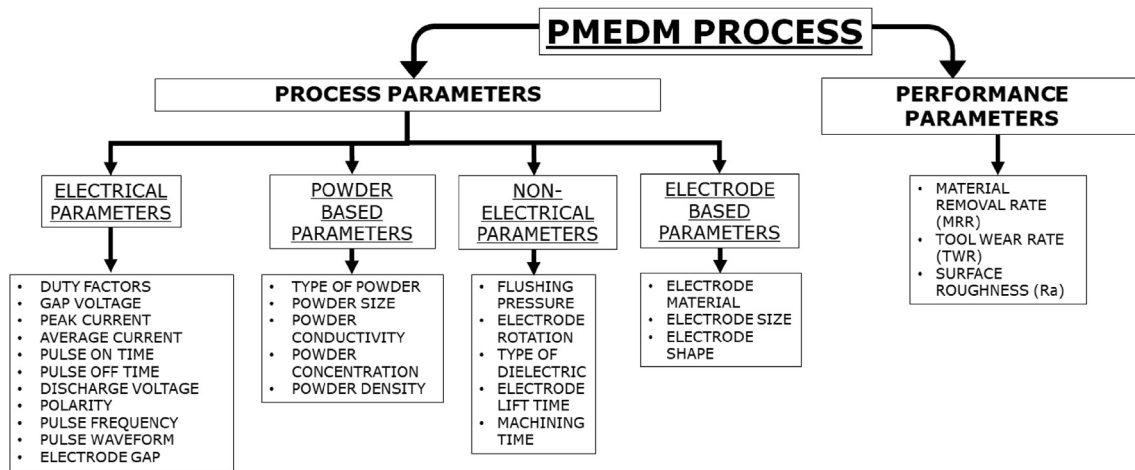


Figure 7. Parametric analysis of PMEDM process.

Table 1. Properties of typical dielectrics used in PMEDM [44].

Dielectric Name	Specific heat (J/kg-K)	Thermal conductivity (W/m K)	Breakdown strength (kV/mm)	Flashpoint (°C)
Deionized water	4200	0.623	65–70	Not Applicable
Kerosene	2100	0.14	24	37–65
Mineral oil	1860	0.13	10–15	160
Silicon oil	1510	0.15	10–15	300

continuous heating as there is a constant attack of ions and electrons on the electrodes which ultimately lead to intense heating of the workpiece. Because of this continuous flow of discharge current, the temperature increases and forms a small molten metal pool on the electrode surfaces. Some of the molten metal vaporizes directly. In this phase, the size of the molten metal pool keeps on increasing as the plasma channel keeps widening (Figure 2(iv)). Ejection Phase: During this phase, the plasma channel collapses as the voltage is shut and the pressure exerted by the neighboring dielectric. This creates a tiny cavity at the surface of the workpiece as the molten metal pool is powerfully drawn into the dielectric (Figure 2(v)). The infinitesimal small quantities of the workpiece material is removed in molten metal form, which solidifies and forms debris. Dielectric flushing through the inter-electrode gap washes this debris away from the discharge zone. The increase in the gap after the spark changes the position of the next spark where the electrodes are closest. Likewise, a facsimile of the opposite nature is formed on the workpiece surface because of thousands of such electric discharges taking place at numerous locations.

The generation of very high temperature and rapid cooling down causes re-solidification of the molten metal and forms a recast layer on the machined surface [15]. Properties like Corrosion resistance,

wear-resistance, and fatigue strength are hampered due existence of microcracks of this layer. To reinstate the surface integrity post-machining operations are mandatory [16]. In spite of the EDM process's capability of machining any electrically conductive material, its application in industries is limited due to poor surface quality, low surface integrity, and low productivity. Researchers have developed new and improved variants of the EDM process to enhance process performance. Some of the techniques are Rotary EDM (REDM), Ultrasonic EDM (UTEDM), Powder-mixed EDM (PMEDM), Near dry EDM, Magnetic assisted EDM (MAEDM), etc...

4. PMEDM process

Powder Mixed EDM (PMEDM) is an advanced EDM technology in which fine abrasive electrically conductive powder is added in the dielectric. Suspended metallic powders in dielectric decrease its insulating strength and consequently increases the inter-electrode gap conditions, which improves EDM performance and delivers superior surface finish compared to conventional EDM. The working principle of the PMEDM process states that upon application of appropriate voltage an electric field is generated which gives rise to positive and negative charges on the powdered particles. These energized powder particles get accelerated and start moving in a zigzag manner which leads to improving the spark gap between electrodes. In the direction of current

Table 3. Effect of operating condition on side clearance [35].

Rate of Cutting	Finish	Clearance (Side in mm)
Very Slow	Fine	0.03–0.06
Medium	Medium	0.2–0.3
Rapid	Course	0.5–0.6

Table 2. Economic and Technical considerations of various PMEDM electrode materials [35, 45].

Material	Density (g/cm ³)	Melting temperature (°C)	Thermal conductivity (W/m.k.)	Material Removal Rate	Tool Wear Rate	Cost	Manufacturing
Copper	8.96	1084	401	High for Rough Machining	Low	High	Easy
Brass	8.73	930	159	High for Finishing	High	Low	Easy
Tungsten	19.25	3695	173	Low	Lowest	High	Difficult
Tungsten Copper Alloy	15.2	3500	27.21	Low	Low	High	Difficult
Cast Iron				Low	Low	Low	Easy
Carbon steel	7.85	1460	51.9	Low	High	Low	Easy
Zink based Alloy	7.14	693	116	High for Rough Machining	High	High	Easy (Die Casting)
Graphite	1.811	3350		High	Low	High	Difficult

Table 4. Properties of various additives powders.

Material	Density (g cm ⁻³)	Thermal conductivity (W cm ⁻¹ °C ⁻¹)	Electrical conductivity (μ Ω cm ⁻¹)	Melting point (°C)	Specific heat (cal g ⁻¹ °C ⁻¹)	Remarks
Aluminum (Al)	2.70	2.38	2.45	660	0.215	Reduces TWR, improves the shape of the machined profile and leads to mirror finish surfaces [46].
Chromium (Cr)	7.16	0.67	12.7	1875	0.11	Improve the machining efficiency and electrode wear ratio tended to decrease [24].
Silicon Carbide (SiC)	3.21	1–5	1 × 10 ⁹	2975	0.18	MRR, TWR and Surface roughness increases [23].
Silicon (Si)	2.33	1.5	1 × 10 ⁵	1410	0.17	Addition of Si powder to dielectric reduces the surface roughness [47]
Tungsten (W)	19.3	1.673	5.6	3410	0.031	Surface micro hardness increases, which increases part life [48].
Titanium (Ti)	4.72	0.22	55	1668	0.125	Surface hardness increases and fewer micro-cracks are observed on the surface [49].
Molybdenum Disulfide (MoS ₂)	5.06	0.138	106	1185	0.07	MRR, profile depth and machined surface quality is improved [50].
Boron Carbide (B ₄ C)	2.52	2.79	5.5 × 10 ⁴	2763	-	Efficient discharge distribution capabilities of the powder improves MRR and machining efficiency remarkably [51].
Graphite (Gr/C)	1.3–1.95	0.25–4.70	500–3000	4550	0.17–0.20	Graphite powder increases electrical conductivity and provides lubricity, these result in MRR improvement and reduction in TWR.
Molybdenum (Mo)	10.2	1.39	5.27	2610	0.06	EDM wires are made from Molybdenum as it has properties like high tensile strength and good conductivity.
Alumina (Al ₂ O ₃)	3.98	0.251	103	2072	0.17	Surface finish and topography has improved by addition of nano-sized alumina powder [52].
Carbon nanotubes (CNTs)	2	4	50	2800	-	The addition of CNV particles decreases surface roughness, reduces the length and width of surface cracks and thickness of the recast layer [53].

flow particles, interlocking takes place. This chain helps in bridging the discharge gap between electrodes and thereby insulating strength of the dielectric fluid decreases and the spark gap increases. Figures 3 and 4 illustrate the Principle of Powder Mixed EDM and Mechanism of PMEDM respectively.

5. Mechanism of Material removal of PMEDM

In PMEDM, an electrical field of intensity 105–107 V/m is generated when a voltage of 80–320 V is applied across the electrodes because of which Positive and Negative charges accumulate at the top and bottom of the powder particles respectively [17]. Foremost discharge breakdown occurs where the electric field density is the utmost (between 'a' and 'b' in Figure 5). This breakdown may be between powder particles or between powder particles and tool or workpiece electrode. After the first discharge relocation of electric charges takes place which then gathers at point 'c' and 'd'. Depending upon the electric field density series of sparks keeps on occurring further [18, 19]. Interlocking between different powder particles forms a chain that causes easy short-circuiting and leads to an early explosion in the gap [20]. The combined effect of particle bridging and suspended additive particles modifies the plasma channel reduces the discharge power density and pulse explosive gas pressure.

5.1. Enlargement of discharge gap

The discharge gap size mainly depends upon the physical and electrical properties of powder particles. The presence of free electrons in powder particles at high-temperature conditions reduces dielectric resistance. Hence spark can be generated from a longer distance which practically enlarges the discharge gap [21, 22].

5.2. Widening of discharge passage

Powder particles get energized and start moving hastily along with ions and electrons after the first discharge. More electrons and ions are generated as these powder particles colloid with dielectric molecules and thus produce more electric charges compared to conventional EDM. This phenomenon reduces hydrostatic pressure acting on the plasma channel

thereby increased the discharge gap. This widened discharge column forms large shallow cavities on the surface.

5.3. Multiple discharges

Multiple craters in a single pulse are formed because of the uniform distribution of energy because of the rapid Zigzag movement of the particles. Voltage vacillates hastily during a single pulse duration due to multiple discharges [22, 23]. Figure 6 represents a typical waveform of current and voltage (a) for conventional EDM – Pure water Dielectric, (b) PMEDM – Pure Water added with SiC powder [23].

6. PMEDM process variables

PMEDM Parameters are majorly classified into two categories: Process parameters, are controllable machining input variables that govern the machining performance and Performance Parameters, are used to gauge process performance under selected process parameters. Figure 7 illustrates the parametric analysis of the PMEDM process.

6.1. Electrical parameters

6.1.1. Peak current (I_p)

In every single pulse-on time the current rises till it reaches pre-set level. The surface area of the to be machined workpiece governs the amperage requirement. An increase in pulse on current increases plasma channel pressure as number of electrons and ions per unit area increases. Increased current allows easy ejection of material as the specific impulsive force enhances [25, 26]. Hence high peak currents are used in roughing operation or to machine larger surface area. Higher peak currents improve MRR but at the cost of compromising Tool wear rate and surface integrity. The development of improved electrode materials like Graphite electrode allows operating at higher currents comfortably.

6.1.2. Discharge voltage (V)

Open gap voltage increases till it creates an ionization path through the dielectric for the current to flow. The open-circuit voltage drops as the currents start flowing through the plasma channel until it stabilizes. A

working gap between two electrodes can be set by selecting an appropriate voltage. The selection of discharge voltage depends upon the breakdown strength of the Dielectric and inter-electrode gap [27]. Discharge voltage influences spark energy and thereby MRR, TWR and SR.

6.1.3. Pulse-on time (T_{on})

It is the time for which current is allowed to flow per cycle. It is generally communicated in microseconds. The ionization of dielectric takes place during this period. The amount of energy applied during the pulse on-time decides the amount of material removed [28]. For longer pulse on-time more energy is focused on the workpiece resulting in a broader and deeper crater, the recast layer will be larger and the heat-affected zone will be deeper. As machining will be done only during pulse on time the duration of pulses and the frequency of pulses are critical parameters.

6.1.4. Pulse-off time (T_{off})

Pulse off time is the duration for which supply voltage is cut off. Basically, it is the intermediate time between two pulse-on times. During this period dielectric regains its strength by de-ionizing and the debris is washed away from the spark gap. As no machining is done in the phase it's time should be minimum. But decreasing Pulse off time might lead to process instability because of improper and inefficient flushing.

6.1.5. Duty cycle (τ)

It is the ratio of Pulse on time to total cycle time. Higher duty cycle value indicates that during the pulse spark energy is supplied for longer duration resulting in higher MRR. When the duty cycle becomes too long process becomes unstable because of improper flushing [29, 30].

6.1.6. Polarity

The polarity of the electrode can be negative or positive. Positive Polarity states that the workpiece is connected to the positive polarity and the tool is connected to negative polarity. Excess material will always be removed from the electrode which is connected to positive polarity. Operating with positive polarity maximum energy is available at anode delivering significant material is removed from the workpiece. During longer discharges, as the proportion of ion flow increases with pulse duration high tool wear takes place. In practice, Tool and Workpiece material, Pulse length durations and Current density are affecting parameters for selection of polarity. The latest power supply units generate an opposite polarity swing pulse for every 15 standard pulses to prevent arcing.

6.1.7. Electrode gap

Performance of PMEDM process is largely dependent on the stability of spark and efficiency of flushing. Gap stability and System's reaction speed are of the utmost importance for better performance. The reaction speed should be high enough to respond to open gap conditions. Average gap voltage readings are used to measure the prevailing gap width. Electro-mechanical or Electro-hydraulic servo systems are employed to maintain the desired gap.

6.1.8. Gap voltage

The time required to bridge the inter-electrode gap with electrons and ions increases as the spark gap increases which results in a reduction in MRR [31]. Higher the Gap voltage better is the surface finish [32]. The thickness of the recast layer increases as expansion in the spark gap allows more power into it. At a higher gap voltage discharge column is diverged hence, recast layer thickness reduces [33].

6.2. Non-electrical parameters

6.2.1. Dielectric flushing

High dielectric strength, Effective quenching, Hasty post breakdown recovery, Flushing ability and a good degree of fluidity are the main

characteristics of EDM Dielectric. Efficient flushing is mandatory because the presence of debris in the inter-electrode gap reduces process efficiency and might initiate arcing which deteriorates dimensional accuracy as well as surface integrity. Type of dielectric and its flushing technique has an effect on MRR, TWR, crack density and recast layer thickness [34]. Various flushing techniques are available like Side flushing, Suction through the electrode, Pressure through the electrode, Jet flushing, Vacuum flushing, Injection flushing [35]. The latest technology is to use servo-controlled cyclic reciprocation or vibrating tool electrode which will create a hydraulic pumping action that helps chip removal from the inter-electrode gap.

6.2.2. Workpiece rotation

Rotary motion given to the workpiece improve the temperature distribution and circulation of the dielectric fluid yielding improvement in SR and MRR [35]. Along with the rotary motion of the workpiece, if the machining axis is made horizontal, debris evacuation and erosion efficiency improve [36, 37, 38, 39].

6.2.3. Electrode rotation

Surface quality, MRR, and machining process stability improve as Vibro-rotary motion improves inter-electrode gap flushing [40, 41, 42]. Due to the rotary motion of the electrode alloying of migrating elements and debris is also observed [43].

6.2.4. Dielectric fluid

The three basic functions of dielectric fluid in PMEDM process are; (i) It acts as an insulating medium though flow of currents occurs after breaking down upon application of suitable voltage, (ii) Flushing of debris from the inter-electrode gap thus clearing machined area (iii) It acts as medium to carry away the heat from the electrodes which is generated by the discharge. Mineral Oils, Kerosene, deionized water, Light Transformer Oil, EDM oils and Synthetic oils are examples of commonly used EDM oils. Properties of typical dielectrics used in PMEDM are given in Table 1.

6.3. Electrode based parameters

6.3.1. Electrode material

The characteristics that define appropriateness of good PMEDM electrode material are, Electrode should achieve maximum material removal rate, should have less tool wear rate and it can be manufactured into desired shape and size economically. Various electrode materials are Brass, Copper, and copper alloys, Copper Tungsten, Graphite, Molybdenum, Silver tungsten, Tellurium copper, etc. Table 2 represents a comparison of various materials on the basis of economic and technical considerations.

6.3.2. Electrode size and shape

The performance of PMEDM depends upon the shape configuration of the electrode as the process produces a mirror image of the tool on the workpiece. A minimum amount of clearance is always provided between the work cavity to be produced and the tool electrode. The magnitude of clearance varies with tool and workpiece material combination and material removal rate hence, different tools are to be used for roughing operations and finishing operations. Table 3 Correlates Rate of cutting, clearance values and type of finish.

6.4. Powder-based parameters

6.4.1. Type of powder

The addition of powder in dielectric increases material removal rate, improves the surface quality and reduces tool wear rate. Different powders have a different effect on process performance. Some of the powder characteristics that affect performance are; Electric conductivity, Suspension capabilities, Thermal conductivity, and Non-magnetic nature.

The addition of inorganic oxide powders does not result in improvement in performance characteristics they disperse non-uniformly in the dielectric. Properties of various powder materials are listed in Table 4.

6.4.2. Powder size

Additive particle size is an influential parameter in machined surface quality [54]. Experimental results indicate that the inter-electrode gap is more in the case of larger particles which results in greater contamination and lower deionization between the workpiece and tool. Larger powder size increase in the gap but increases surface roughness and reduces MRR [55].

6.4.3. Powder conductivity

The addition of electrically conductive fine powder in dielectric results increases in the discharge gap which improves the flushing of debris and enhances spark frequency [52, 56]. Shallow craters are formed on the workpiece surface as high thermal-conductivity of these particles confiscate a large amount of heat from the inter-electrode gap [57, 58].

6.4.4. Powder concentration

MRR is augmented by increasing powder concentration as it multiplies the number of discharges [61]. Surface roughness is reduced as the energy per spark is reduced [59]. An optimum powder concentration is required as a continuous increase in concentration increases the extent of powder particles in the discharge gap which in turn impede the transfer of discharge energy to the workpiece. This leads to short-circuiting and arcing thus reducing MRR and Surface quality [60].

6.4.5. Powder density

The density of the powder particle is affected by the surface forces which allows uniform particle distribution in the dielectric. Lower density helps in balancing these forces and also reduces powder quantity requirement as the amount of powder settling down at the tank bottom reduces [62].

6.4.6. PMEDM Performance Parameters

Performance quality of PMEDM process is measured by various factors like Material Removal Rate (MRR), Tool Wear Rate (TWR), Wear Ratio (WR), Surface Roughness (SR) and Surface Quality.

6.4.7. Material removal rate (MRR)

The volume of material removed per unit time is MRR. It is the most important factor looking for a manufacturer's perspective and every manufacturer wants to maximize it. In the case of PMEDM process Low melting point materials have high MRR and low surface finish [63]. Peak current and Pulse on time are the major affecting parameters to MRR. EDM process has low MRR compared to conventional machining processes.

Material Removal Rate

$$\text{MRR}(\text{mm}^3/\text{min}) = \frac{\text{Workpiece weight loss(g)} \times 1000}{\text{Density(g/cm}^3) \times \text{machining time(min)}} \quad (1)$$

6.4.8. Tool wear rate (TWR)

TWR is the rate at which material is eroded from the Tool electrode. It is calculated by taking a ratio of loss of weight of the electrode and the time of machining. TWR is very important as the precision with which the part is machined is affected as it affects the electrode profile.

Tool Wear Rate

$$\text{TWR}(\text{mm}^3/\text{min}) = \frac{\text{Tool weight loss(g)} \times 1000}{\text{Density(g/cm}^3) \times \text{machining time(min)}} \quad (2)$$

6.4.9. Wear ratio (WR)

WR is the ratio of Tool wear rate and Material removal rate. For different tool and workpiece material combination, values of MRR and

TWR are different. An optimum tool-workpiece material pair is to be selected which gives the lowest WR value.

Wear Ratio

$$\%WR = \frac{\text{Tool wear rate}}{\text{Material removal rate}} \times 100 \quad (3)$$

6.4.10. Surface roughness (SR)

SR is generally measured in arithmetic mean (Ra) terms, according to ISO 4987:1999 is defined as the arithmetic average roughness of the deviations of the roughness profile from the central line. It is the measure of surface texture. Surface roughness increases with an increase in discharge current and pulse on time as heat is focussed on the workpiece for prolong time resulting in deeper and wider craters [64]. Optimum surface finish is achieved at low operating currents [65, 66].

6.4.11. Surface quality

It is a measure of surface roughness, recast layer thickness, heat-affected zone, and micro-cracks density. Recast Layer is formed due to the deposition of rapidly cooled unflushed molten material due to improper flushing. Heat-Affected Zone (HAZ) is a layer of parent material below the recast layer with altered metallurgical properties. The material below this zone is not affected by the process. Researchers have also tried to use PMEDM as a surface treatment process [66].

6.5. Applications of PMEDM

PMEDM is a good replacement for conventional EDM to manufacture parts necessitating High Surface integrity. PMEDM is used to manufacture automobile parts, medical implants, and Surgical Equipment.

- PMEDM results in a mirror-like reflective surface near mirror-like surface finish characteristics.
- PMEDM is also used as a surface modification and treatment process as it can improve surface microhardness, corrosion resistance, and reduced friction coefficient.
- Intricate profiles, Complex 3D shapes, thin and fragile components can be machined successfully using the PMEDM process irrespective of their strength and hardness.
- Manufacturing of micro-sized sophisticated mechanical elements like micro-engines, micro gears, microturbine rotors, micro-pumps is possible using the PMEDM process.
- Nano Powder Mixed EDM increases the biocompatibility of materials and hence can be used to manufacture biomedical implants.
- Application of PMEDM in machining advanced material like Metal Matrix Composite (MMCs) Materials is perceived promising.

6.6. Literature review

In 1980, Erden and Bilgin investigated the effect of powder additives in the dielectric fluid while machining of mild steel. An increase in the machining rate was observed with increased impurities concentration. At a higher level of abrasive powder concentration due to early breakdown characteristics, short-circuiting occurs results in poor machining characteristics [67].

Jeswani M.L., et al., (1981) studied the effect of adding 10 μm sized graphite powder into kerosene and the experimental results indicated that 4 g/l addition of fine powder increase MRR by 60% and lowers TWR 30% and machining process stability increases [68].

In the year 1983, Koshy investigated that the desired surface property of the workpiece can be attained by adding powder particles into a dielectric fluid. Carbides are formed by disassociation of the carbons of hydrocarbon-based dielectric and the added doping elements [69].

Narumiya H., et al., (1989) used Al, Si and Gr powder in the concentration range of 2 g/l to 40 g/l. The results showed that an increase in powder concentration increases the inter-electrode gap distance. Gap

distance and the surface finish has no direct relation. Low powder concentration results in a better surface finish for Gr and Si powders [70].

Kobayashi K., et al., (1992) concluded that mixing of Si powder in dielectric for machining SKD-61 Tool steel improves surface finish. The addition of Al and Gr powder results in better surface finish compared to silicon powder [71]. Mohri, et al. reported that mirror-like surfaces are achieved by using Si powder mixed dielectric [72].

Yan and Chen (1994) reported the addition of powder particles reduces surface cracks and improves the homogeneity of the recast white layer. Powder concentration between 02 g/ltr. To 05 g/ltr. results in the lowest surface roughness levels [73]. Yu and coworkers conducted experiments with Al powder to machine tungsten carbide. The results showed a spark gap enlargement and improved MRR due to better energy dispersion [74].

In 1995, Ming and He conducted experiments with a Copper electrode and high carbon steel workpiece. Results indicated that the addition of conductive powder and lipophilic surface agents reduces the tendency for crack inception and the extent of crack propagation on the machined surface. These additives can increase the surface microhardness and reduce the loss of alloy elements [75].

In 1998, Wong Y.S., et al., achieved a near mirror finish on SKH-54 tool steel with Silicon powder added PMEDM process at 1A current and 0.75Hz pulse on time. The machined surface was poised of smoothly overlapped, uniformly sized shallow craters [76]. Uno et al. used nickel powder mixed dielectric to modify the surface of aluminum bronze components. The addition of nickel powder improved the surface abrasion-resistant property by deposition of a layer on an EDMed surface [77].

Chow et al. (2000) conducted experiments for machining of titanium alloy using Al and SiC powders in kerosene for the micro-slit machining. The addition of these powders increases inter-electrode gap distance, resulting in higher MRR and efficient debris flushing [78].

In 2001, Furutani K. used titanium powder mixed kerosene as dielectric fluid to machine carbon steel with negative polarity. Results indicated a layer of titanium carbide (hardness 1600HV) is formed while operating at 3A peak current and pulse duration of 2 Hs [79]. Tzeng Y.F. examined the effect of powder characteristics on EDM machining efficiency. The results revealed that the suspension of 70–80 nm-sized powder delivers the highest MRR [54].

Peças P, et al., in 2003, experimented with Si powder-based PMEDM for the manufacturing of AISI H13 tool steel. Experiments were conducted to develop a relationship between pulse energy and surface roughness. Results, in particular, showed that for powder concentration of 2 g/ltr. highly reflective and smooth craters were developed [80].

In the year 2004, Klocke F. investigated the influence of the powder particles in micro-sinking-EDM and found out that AL mixed dielectric forms a large plasma channel using a high-speed framing camera (HFSC) technique. Experimental results revealed that concentration and type of the powder mixed in the dielectric are the major affecting parameters as they affect the discharge energy distribution. Powder's physical properties affect the recast layer composition and morphology [81].

Wu KL., et al., (2005) followed the Taguchi method and used surfactant along with Al powder in the dielectric to study the problem of powder settlement in the dielectric tank. Results stated that due to higher wetting capacity surfactant the agglomeration of powder is reduced and surface quality of the order 0.2µm is achieved. The negative polarity of the tool electrode delivered an increase in surface hardness [82]. H.K. Kansal et al. used a Response surface methodology to optimize the process parameters – Si powder concentration, Peak current, Pulse on time and duty cycle. The researcher reported that the addition of Si powder in dielectric improves surface finish and increases MRR [28].

In 2006, Kansal H.K., Singh, S., and Kumar, P. implemented RSM for investigating the machining performance of Metal Matrix Composite Al–10%SiCP using Aluminium, Copper, Silicon carbide and chromium powders as additives. Results indicated that the addition of fine powder increases MRR and reduces TWR [83].

Yeo S H., et al., (2007) conducted experiments at low discharge energies from 2.5µJ to 25µJ, with and without the addition of powder, results showed a substantial variance in crater morphology. Powder addition was resulting in smaller diameter circular shape craters [84]. H.K. Kansal et al. reported that the complexity of PMEDM process in-context with suspended particles thermos-physical properties deserves comprehensive exploration. The higher cost of powder, dielectric disposal, and environmental effects are the major issues to be addressed in the future for PMEDM. They also reported that the application of nozzle flushing at the interface does not have a significant effect on MRR [85].

Han-Ming Chow, Chowa, Lieh-Dai Yangb and Ching- Tien Lina (2008) investigated Sic powder-based EDM with pure water as a dielectric to fabricate micro-slits in Ti6Al4V alloy. They concluded that the suspension of SiC powder in pure water increases TWR and delivers a larger slit. Machined burr is less while using Sic PMEDM compared to pure water EDM [86].

Furutani K., et al., (2009) conducted experiments with Ti powder suspended EDM to accelerate the machining process and concluded that TiC deposition was possible at 5 µJ under and smaller powder density. They reported that a smaller range of pulse on-time and large discharge current helps in the formation of carbides. TiC layer with a hardness of 2000 Hv was achieved [87]. Kun Ling Wua, Biing Hwa Yanb, Jyh-Wei Lee and Chun Gian Ding investigated the influence of surfactant in PMEDM of mold steel (SKD61). Particle accumulation is decreased as surfactant molecules well cover the surface of the carbon dregs and debris. The addition of surfactant in the PMEDM process has shown improvement in MRR by 40 % but the surface roughness is deteriorated [88].

In 2010, Kumar S. & Singh, R conducted experiments with manganese powder suspended dielectric and analyzed the amount of material removal. The researcher found that the surface properties changes due to the migrated material from the fluid. Results showed that % of manganese and carbon increased to 95 and 1.03 respectively delivering microhardness increase. The low peak current and shorter pulse on-time favors surface alloying [89]. Sharma S., A. Kumar, N. Beri & D. Kumar analyzed Al powder-based PMEDM performance with reverse polarity. It was reported that machining characteristics are affected significantly by powder characteristics. An increase in the Al powder concentration and particle size change results in an improvement in surface integrity [90].

Ojha et al. (2011) analyzed Material Removal Rate and Tool Wear Rate with Chromium powder suspended dielectric for machining EN8 – Carbon steel material. Experimental results concluded that an increase in powder concentration increases MRR and an increase in Tool diameter reduces Tool wear [91]. Sharma S. et al. (2011) used cold treated copper electrodes and graphite suspended dielectric PMEDM to evaluate the machining performance in terms of TWR. Results revealed that the addition of graphite powder along with cold treated electrodes tends to reduce the Tool wear rate [92].

Syed & Palaniyand (2012) Used Al powder mixed distilled water as a dielectric in PMEDM to analyze Material Removal Rate and Surface Roughness while machining W300 die steel workpiece with an electrolytic copper electrode. Experimental results indicated that for higher MRR positive polarity is preferred and for better surface finish negative polarity is preferred [93].

Mathapathi U. et al. (2013) Analyzed Graphite & Cr Powder-based PMEDM for machining of ASID3/HCHCR - Cold Work Steel with High Carbon High Chromium contents. Results stated that MRR is most affected by Peak current and increases as the powder concentration increases. MRR also increases by increasing Tool lift time [94]. Bhattacharya et al. (2013) Used Tungsten, Graphite and Silicon powder in PMEDM to appraise the enhancement in machined surface properties of die steel material. The addition of Tungsten powder improved surface finish and microhardness of the machined surface [56].

Goyal Shivam, Singh Rakesh Kumar, (2014) Experiments were conducted with Al fine powder based PMEDM with copper electrode for AISI 1045 Steel machining by varying powder grain size and concentration.

Experimental results stated that MRR is reduced if the concentration of powder particles is very low or very high. Surface finish improves with the increase in Al powder concentration [95]. Mahendra G. Rath studied Effect of Aluminum oxide, Silicon carbide and Graphite Powder Mixed dielectric in EDM of Inconel 718. MRR and TWR are measured to analyze Machining characteristics. A current of 18 A, a Duty cycle of 85 % and Ton of 5 μ s with added Graphite powder in dielectric resulted in maximum MRR. 12 A current, duty cycle of 90 % and Ton of 20 μ s with silicon carbide powder added dielectric resulted in the lowest TWR [96]. Sarabjeet Singh Sidhu et al. examined surface alteration of different types of metal matrix composites (MMCs) 30vol%SiC/A359, 10vol% SiC-5vol % quartz/Al and 65vol%SiC/A356.2 adopting EDM graphite powder mixed EDM process. An increase in reinforcing particle density increases microhardness [97]. Harmesh Kumar, studied carbon nanotubes (CNTs) mixed PMEDM on AISI-D2 steel to achieve a mirror-like surface finish. Experiments were conducted to analyze the effect of peak current, pulse duration and CNTs powder concentration on work piece's surface topography. Results indicated that the addition of CNTs in a proper proportion improves MRR and surface finish. CNT's concentration and peak current have a major effect on MRR [98].

In the year 2015, Hussain et al. studied the effect of Al powder-based EDM on MRR of metal matrix composites (Al/SiC). Various process parameters were selected for conduction of experiments and the results showed that at 2A peak current MRR starts improving [99]. Bhiksha Gugulothu et al. Taguchi parameter design approach was used to investigate the powder concentration effect in graphite powder mixed PMEDM for machining of Ti-6Al-4V alloy. SR and MRR are measured to analyze the effect of change in various process parameters. Experimental results revealed that as the peak current increases SR and MRR also increases [100]. Nihal Ekmekci et al. Ti6Al4V alloys are machined using Hydroxyapatite (HA) powder suspension in deionized water. Scanning electron microscope results indicated that powder particles form HA rich layer on the workpiece as they migrate from the dielectric. Due to the attainment of high temperatures at a very high pulse current and small pulse on time a decomposed layer forms on the surface [101]. Murahari Kolli and Adepu Kumar conducted experiments with Surfactant & Gr powder added PMEDM for machining of titanium alloy. MRR, SR, and changes in Surface topography, as well as dielectric fluid behaviour, were measured. From the results, it was found that the addition of surfactant and graphite powder into the dielectric improved MRR and SR. The addition of surfactant reduced graphite powder and sediment particle agglomeration. Machining efficiency improved as the addition of surfactant in dielectric increases the conductivity and suspended debris particles in dielectric fluid reduced the abnormal discharge conditions [102].

Nipun D. Gosai & Anand Y. Joshi (2016) Studied the effect of Si powder added PMEDM for machining of Ti6Al4V. Response surface methodology was used to model the experiments and the effect of change in various parameters was studied on MRR and surface roughness (Ra). The addition of silicon powder improves SR and MRR both. A combination of high powder concentration and high peak current delivers improvement in MRR and reduction in SR [103]. L. Li et al. studied SiC abrasive mixed EDM with magnetic stirring for titanium alloy. SEM and X-ray diffraction (XRD) techniques were used to analyze the chemical composition and structural features. Results stated that SiC layer was formed with improved hardness. The layer strength and quality improved upon increasing pulse width [104]. S. Tripathy, D.K. Tripathy, Technique for an order of preference by similarity to ideal solution (TOPSIS) and Grey Relational Analysis (GRA) techniques were implemented to assess the efficacy of various process parameters using copper electrode and chromium powder mixed EDM in the machining of H-11 die steel. It is observed from the experimental results that the addition of properly sized particles in proper concentration improves surface finish [105].

Chander Prakash, H.K.Kansal et al. (2017) PMEDM technique was used to fabricate a biomimetic novel nano-porous layer on the β -phase Ti

alloy, which enhances bone-implant bio-mechanical anchorage. Results the surface generated by the process improves adhesion and growth of osteoblastic like the cell (MG-63) [106]. S. Tripathy, D.K. Tripathy, Investigated the process variable's effect on micro-hardness using chromium powder mixed EDM for H-11 die steel workpiece. Process parameters like a pulse on time, peak current, powder concentration, duty cycle were varied to analyze the effect on micro-hardness. SEM and EDS techniques were used to compute the migrated material from tool to workpiece [107]. A. M. Abdul-Rani, A. M. Nanimina et. Al. Experiments were conducted on nano aluminum powder mixed EDM to machine Ti6Al4V workpiece with a copper-tungsten electrode. Experimental results stated that the addition of nano aluminum powder reduces micro-cracks and craters thereby improving surface finish. Uniform distribution of Al particles and generated carbides enriched surface layer due to alloying of transfer elements improves osseointegration for the surface [108].

Tahsin T. Öpöz, Hamidullah Yaşar (2018), et. Al. Examined PMEDM of Ti-6Al-4V-ELI material for the influence of SiC powder concentration on particle deposition, subsurface structures, and surface topography. Results showed that low pulse currents and higher suspended particle concentration improve the material transfer mechanism. At a very high pulse, the current material transfer mechanism is depleted due to the scantiness of secondary discharges [109]. Vinay Kumar, Amit Kumar, et. Al. Studied the effect of aluminum oxide (Al₂O₃) micro powder mixed EDM for machining Inconel 825 workpiece. Process parameters were varied and the effect was measured on MRR, SR and surface integrity. It is observed from the experimental results that peak current, pulse on time and gap voltage are major affecting parameters on SR and MRR. The addition of powder surface roughness improves [110]. L. Selvarajan, J. Rajavel, et. Al. Reviewed EDM of various industrial demanded composite materials like in detail and explained the effect of varying parameters on process performance [111]. Suvan Dev Choudhury, Neelabh Jyoti Saharia, et. Al. Studied hybrid Powdered Mixed EDM with Aluminium and Multi-Walled Carbon Nano Tube (CNT) powders mixed in kerosene for EN19 alloy steel machining with brass electrode [112].

B. Surekha, T. Sree Lakshmi, et. Al. (2019) investigated aluminum powder added EDM for machining of EN-19 alloy steel using a Brass electrode. Experimental results suggest that MRR is significantly affected by Gap voltage and Peak current [113].

7. Challenges in PMEDM

It is observed from the available literature that the addition of powder into a dielectric fluid in EDM improves MRR, Surface integrity and can help to obtain mirror-like surface finish. Despite having considerable advantages over the conventional EDM process, the PMEDM process is used in industry at a very slow pace as the machining mechanism is still not well understood. Thermo-physical properties of the added powder particles require thoroughgoing investigation. High power consumption, dielectric fluid purchase, and disposal cost and environmental concerns have also restricted PMEDM's industrial application. Some of the issues and challenges that are to be addressed in the future are mentioned here.

- Proper selection of dielectric and its pumping mechanism is mandatory for powder particles smooth flow in the inter-electrode gap.
- The amount of powder required for surface modification application of PMEDM is very high compared to other conventional methods, which makes PMEDM expensive.
- Separation of powder particles and debris is very difficult when the suspended powder is non-magnetic.
- Agglomeration and settlement of powder particles at the tank bottom is an issue.
- Compared to the conventional EDM process, PMEDM is less environmental-friendly due to the discharge of a large number of toxic solid, liquid and gaseous wastes.

8. Conclusion

EDM is one of the most preferred Non-traditional manufacturing techniques used to machine high strength, high hardness electrically conductive materials. PMEDM is an improved technique, which holds a bright promise and overcomes the drawbacks of the conventional EDM process. Many researchers have experimented with different powder materials and various dielectrics combinations.

This paper presents a brief summary of published research work based on the experimental investigation on PMEDM. Few conclusions drawn from the present review are;

- Additive powder mixed dielectric used in PMEDM plays a significant role in improving material removal rate and reducing tool wear rate compared to conventional EDM process.
- Use of powder mixed dielectric helps to attain mirror-like surface finish, suspended additive powder particle alloying helps to modify Surface characteristics, Totally Burr free & no stresses produced in the workpiece.

9. Future scope

- Effect of Powder type, Powder particle shape & size, and Powder concentration on properties like microstructure, microhardness, fatigue resistance, corrosion and wear resistance needs a thorough study.
- Effect of Nanosized powder mixed dielectric need to be investigated as the smallest sized powder will have better suspension.
- In most cases, a flat-based dielectric storage tank is described in the literature. The influence of different tank bases needs to analyze as it affects powder particle settlement at the base and in the corners.
- The influence of tank volumes was employed, need to investigate the influence of different volumes on PMEDM performance and determine the optimal volume.
- Very less amount of literature is available for the application of EDM and PMEDM in biomedical implants machining. It will be advantageous to investigate the application of PMEDM in biomedical implant manufacturing.
- Very few research literature is available on powder mixed EDM of Metal Matrix Components (MMCs) and Electrically Non-conducting materials/alloys etc.

Declarations

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

References

- [1] J. Benes, Cutting Difficult Machine Materials, 01/24/2007.
<http://www.Americanmachinist.com/304/Issue/Article/False./44740/Issue S.>

- [2] V.K. Jain, Advanced Machining Processes, Allied Publishers, New Delhi, 2009.
- [3] T.Y. Tai, S.J. Lu, Improving the fatigue life of electro-discharge machined SKD-11 tool steel via the suppression of surface cracks, *Int. J. Fatigue* 31 (3) (2009) 433–438.
- [4] K.H. Ho, S.T. Newman, State of the art electrical discharge machining (EDM), *Int. J. Mach. Tool Manuf.* 43 (Issue 13) (October 2003) 1287–1300.
- [5] B.R. Lazarenko, "To Invert the Effect of Wear on Electric Power Contacts", Dissertation of the All-Union Institute for Electro Technique in Moscow/CCCP, Russian, 1943.
- [6] S. Singh, S. Maheshwari, P.C. Pandey, Some investigations into the electric discharge machining of hardened tool steel using different electrode materials, *J. Mater. Process. Technol.* 149 (2004) 272–277.
- [7] C.J. Luis, I. Puertas, G. Villa, Material removal rate and electrode wear study on the EDM of silicon carbide, *J. Mater. Process. Technol.* 164–165 (2005) 889–896.
- [8] M. V. Kavade, M. M. Jamadar, Effect of aluminium powder mixed EDM on machining characteristics of die steel (AISI D3), *Int. J. Mech. Prod. Eng.* (8) (2014) 25–28. ISSN: 2320-2092.
- [9] O.A. Abu Zeid, On the effect of electro-discharge machining parameters on the fatigue life of AISI D6 tool steel, *J. Mater. Process. Technol.* 68 (1) (1997) 27–32.
- [10] L. Li, L. Gu, X. Xi, W. Zhao, Influence of flushing on performance of EDM with bunched electrode, *Int. J. Adv. Manuf. Technol.* 58 (1–4) (2012) 187–194.
- [11] A.M. Nanimina, A.M.A. Rani, F. Ahmad, S.H.J. Lo, Application of Electro-Discharge Machining on Al₂O₃ Particle Reinforced Aluminum Composite, *WORLD JOURNAL OF ENGINEERING*, 2009.
- [12] K.M. Tsai, P.J. Wang, Predictions on surface finish in electrical discharge machining based upon neural network models, *Int. J. Mach. Tool Manuf.* 41 (2001) 1385–1403.
- [13] J.A. McGeough, H.A. Rasmussen, Macroscopic model of electro-discharge machining, *Int. J. Mach. Tool Des. Res.* 22 (1982) 333–339.
- [14] N.K. Foteyey, Electro-physical machining surface quality after electric discharge machining, *Russ. Eng. Res.* 17 (1997) 73–79.
- [15] J.H. Zhang, T.C. Lee, W.S. Lau, X. Ai, Spark erosion with ultrasonic frequency, *J. Mater. Process. Technol.* 68 (Issue 1) (15 June 1997) 83–88.
- [16] B. Ekmekci, A. Erden, Remarks on surface integrity of electric discharge machined surfaces: a state of art review, in: *The Eleventh International Conference on Machine Design and Production*, Antalya, Turkey 1, 2004, pp. 411–428.
- [17] H.K. Kansal, S. Singh, P. Kumar, Technology and research developments in powder mixed electric discharge machining (PMEDM), *J. Mater. Process. Technol.* 184 (2007) 32–41.
- [18] W.S. Zhao, Q.G. Meng, Z.L. Wang, The application of research on powder mixed EDM in rough machining, *J. Mater. Process. Technol.* 129 (2002) 30–33.
- [19] Z.Z. Lu, F.L. Zhao, Y.Y. Yang, Research on dielectric breakdown and discharge channel in powder-mixed EDM, *Dalian Ligong Daxue Xuebao / J. Dalian Univ. Technol.* 48 (3) (2008) 373–377.
- [20] G.S. Prihandana, M. Mahardika, M. Hamdi, Y.S. Wong, K. Mitsui, Accuracy improvement in nano graphite powder-suspended dielectric fluid for micro-electrical discharge machining processes, *Int. J. Adv. Manuf. Technol.* 56 (1–4) (2011) 143–149.
- [21] F.L. Zhao, Z.Z. Lu, H. Wang, Z.Q. Qian, Research on effecting mechanism of particles in powder-mixed EDM, *Dalian Ligong Daxue Xuebao / J. Dalian Univ. Technol.* 45 (2005) 668–671.
- [22] H.M. Chow, L.D. Yang, C.T. Lin, Y.F. Chen, The use of SiC powder in water as dielectric for micro-slit EDM machining, *J. Mater. Process. Technol.* 195 (1–3) (1 January 2008) 160–170.
- [23] K.Y. Kung, J.T. Horng, K.T. Chiang, Material removal rate and electrode wear ratio study on the powder mixed electrical discharge machining of cobalt-bonded tungsten carbide, *Int. J. Adv. Manuf. Technol.* 40 (2009) 95–104.
- [24] X. Bai, Q.H. Zhang, T.Y. Yang, et al., Research on material removal rate of powder mixed near dry electrical discharge machining, *Int. J. Adv. Manuf. Technol.* 68 (5–8) (September 2013) 1757–1766.
- [25] X. Bai, Q.H. Zhang, J.H. Zhang, et al., Machining efficiency of powder mixed near dry electrical discharge machining based on different material combinations of tool electrode and workpiece electrode, *J. Manuf. Process.* 15 (4) (October 2013) 474–482.
- [26] H.K. Kansal, S. Singh, P. Kumar, Application of Taguchi method for optimization of powder mixed electric discharge machining, *Int. J. Manuf. Technol. Manag.* 7 (2–4) (2005) 329–341.
- [27] H.K. Kansal, S. Singh, P. Kumar, Parametric optimization of powder mixed electrical discharge machining by response surface methodology, *J. Mater. Process. Technol.* 169 (3) (2005) 427–436.
- [28] S. Assarzadeh, M. Ghoreishi, A dual response surface desirability approach to process modeling and optimization of Al₂O₃ powder-mixed electrical discharge machining (PMEDM) parameters, *Int. J. Adv. Manuf. Technol.* 64 (9–12) (February 2013) 1459–1477.
- [29] A. Kumar, S. Maheshwari, C. Sharma, et al., Analysis of machining characteristics in additive mixed electric discharge machining of nickel-based superalloy Inconel 718, *J. Mater. Manuf. Process.* 26 (8) (2011) 1011–1018.
- [30] K.L. Wu, B.H. Yan, J.W. Lee, et al., Study on the characteristics of electrical discharge machining using dielectric with surfactant, *J. Mater. Process. Technol.* 209 (8) (21 April 2009) 3783–3789.
- [31] B. Singh, J. Kumar, S. Kumar, Experimental investigation on surface characteristics in powder-mixed electro-discharge machining of AA6061/10%SiC composite, *J. Mater. Manuf. Process.* 29 (3) (2014) 287–297.
- [32] Y.C. Lin, B.H. Yan, F.Y. Huang, "Surface modification of Al–Zn–Mg aluminum alloy using the combined process of EDM with USM", *J. Mater. Process. Technol.* 115 (3) (24 September 2001) 359–366.

- [33] Y.S. Wong, L.C. Lim, L.C. Lee, Effect of flushing on electro-discharge machined surfaces, *J. Mater. Process. Technol.* 48 (1–4) (15 January 1995) 299–305.
- [34] P.C. Pandey, H.S. Shan, *Modern Machining Process*, Tata McGraw- Hill Publishing Company Ltd, 1999, pp. 84–113.
- [35] Y.H. Guu, H. Hocheng, Effects of workpiece rotation on machinability during electrical discharge machining, *J. Mater. Manuf. Process.* 16 (1) (2001) 91–101.
- [36] M. Kunieda, T. Masuzawa, A fundamental study on a horizontal EDM, *CIRP Annals* 37 (1) (1988) 187–190, 1988.
- [37] T. Masuzawa, K. Okajima, T. Taguchi, EDM-lathe for micromachining, *CIRP Annals* 51 (1) (2002) 355–358.
- [38] N. Mohri, J. Tsukamoto, M. Fujino, Drilling of deep microholes by EDM, *CIRP Annals* 38 (1) (1989) 195–198.
- [39] B.H. Yan, C.C. Wang, W.D. Liu, F.Y. Huang, Machining characteristics of Al2O3/6061Al composite using rotary EDM with a disklike electrode, *Int. J. Adv. Manuf. Technol.* 16 (5) (2000) 322–333.
- [40] K. Kagaya, Y. Oishi, K. Yada, “Micro-electro discharge machining using water as a working fluid—I: micro-hole drilling, *Precis. Eng.* 8 (3) (1986) 157–162.
- [41] T. Sato, T. Mizutani, K. Yonemochi, K. Kawata, The development of an electro-discharge machine for micro-hole boring, *Precis. Eng.* 8 (3) (1986) 163–168.
- [42] J.S. Soni, Microanalysis of debris formed during rotary EDM of titanium alloy (Ti6Al 4V) and die steel (T 215 Cr12), 177, “Wear - ELSEVIER, 1994, pp. 71–79.
- [43] Y. Zhang, Y. Liu, Y. Shen, R. Ji, Z. Li, C. Zheng, Investigation on the influence of the dielectrics on the material removal characteristics of EDM, *J. Mater. Process. Technol.* 214 (5) (May 2014) 1052–1061.
- [44] J. Cyril Pilligrin, P. Asokan, J. Jerald, G. Kanagaraj, “Effects of Electrode Materials on Performance Measures of Electrical Discharge Micro-machining”, *Materials and Manufacturing Processes*, 2018 (Print) 1532-2475 (Online).
- [45] Y.S. Wong, L.C. Lim, I. Rahuman, W.M. Tee, Near-mirror-finish phenomenon in EDM using powder-mixed dielectric, *J. Mater. Process. Technol.* 79 (1–3) (1998) 30–40, 1 July 1998.
- [46] A. Molinetti, F.L. Amorim, P.C. Soares Jr., T. Czelusniak, Surface modification of AISI H13 tool steel with silicon or manganese powders mixed to the dielectric in electrical discharge machining process, *Int. J. Adv. Manuf. Technol.* 83 (5–8) (2015) 1057–1068, 83, pp. 1057–1068.
- [47] S. Kumar, U. Batra, Surface modification of die steel materials by EDM method using tungsten powder-mixed dielectric, *J. Manuf. Process.* 14 (1) (January 2012) 35–40.
- [48] P. Janmanee, A. Muttamara, Surface modification of tungsten carbide by electrical discharge coating (EDC) using a titanium powder suspension, *Appl. Surf. Sci.* 258 (19) (15 July 2012) 7255–7265.
- [49] G.S. Prihandana, M. Mahardika, M. Hamdi, Y.S. Wong, K. Mitsui, “Effect of micro-powder suspension and ultrasonic vibration of dielectric fluid in micro-EDM processes—Taguchi approach”, *Int. J. Mach. Tool Manuf.* 49 (12–13) (2009) 1035–1041, October 2009.
- [50] G. Kibria, B. Bhattacharyya, Analysis on geometrical accuracy of microhole during micro-EDM of Ti-6Al-4V using different dielectrics, in: *AIP Conference Proceedings* 1315, 2011, p. 155.
- [51] M.P. Jahan, M. Rahman, Y.S. Wong, Modeling and experimental investigation on the effect of nanopowder mixed dielectric in micro-electro-discharge machining of tungsten carbide, *Proc IMechE, Part B, J. Eng. Manuf.* 224 (11) (2010) 1725–1739.
- [52] Behnam Khosrozadeh, Mohammadreza Shabgard, Effects of simultaneous ultrasonic vibration of tool and addition of carbon nanotube into the dielectric in EDM process on machining outputs and surface integrity of Ti-6Al-4V alloy, *Indian J. Eng. Material Sci.* 24 (February 2017) 45–56.
- [53] Y.F. Tzeng, C.Y. Lee, Effects of powder characteristics on electro-discharge machining efficiency, *Int. J. Adv. Manuf. Technol.* 17 (2001) 586–592.
- [54] T. Yih-fong, C. Fu-chen, Investigation into some surface characteristics of electrical discharge machined SKD-11 using powder-suspension dielectric oil, *J. Mater. Process. Technol.* 170 (2005) 385–391.
- [55] A. Bhattacharya, A. Batish, N. Kumar, Surface characterization and material migration during surface modification of die steels with silicon, graphite and tungsten powder in EDM process, *J. Mech. Sci. Technol.* 27 (1) (2013) 133–140.
- [56] T.Y. Fong, F.C. Chen, Investigation into some surface characteristics of electrical discharge machined SKD-11 using powder-suspension dielectric oil, *J. Mater. Process. Technol.* 170 (1–2) (2005) 385–391.
- [57] B. Jabbaripour, M.H. Sadeghi, M.R. Shabgard, et al., Investigating surface roughness, material removal rate and corrosion resistance in PMEDM of r-TiAl intermetallic, *J. Manuf. Process.* 15 (1) (2013) 158–166.
- [58] H.M. Chow, B.H. Yan, F.Y. Huang, et al., Study of added powder in kerosene for the micro-slit machining of titanium alloy using electro-discharge machining, *J. Mater. Process. Technol.* 101 (1) (2000) 95–103.
- [59] G.S. Prihandana, T. Sriani, M. Mahardika, et al., Application of powder suspended in dielectric fluid for fine finish micro-EDM of Inconel 718, *Int. J. Adv. Manuf. Technol.* 75 (1–4) (2014) 599–613.
- [60] S. Padhee, N. Nayak, S.K. Panda, et al., Multi-objective parametric optimization of powder mixed electro-discharge machining using response surface methodology and non-dominated sorting genetic algorithm, *Sadhana* 37 (2) (2012) 223–240.
- [61] M.M. Sari, M.Y. Noordin, E. Brusa, Evaluating the electrical discharge machining (EDM) parameters with using carbon nanotubes, *IOP Conf. Ser. Mater. Sci. Eng.* 40 (2012), 012019.
- [62] I. Puertas, C.J. Luis, L. Alvarez, Analysis of the influence of EDM parameters on surface quality, MRR and EW of WC-Co, *J. Mater. Process. Technol.* 153 (2004) 1026–1032.
- [63] M. Kiyak, O. Cakir, Examination of machining parameters on surface roughness in EDM of tool steel, *J. Mater. Process. Technol.* 191 (1–3) (2007) 141–144.
- [64] Y.S. Liao, J.T. Huang, Y.H. Chen, A study to achieve a fine surface finish in Wire-EDM, *J. Mater. Process. Technol.* 149 (1–3) (2004) 165–171.
- [65] N. Tosun, C. Cogun, A. Inan, The effect of cutting parameters on workpiece surface roughness in wire EDM, *Mach. Sci. Technol.* 7 (2) (2003) 209–219.
- [66] B.M. Schumacher, EDM technology for precision workpieces with excellent surface quality, in: *Proceedings of the ISEM 7, 1983*, pp. 124–135.
- [67] A. Erden, S. Bilgin, Role of impurities in electric discharge machining, in: *Proceedings of the 21th International Machine Tool Design and Research Conference*, Macmillan, London, 1980, pp. 345–350.
- [68] M.L. Jeswani, Effects of the addition of graphite powder to kerosene used as the dielectric fluid in electrical discharge machining, *Wear* 70 (1981) 133–139.
- [69] G. Koshy, P.K. Philip, A. Geddam, Hardening of surface layers using electric discharge techniques, in: *Proceedings of the 11th AIMTDR Conference*, IIT, Madras, 1983, pp. 315–319.
- [70] H. Narumiya, N. Mohri, N. Saito, H. Ootake, Y. Tsunekawa, T. Takawashi, K. Kobayashi, EDM by powder suspended working fluid, *Proc Int Sympo Electro-Machining* IX Japan, 1989, pp. 5–8.
- [71] K. Kobayashi, T. Magara, Y. Ozaki, T. Yatomi, The present and future developments of electrical discharge machining, in: *Proceedings of the 2nd International Conference on Die and Mould Technology*, Singapore, 1992, pp. 35–47.
- [72] N. Mohri, N. Saito, H. Narumiya, Y. Kawatsu, K.T. Ozaki, K. Kobayashi, Finish machining by EDM using powder suspended working fluids, *J. JSEME* 49 (1992).
- [73] B.H. Yan, S.L. Chen, Characteristics of SKD11 by complex process of electrical discharge machining using liquid suspended with alumina powder, *J. Japan Inst. Metals* 58 (9) (1994) 1067.
- [74] C.P. Yu, W.C. Chen, S.W. Chang, C.C. Chang, Effects of the concentration of suspended aluminum powder in dielectric fluid on EDM of carbide of tungsten, in: *Proceedings of the 13th Conference of Chinese Society of Mechanical Engineers*, Taiwan, 1996, pp. 445–450.
- [75] Q.Y. Ming, L.Y. He, Powder suspension dielectric fluid for EDM, *J. Mater. Process. Technol.* 52 (1) (1995) 44–54.
- [76] Y.S. Wong, L.C. Lim, I. Rahuman, W.M. Tee, Near-mirror-finish phenomenon in EDM using powder-mixed dielectric, *J. Mater. Process. Technol.* (Switzerland) 79 (1998) 30–40.
- [77] Y. Uno, A. Okada, Y. Hayashi, Y. Tabuchi, Surface integrity in EDM of aluminum bronze with nickel powder mixed fluid, *J. Jpn. Soc. Electr. Mach. Eng.* 32 (70) (1998) 24–31.
- [78] H.M. Chow, B.H. Yan, F.Y. Huang, J.C. Hung, Study of added powder in kerosene for the micro-slit machining of titanium alloy using electro-discharge machining, *J. Mater. Process. Technol.* 101 (2000) 95–103.
- [79] K. Furutani, A. Saneto, H. Takezawa, N. Mohri, H. Miyake, Accretion of titanium carbide by electrical discharge machining with powder suspended in working fluid, *Precis. Eng.* 25 (2001) 138–144.
- [80] E. Henriques, Influence of silicon powder-mixed dielectric on conventional electrical discharge machining 43 (2003) 1465–1471.
- [81] F. Klocke, D. Lung, G. Antonoglou, D. Thomaidis, The effects of powder suspended dielectrics on the thermal influenced zone by electro-discharge machining with small discharge energies, *J. Mater. Process. Technol.* 149 (2004) 191–197.
- [82] K.L. Wu, B.H. Yan, F.Y. Huang, S.C. Chen, Improvement of surface finish on SKD steel using electro-discharge machining with aluminum and surfactant added dielectric, *Int. J. Mach. Tool Manuf.* 45 (2005) 1195–1201.
- [83] H.K. Kansal, S. Singh, P. Kumar, An experimental study of the machining parameters in powder mixed electric discharge machining of Al-10%SiCp metal matrix composites, *Int. J. Manuf. Technol. Manag.* 1 (4) (2006) 396–411.
- [84] S.H. Yeo, P.C. Tan, W. Kurnia, Effects of powder additives suspended in dielectric on crater characteristics for micro-electrical discharge machining, *J. Micromech. Microeng.* 17 (2007) N91–N98.
- [85] Sehijpal Singh Kansal, P. Kumar, Effect of silicon powder mixed EDM on machining rate of AISI D2 Die steel, *J. Manuf. Process.* 9 (1) (2007) 13–22.
- [86] Han-Ming Chowa, Lieh-Dai Yangb, Ching-Tien Lina, Yuan-Feng Chena, The use of SiC powder in water as dielectric for micro-slit EDM machining,, *J. Mater. Process. Technol.* 195 (2008) 160–170.
- [87] K. Furutani, H. Sato, M. Suzuki, Influence of electrical conditions on performance of electrical discharge machining with powder suspended in working oil for titanium carbide deposition process, *Int. J. Adv. Manuf. Technol.* 40 (11) (2009) 1093–1101.
- [88] Kun Ling Wua, Bing Hwa Yanb, Jyh-Wei Lee, Chun Gian Ding, Study on the characteristics of electrical discharge machining using dielectric with surfactant, *J. Mater. Process. Technol.* 2 (9) (2009) 3783–3789.
- [89] S. Kumar, R. Singh, Investigating surface properties of OHNS die steel after electrical discharge machining with manganese powder mixed in the dielectric, *Int. J. Adv. Manuf. Technol.* (2010).
- [90] S. Sharma, A. Kumar, N. Beri, D. Kumar, Effect of aluminium powder addition in dielectric during electric discharge machining of Hastelloy on machining performance using Reverse polarity, *Int. J. Adv. Eng. Technol.* 1 (3) (2010) 13–24.
- [91] K. Ojha, R.K. Garg, K.K. Singh, Experimental Investigation and Modeling of PMEDM Process with Chromium Powder Suspended Dielectric, 2011, pp. 65–81.
- [92] Saurabh Sharma, Anil Kumar, Naveen Beri, Study of tool wear rate during powder mixed EDM of Hastelloy steel, *Int. J. Adv. Eng. Technol.* (2011).
- [93] K.H. Syed, K. Palaniyandi, Performance of electrical discharge machining using aluminum Powder suspended distilled water, *Turk. J. Eng. Environ. Sci.* 36 (3) (2012) 195–207.
- [94] U. Mathpathi, S.K. Jeevraj, I.C. Ramola, Analysis of material removal rate with powder mixed dielectric, *IJCAE* 4 (3) (2013) 316–332.

- [95] S. Goyal, R.K. Singh, Parametric study of powder mixed EDM and optimization of MRR & surface roughness, *Int. J. Sci. Eng. Technol.* 3 (1) (2014) 56–62.
- [96] Mahendra G. Rath, Deepak V. Mane, Study on effect of powder mixed dielectric in EDM of Inconel 718", *Int. J. Sci. Res. Publ.* 4 (11) (November 2014).
- [97] Sarabjeet Singh Sidhu, Ajay Batish, Sanjeev Kumar, Study of surface properties in particulate- reinforced metal matrix composites (MMCs) using powder-mixed electrical discharge machining (EDM), *Mater. Manuf. Process.* 29 (1) (2014) 46–52.
- [98] Harmesh Kumar, Development of mirror-like surface characteristics using nanopowder mixed electric discharge machining (NPMEDM), *Int. J. Adv. Manuf. Technol.* (2014).
- [99] K.H. Syed, G.P. Anuraag, G. Hemanth, S.A. Subahan, Powder-Mixed EDM Machining of Aluminium-Silicon Carbide Composites 8 (January) (2015) 133–137.
- [100] Bhiksha Gugulothu, D. Hanumantha Rao, G. Krishna Mohana Rao, Optimization of Edm Process Parameters and Graphite Powder Concentration on Electrical Discharge Machining of Ti-6al-4v Alloy Using Taguchi Method 1 (5) (2015) 2394–6210.
- [101] Nihal Ekmekci, BülentEkmekci, Electrical Discharge Machining of Ti6Al4V in Hydroxyapatite Powder Mixed Dielectric Liquid, *Materials and Manufacturing Processes*, 2015.
- [102] Murahari Kolli, Adepu Kumar, "Surfactant and graphite powder-assisted electrical discharge machining of titanium alloy", in: *Proc IMechE Part B:J Engineering Manufacture*, 2015.
- [103] Nipun D. Gosai, Anand Y. Joshi, Experimental investigation and optimization of process parameters used in the silicon powder mixed electro discharge machining of Ti-6Al-4V alloy using response surface methodology, *J. Manuf. Sci. Prod.* 16 (1) (2016) 21–32.
- [104] L. Li, L. Zhao, Z.Y. Li, L. Feng, X. Bai, "Surface Characteristics of Ti-6Al-4V by SiC Abrasive Mixed EDM with Magnetic Stirring", *Materials and Manufacturing Processes*, 2017 (Print).
- [105] S. Tripathy, D.K. Tripathy, "Multi-attribute optimization of machining process parameters in powder mixed electro-discharge machining using TOPSIS and grey relational analysis", *Engineering Science and Technology, Int. J.* 19 (1) (March 2016) 62–70.
- [106] Chander Prakash, H.K. Kansal, B.S. Pabla, SanjeevPuria, "on the influence of nanoporous layer fabricated by PMEDM on β -Ti implant: biological and computational evaluation of bone- implant interface", *Proceedings, Mater. Today* 4 (2) (2017) 2298–2307. Part A.
- [107] S. Tripathy, D.K. Tripathy, An approach for increasing the micro-hardness in electrical discharge machining by adding conductive powder to the dielectric, *Proceedings, Mater. Today* 4 (2) (2017) 1215–1224. Part A.
- [108] A.M. Abdul-Rani, A.M. Nanimina, T.L. Ginta, M.A. Razaka, Machined surface quality in nano aluminum mixed electrical discharge machining, *Procedia Manuf.* 7 (2017) 510–517.
- [109] T. Tahsin, Öpöz, Hamidullah Yaşar, Nihal Ekmekci, BülentEkmekci, "Particle migration and surface modification on Ti6Al4V in SiC powder mixed electrical discharge machining", *J. Manuf. Process.* 31 (January) (2018) 744–758.
- [110] Vinay Kumar, Kumar Amit, Sanjay Kumar, N.K. Singh, Comparative study of powder mixed EDM and conventional EDM using response surface methodology, *Proceedings, Mater. Today* 5 (9) (2018) 18089–18094. Part 3.
- [111] L. Selvarajan, J. Rajavel, V. Prabakaran, B. Sivakumar, G. Jeeva, A review paper on EDM parameter of composite material and industrial demand material machining, *Proceedings, Mater. Today* 5 (2) (2018) 5506–5513. Part 1.
- [112] Suvan Dev Choudhury, Neelabh Jyoti Sahari, B. Surekha, Goutam Mondal, Study on the influence of hybridized powder mixed dielectric in electric discharge machining of alloy steels", *Proceedings, Mater. Today* 5 (9) (2018) 18410–18415. Part 3.
- [113] B. Surekha, T. Sree Lakshmi, Hemalata Jena & Priyaranjan Samal, "Response surface modelling and application of fuzzy grey relational analysis to optimize the multi-response characteristics of EN-19 machined using powder mixed EDM", *Aust. J. Mech. Eng.* (2019) (Print) 2204-2253 (Online).