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Effect of Powder Mixed Electrical Discharge Machining (PMEDM) on Machining Parameters of Various Materials with Different Powders: A Review

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Abstract: Material with unique metallurgical properties such as Titanium, Haynes-25, Molybdenum, Columbium C-103, hardened steels, and other superalloys was developed to meet the demands of extreme applications in aerospace, automobile, and nuclear reactor industries. Machining these materials using a conventional machining process is a challenging task. Electrical discharge machining (EDM) is one of the most suitable non-conventional processes to achieve precise quality components with optimum tooling cost. EDM process becomes a natural choice for machining of superalloys; its low machining removal rate and poor surface quality have been the key problems restricting its development. To overcome these drawbacks, the nanopowder suspended dielectric oil is used, which increases its conductive strength and increases the discharge gap between the tool and workpiece. This newly developed material removal process is called Powder Mixed Electrical Discharge Machining (PMEDM). This paper presents the review work done to improve the performance characteristics of machining like MRR, TWR, EWR, SR, Microhardness, and SCD for different Machining parameters. This paper also reviewed the industrial and academic work performed by various researchers from the origin to the development of PMEDM over the past decades. The research findings with major challenges along with the future scope have also been paved out.
Keywords: PMEDM, Machining parameters, Material removal rate, Surface quality, Microhardness, Metallurgical properties, Superalloys

I. INTRODUCTION

Material with unique metallurgical properties such as Titanium, Haynes-25, Molybdenum, Columbium C-103, hardened steels, and other superalloys was developed to meet the demands of extreme applications in aerospace, automobile, and nuclear reactor industries. These materials are not only harder, tougher, less heat-sensitive, and more resistant to corrosion but also more difficult to machine. For all traditional machining processes, machining of complex shapes with high surface finish and high accuracy levels at economic cutting speeds is very challenging, which demands new technology to machine these " difficult-to-cut" materials with precision.

EDM is one of the most suitable non-conventional processes to achieve precise quality components with optimum tooling cost. EDM process becomes a natural choice for machining of superalloys. Over the years, researchers have developed new techniques for enhancing the EDM performance. Some of them include the Ultrasonic-Assisted EDM, Hybrid EDM, Rotating disk electrode-EDM, Dry EDM, and Powder mixed EDM.

The invention of the powder-mixed electric discharge machining (PMEDM) process took place around the late 1970s and the first publication came in 1980. In PMEDM, the addition of proper powder particles to the dielectric leads to a superior surface finish and better machining rate compared to those for traditional EDM (without the powder-mixed dielectric) [1].

A. EDM Process

Electrical discharge machining (EDM) is one of the most widely used non-traditional machining processes. The main attraction of EDM over traditional machining processes such as metal cutting using different tools and grinding is that this technique utilizes a thermoelectric process to erode undesired materials from the workpiece by a series of discrete electrical sparks between the workpiece and the electrode. The traditional machining processes rely on a harder tool or abrasive material to remove the softer material whereas non-traditional machining processes such as EDM use an electrical spark or thermal energy to erode unwanted material in order to create the desired shape. So, the hardness of the material is no longer a dominating factor for the EDM process. A schematic of an EDM process is shown in Figure 1, where the tool and the workpiece are immersed in a dielectric fluid [2].

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1) *Working principle of EDM:* As shown in Figure 1, at the starting of the EDM operation, a high voltage is applied across the narrow gap between the electrode tool and the workpiece. This high voltage induces an electric field in the insulating dielectric that is present in a small gap between electrode and workpiece. This cause conducting particles suspended in the dielectric to concentrate on the points of the strongest electrical field. When the potential difference between the electrode and the workpiece is sufficiently high, the dielectric breaks down and a transient spark discharges through the dielectric fluid, removing a small amount of material from the workpiece surface.

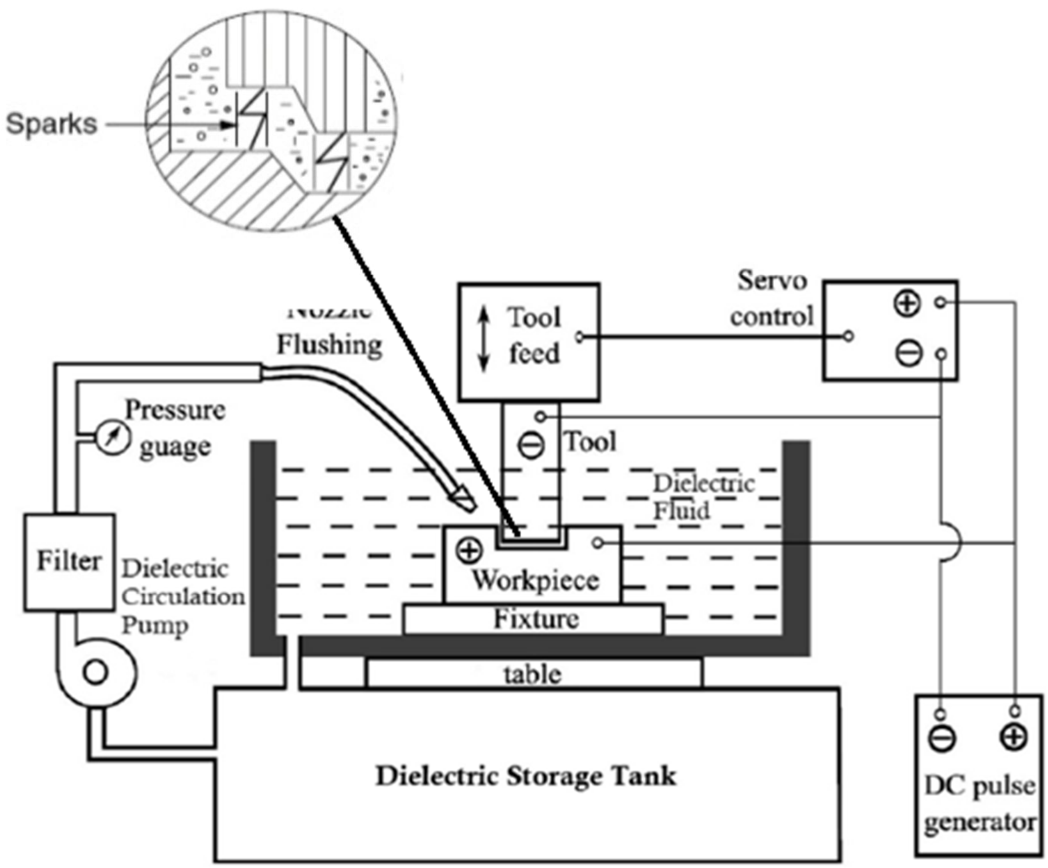

Figure 1 Schematic representation of EDM process.

EDM removes material by discharging an electrical current, normally stored in a capacitor bank, across a small gap between the tool (cathode) and the workpiece (anode).

2) *Advantages*
a) Every conductive material can be cut by this process.
b) It is independent of the hardness of workpiece so hardened workpiece can be machined easily.
c) Complex die sections and complex shapes can be produced accurately.
d) This process is burr-free.
e) A thin section can be easily machined without deforming the part.

3) *Disadvantages*
a) In this machining process, high tool wear occurs.
b) Tool wears limits the accuracy and surface finish of the metal.
c) Only good conductors of electricity can be machined by EDM.

II. PMEDM PROCESS

In powder mixed electric discharge machining (PMEDM) process, for effective utilization of discharge energy at the machining zone in EDM. Different types of powder particles are mixed in the dielectric fluid at various concentrations. A typical dielectric fluid circulation system used in PMEDM is shown in figure 2. This kind of specially designed mechanical system is mounted in the working tank of the EDM setup.

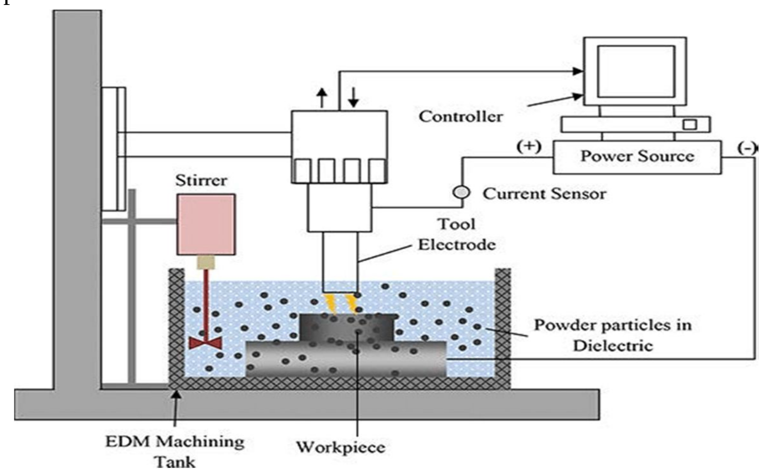

Figure 2 Schematic diagram of PMEDM.

A. *Machining Mechanism of PMEDM*

1) *Enlarged Discharging Gap:* For conventional EDM, the relative uniformity and the same insulated property of the work fluid components from even density electric field, and resulted in little initiating abilities of discharge breakdown and small discharge gaps. However, for PMEDM machining, lots of current-conducting micro-powders cause electric field aberration in the discharge gap, as shown in figure 3 under the pressure of gap voltage, lots of positive and negative charges gather respectively at the top and bottom of the powders. The nearer the point is to the top or bottom, the higher is the electric charge density. Then at points a and b between two nearby powder, where the electric discharge breakdown will firstly occur when the electric field density exceeds the breakdown resistance capability. Discharge breakdown then causes a short circuit between the two powder particles and the redistribution of electric charges. More electric charges then gather at point c and d, which leads to the discharge between these two powder and other powders, resulting in "series discharge" and accordingly the discharge breakdown between the electrode and the workpiece. As the distance between powders becomes smaller than the discharge gaps and more electric charges gather at the vertexes of the powder than at other points, "series discharge" occurs easily and "series discharge" with certainty will cause discharge through the whole discharge gap. Thus electric discharge can easily occur in the process of PMEDM and has enlarged discharge gaps [3].

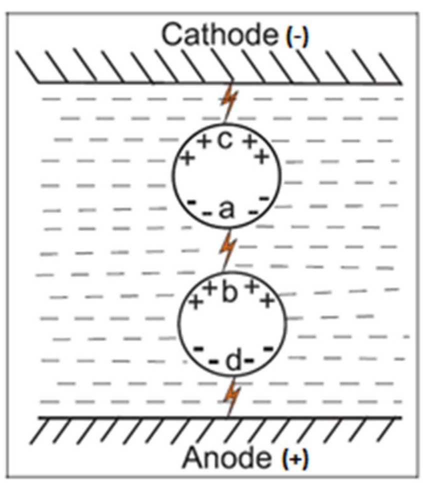

Figure 3 Schematic diagram of "series discharge".

2) *Widening of the Discharge Passage:* After the first discharge, powder particles in the inter-electrode gap get energized and move quickly along with ions and electrons. These energized particles collide with dielectric molecules and generate more ions and electrons. Thus, more electric charges are produced in PMEDM compared to traditional EDM. Increased discharge gap also helps in the reduction in hydrostatic pressure acting on the plasma channel. The combined influence of these two phenomena ensures the widening of the discharge passage. The enlarged and widened discharge column reduces the intensity of discharge energy, leading to the formation of large shallow cavities on the workpiece surface [3].
3) *Multiple Discharges:* Multiple discharge paths are observed in PMEDM due to the rapid zigzag movement of the suspended powder particles which maintain a uniform distribution of energy and development of multiple craters by single discharge. A typical voltage waveform in a PMEDM operation is shown in Figure. Unlike traditional EDM, the discharge waveform in the case of PMEDM is significantly different from the input pulse. There are more disturbances in voltage and current signals during a pulse-on time indicating multiple discharges [3].

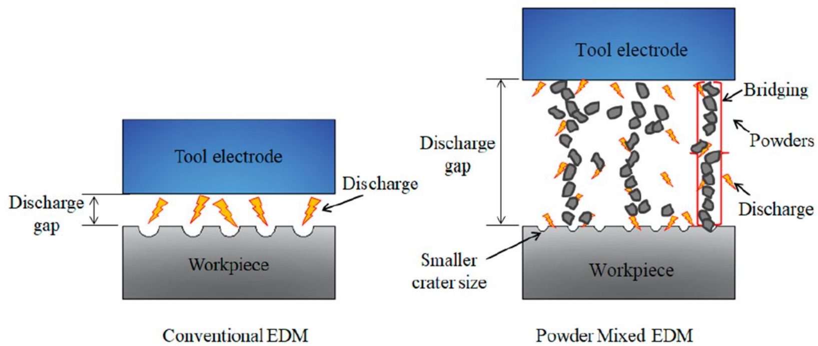

Figure 4 Illustration of conventional EDM and power-mixed EDM.

III. PMEDM PROCESS PARAMETERS

Process parameters in PMEDM define the machining conditions in which experiments are carried out. Figure 4 illustrates the classification of different types of PMEDM parameters. The effect of important process parameters on the machining characteristics of PMEDM process is discussed below.

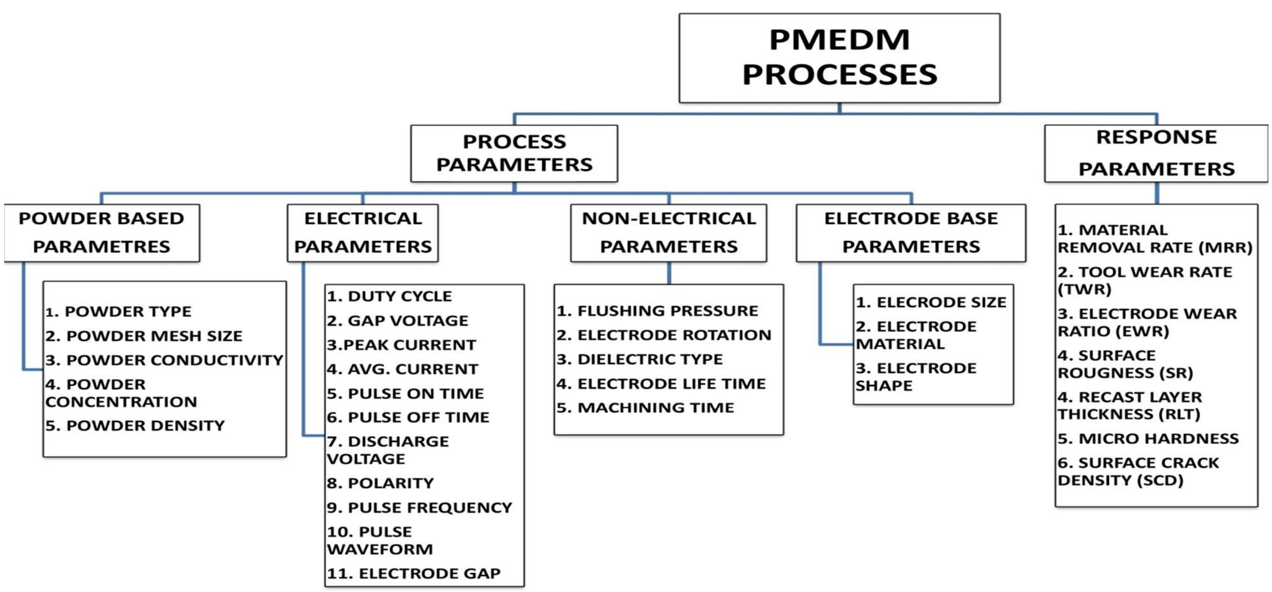

Figure 5 Parametric analysis of PMEDM process.

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A. *Powder Based Parameters*

PMEDM performance depends on the type of powder, powder concentration, particle mesh size, powder density, and powder conductivity. The following process parameters are considered into account.

1) *Powder Type:* The addition of the powder the dielectric fluid could be improved the MRR considerably and reduce the TWR and enhance the quality of the work surface. But the various powders would affect the performance features of the EDM method differently (Table 1).

Table 1 commonly used PMEDM powder and its physical characteristics are shown.

Material	Density (g/cm^3)	Electrical resistivity ($\mu\ \Omega/cm$)	Thermal conductivity (W/m-K)	Remarks
Alumina (Al_2O_3)	3.98	103	25.1	The addition of Al_2O_3 powder improves SR [33].
Aluminum (Al)	2.70	2.89	236	Al powder added EDM oil gives a high MRR and better surface integrity [17].
Graphite (C)	1.26	103	3000	The addition of graphite powder provides high MRR [56]
Silicon Carbide (Sic)	3.22	1013	300	SiC powder mixed EDM increases MRR and decreases TWR and SR [39].
Silicon (Si)	2.33	2325	168	Si powder mixed EDM exhibits better surface morphology [4].
Tungsten (W)	19.25	5.3	182	Tungsten powder mixed EDM increases microhardness [75].
Born Carbide (B_4C)	2.52	5.5×10^5	27.9	Efficient discharge distribution capabilities of the powder improve MRR and machining efficiency remarkably [46].
Carbon Nano tubes (CNTs)	2.0	50	4000	The addition of CNTs into dielectric fluid is increases the MRR and decreases the SR [70].
Chromium (Cr)	7.16	2.6	95	Nano-chromium powder particles give highest MRR comparing to the conventional EDM [8].
Copper (Cu)	8.96	1.71	401	The addition Cu of powder in the dielectric improves the MRR and SR [11].
Manganese (Mn)	7.43	174	7.17	surface hardness is improved [18]
Tungsten Carbide (WC)	15.63	6.5	28	Tungsten carbide powder added dielectric fluid improves the SR and micro hardness [22].
Tantalum carbide (TaC)	13.9	30	27.9	TaC powder in kerosene dielectric fluid is produces better surface finish [51].
Titanium nitride (TiN)	5.21	25	29	The hardness of surface with TiN mixed EDM is higher than conventional EDM [52]

2) *Powder Mesh Size:* Additive particle mesh size is an influential parameter in machined surface characteristics. Experimental results indicate that the inter-electrode gap is more in the case of larger particles which results in higher contamination and lower deionization between the workpiece and electrode. Larger powder size increase in the gap but increases surface roughness and decreases MRR [77].
3) *Powder Concentration:* The addition of the appropriate amount of powder to dielectric fluid gives better enhancement in MRR, SR, and TWR. The powder concentration is the most important parameter to maximize MRR and minimize EWR and SR [13].

B. Electrical Parameters

1) *Duty Cycle:* The duty cycle is a percentage of the on-time relative to the total cycle time. Generally, higher duty cycles mean increased cutting efficiency. The duty cycle is calculated by dividing the on-time by the total cycle time (on-time + off-time). The result is multiplied by 100 for the percentage of efficiency or duty cycle [4].

$$\boldsymbol{Duty\ Cycle}\ (\%) = \frac{\boldsymbol{Pulse\ on - time\ (\mu s)}}{\boldsymbol{Total\ cycle\ time\ (\mu s)}}$$

2) *Gap Voltage:* Gap voltage is the voltage in the gap between two electrodes. The total energy of the spark is determined by the applied voltage. Depending on the setting of the voltage, the inter-electrode gap (IEG) is set by the servo control. A larger value of the inter-electrode gap (IEG) improves the flushing of debris from the machining zone and makes the next discharge stable, ultimately improving the MRR [40].
3) *Peak Current:* The peak current is the maximum amount of current which output is capable of sourcing for brief periods of time. When a power supply or an electrical device is first turned on, high initial current flows into the load, starting at zero and rising until it reaches a peak value, known as the peak current. Peak current is positively affected to MRR and SR [15].
4) *Average Current:* Peak current is the maximum current available for each pulse from the power supply. The average current is the average of the amperage in the spark gap measured over a complete cycle. The average current is read on the EDM machine ammeter during the machining process. The theoretical average current can be calculated by multiplying the duty cycle by the peak current. Average current is an indication of machining operation efficiency with respect to metal removal rate [4].

$$Average\ Current\ (A)\ =\ Duty\ cycle\ (\%)\ x\ Peak\ Current\ (Ip)$$

5) *Pulse on-Time:* Metal removal is directly proportional to the amount of energy applied during the pulse on-time. This energy is controlled by the peak amperage and the length of the on-time. The longer the on-time pulse is sustained the more workpiece material will be melted away. The resulting crater will be broader and deeper than a crater produced by a shorter on-time. These large craters will create a rougher surface finish. Extended on-times also allow more heat to sink into the workpiece and spread, which means the recast layer, will be larger and the heat-affected zone will be deeper. The TWR is increase with increase in peak current and pulse on time [24].
6) *Pulse off-Time:* The cycle is completed when sufficient pulse off-time is allowed before the start of the next cycle. Pulse off-time will affect the speed and stability of the cut. In theory, the shorter the pulse off-time the faster the machining operation will be; however, if the pulse off-time is too short, the ejected workpiece material will not be swept away by the flow of dielectric and the fluid will not be deionized. This will cause the next spark to be unstable. Unstable conditions cause erratic cycling and retraction of the advancing servo. This slows down cutting more than long, stable off-times [4].
7) *Polarity:* Polarity refers to an electrical condition determining the direction of the current flow relative to the electrode. The polarity of the electrode can be either positive or negative. Depending on the application, some electrode/work metal combinations give better results when the polarity is changed [4].
8) *Pulse Frequency:* Pulse frequency is the number of cycles produced across the gap in one second. The higher pulse frequency obtained the finer surface finish. As the number of cycles per second increases, the length of the pulse on-time decreases. Short pulse on-times remove very little metal and create smaller craters. This produces a smoother finish with less thermal damage to the workpiece. Low pulse frequencies are generally used for roughing operations. Longer pulse on-times create craters that are deeper and wider, thus removing more metal. It also allows more heat to sink into the workpiece which means the recast layer will be thicker and the heat-affected zone will be deeper [4].
9) *Electrode Gap:* Electrode gap (spark gap) is the distance between the electrode and the part during the process of EDM. Electro-mechanical or hydraulic systems are used to respond to average gap voltage. To obtain good performance and gap stability a suitable gap should be maintained [4].

C. Non-electrical Parameters

1) *Flushing Pressure:* Flushing is important because eroded particles must be removed from the gap for effective cutting. Flushing also brings fresh dielectric oil into the gap and cools the electrode and the workpiece. Improper flushing pressure causes erratic cutting, which increases machining time. Pressure flushing, also known as injection flushing, is the most common and preferred method for flushing.

2) *Dielectric Type:* EDM dielectric fluid serves two main purposes. First, it acts as a semiconductor between the electrode tool and workpiece to facilitate a stable and controlled spark gap ionization condition. Second, it also acts as a flushing agent to wash and remove the eroded debris from the machined area. Three types of fluids are available for PMEDM: petroleum-based, synthetic, and vegetable-based. Kerosene, deionized water, Transformer Oil, EDM oils, and hydrocarbon oils are examples of commonly used EDM oils. Properties of typical dielectrics used in PMEDM are given in Table 2.

Table 2 Properties of typical dielectrics used in PMEDM [5-80].

Dielectric Name	Specific heat capacity (J/kg-K)	Thermal conductivity (W/m-K)	Breakdown strength (kV/mm)	Flash point (◦C)
Kerosene	2100	0.14	24	37-65
Deionized water	4200	0.623	65-70	Not Applicable
Mineral transformer oil	1860	0.126	70	160
Silicon oil	1510	0.15	50	300

D. Electrode Base Parameters

1) *Electrode Size:* The performance of PMEDM depends upon the size of the electrode as the process produces the material removal rate and tool wear rate. The electrode material removal increment is more than the workpiece material removal increment with the increase of tool electrode diameter, which leads to the increase of relative electrode wear ratio (EWR). The tool electrode with a larger diameter gives a higher taper rate.
2) *Electrode Material:* The selection of the most suitable electrode material is important for the process plan in PMEDM. The major variables to be considered for the selection of electrode material are material removal rate, tool wear rate, surface roughness, manufacturing and material cost. Electrode material should have the basic properties like electrical conductivity, thermal conductivity, a high melting temperature, low wear rate, and resistance to deformation during machining**.** Different electrode materials are Brass, Copper, Copper Tungsten, Graphite, Titanium, Tungsten carbide, etc. Table 3 represents a comparison of different materials based on technical considerations.

Table 3 Technical considerations of various PMEDM electrode materials [5-80].

Material	Density (g/cm³)	Melting temperature (◦C)	Thermal conductivity (W/m-k)	Machinability
Copper	8.96	1084	401	High
Brass	8.73	900 to 940	109	High
Graphite	2.26	3600	25 to 470	Low
Tungsten carbide	15.63	2870	110	Low
Titanium	4.5	1668	17	Low
Tungsten	19.25	3422	173	Low
Tungsten Copper Alloy	15.2	3500	27.21	Low

IV. PMEDM RESPONSE PARAMETERS

The performance characteristic of the PMEDM process is measured by various factors like Material Removal Rate (MRR), Tool Wear Rate (TWR), Electrode Wear Ration (EWR), Surface Roughness (SR), Recast Layer Thickness (RLT), Microhardness and Surface Crack Density (SCD).

A. Material Removal Rate

The volume of material removed per unit time is MRR. The metal removal rate is usually expressed as a cubic millimeter per minute (mm³/min). It is the most important parameter looking for a manufacturer's perspective and every researcher wants to maximize it. The high material removal rate is the most desirable output response for any machining process which leads to increased productivity. The addition of powder in the dielectric improves the MRR [80]. The MRR is expressed as:

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$$\boldsymbol{MRR}\ (\mathbf{mm^3/min}) = \frac{\mathbf{Wi - Wf}}{\boldsymbol{\rho}\ \mathbf{x\ T}}$$

Where, w_i = Weights of the workpiece before the machining process.
w_f = Weights of the workpiece after the machining process.
ρ = Density of the workpiece material.
T = Machining time in minutes.

B. *Tool Wear Rate*

TWR is the rate at which material is eroded from the Tool electrode. There are four different types of wear: volumetric, corner, end, and side. Corner wear is usually the most important since it will determine the degree of accuracy of the final cut. If an electrode can successfully resist erosion at its most vulnerable points, then overall wear will be minimized and maximum electrode life achieved. Weight of the tool before and after the experiment was measured to determine the tool wear rate. The TWR is decreases with the existence of powder in the dielectric [64]. The TWR is expressed as:

$$\boldsymbol{TWR}\ (\mathbf{mm^3/min}) = \frac{\mathbf{ti - tf}}{\boldsymbol{\rho}\ \mathbf{x\ T}}$$

Where, t_i = Weights of the tool before the machining process.
t_f = Weights of the tool after the machining process.
ρ = Density of the tool material.
T = Machining time in minutes.

C. *Electrode Wear Ratio*

The electrode wear ratio is dependent on the material removal rate and the tool wear rate. Lower EWR is desirable to enhance the productivity of the process. It is a ratio of the weight of the electrode tool wear to the weight of the workpiece wear after machining". The powder concentration is the most important parameter to minimize EWR [12]. The EWR is expressed as:

$$\boldsymbol{EWR}\ (\%) = \frac{\boldsymbol{Wt}}{\boldsymbol{Ww}}\ \boldsymbol{x}\ \mathbf{100}$$

Where, W_t = Wear weight of the tool after the machining process.
W_w = Wear weight of the work piece after the machining process.

D. *Surface Roughness*

To evaluate the roughness of the worked surface, a profilometer is used. The arithmetic mean (Ra) is the parameter of surface roughness most frequently used. It is the measure of surface texture. The powder concentration, voltage, and capacitance have been significant influences on surface roughness [7]. Peak current is the most significant factor for the phenomenon of surface modification [78].

E. *Recast Layer Thickness*

During the machining process, each sparks melts a small portion of the workpiece. A portion of this molten material is ejected and washed away. The remaining material re-solidifies to form a surface layer known as the recast layer. This layer can contain an altered microstructure, tensile stresses, microcracks, impurities which can lead to early part failure when put to service. The recast layer thickness can measure by using a scanning electron microscope (SEM). The recast layer thickness is directly proportional to the discharge current and powder concentration [69].

F. *Microhardness*

Microhardness is the hardness of a workpiece material as determined by forcing an indenter such as a Vickers or Knoop indenter into the surface of the material under 15 to 1000 gf load. The purpose of obtaining the microhardness of the material before and after machining was to measure the change in hardness and its effect on the machining surface due to the addition of the powder particles while machining. The powder concentration, duty cycle and pulse on time are the most influencing process parameter toward improvement in Micro-hardness [40]. Powder mixed EDM increases the microhardness of work material [25].

G. *Surface Crack Density*

The formation of thermal stress having a magnitude of more than the fracture strength of work material in an EDM process results in crack formation. Cracking is one of the most significant surface defects, which leads to a reduction in material resistance, fatigue, and corrosion under tensile loading conditions. Since it is not easy to quantify in terms of width, length, or depth, or even by the amount of cracking, it is known as surface crack density. SCD is total length of cracks (μm) per unit area (μm^2) to evaluate the severity of cracking [77]. The increase of peak current and powder concentration decreases SCD [45].

V. LITERATURE REVIEW

M. A. Abhas, et al (2020) investigated PMEDM with the use of two separate powder of nano chromium powder (NCP) and Span-20 to the machining of AISI D2 steel. Experimental results concluded that the best roughness was produced by AISI D2 steel with Nano chromium powder at 2 g/L powder concentration and 20 μs pulse duration. From an experimental study, researchers recommended that use Nano chromium powder (NCP) particles to enhance the quality of the machining zone for AISI D2 steel instead of surfactant [5]. Veenet Kumar, et al (2020) investigated the influence of silicon carbide (SiO_2) powder mixed electric discharge machining of the aluminum metal matrix (AA2024) on the material removal rate (MRR), tool wear rate (TWR) and surface roughness (SR). The presented results showed that the addition of SiO_2 nanopowder in dielectric resulted in decreases MRR and increases TWR as well as SR [6].

P. Sivaprakasam, et al (2020) investigated that the surface characteristics of Inconel 718 alloy with zinc-coated copper electrode using the micro-WEDM process. The result showed that the powder concentration, voltage, and capacitance have a significant influence on surface roughness of the graphite powder micro-WEDM process [7]. Muhammad Umar Farooq, et al (2020) added Si powder into the dielectric fluid at a concentration of 5 g/L, 10 g/L, and 20 g/L. Titanium (Ti-6Al-4V ELI) alloy was used as workpiece material. The results showed that powder concentration is the most significant parameter to control surface roughness and recast layer thickness [8]. B. Singaravel, et al (2020) used vegetable oil as a dielectric in EDM to analyze material removal rate and surface roughness while machining Inconel 800. Experimental results indicated that vegetable oil-based dielectric fluids showed higher MRR than conventional dielectric [9].

Mojtaba Shahbazi Dastjerdi, et al (2020) used aluminum powder mixed dielectric in EDM to analyze material removal rates, surface roughness, and tool wear ratio while machining aluminum composite A413 reinforced. Experimental results indicated that the current intensity has the greatest impact on the MRR and surface roughness, such that when it increases, the MRR and surface roughness both increase promptly. They observed MRR by adding 3g/L aluminum oxide powder in the kerosene dielectric to reduce TWR and the surface roughness [10]. Kamlesh Paswan, et al (2020) studied the effect of added graphene nanopowder into deionized water in the material migration between tool electrode (copper) and workpiece (Inconel 718). The result observed that the improvement in MRR, SR, and TWR is 20.1%, 14%, and 2% respectively [11]. Nor Ain Jamil Hosni, et al (2020) achieved excellent surface integrity by mixing a surfactant (span-20) along with Cr powder in dielectric during the EDM of AISI D2 hardened steel. The added nano-chromium powder particles led to a 45.08% enhancement of the highest MRR compare to conventional EDM. It was also found that the usage of larger powder particles is less effective in improving the MRR than smaller particle sizes [12].

N. A. J. Hosni, et al (2019) used a response surface methodology to optimize the process parameters chromium (Cr) powder concentration, surfactant (Span-20) concentration, peak current, pulse on time, and duty cycle in PMEDM for machining AISI D2 steel. The researcher reported that the Cr powder concentration is the most influencing parameter to maximize material removal rate (MRR) and minimize electrode wear rate (EWR) and surface roughness (SR) [13].

Paridhi Malhotra, et al (2019) conducted experiments with nano-particles of Magnesium in EDM to machined Aluminium 7075 reinforced with 10% by wt Silicon Carbide (AI 7075/10%SiC) and analyzed machining parameters like Material removal rate (MRR) and electrode wear rate (EWR). They reported that under different range of process parameters MRR for powder mixed EDM is found to be much higher than MRR as compared to conventional EDM. As well as EWR is lower in PMEDM then conventional EDM for the same machining conditions [14]. Santosh Kumar Sahu, et al (2019) compared copper powder added kerosene dielectric media to copper powder added transformer oil(as dielectric) to machine Inconel 718 by electro-discharge machining (EDM). Experimental results concluded that an achieved relatively high material removal efficiency and superior surface finish by copper powder with transformer oil. They also analyzed the effect of peak current and pulse on time on machining parameters. They found an increase in pulse on time has reduced the MRR as well as surface roughness and increased peak current has resulted in reducing the degree of surface cracking [15].

S. Sundriyal, et al (2019) followed Taguchi L9 orthogonal array method and used zinc powder in the dielectric to study the machining parameter of EN-31 sample by PMEDM. Results stated that PMEDM leads to the generation of machine products with high surface quality. They observed that powder concentration was dominant in improving the surface finish [16]. B. C. Koli, et al (2019) conducted an experiment to study machining characteristics of aluminum work material by graphite powder assisted reverse μ-EDM process. Experimental results revealed that the lowest dimensional variation in percentage was achieved in powder assisted reverse μ-EDM [17]. B. V. Dharmendra, et al (2019) modified Taguchi approach was adopted to investigate the powder concentration effect in aluminum powder mixed PMEDM for machining of Inconel 800. SR and MRR are measured to analyze the effect of change in various process parameters. Experimental results indicated that the peak current increases MRR ad SR also increases [18]. Akhil Khajuria, et al (2019) researched the process parameters for AA2014 copper-based alloy material discharge machining. As machining parameter is chosen as the process parameters for peak current, discharge voltage, pulse on time, pulse off time, material removal rate, tool wear rate, surface roughness. It is also noted that the powder concentration of $Al_2 0_3$ powder and peak current are important parameters influencing MRR, TWR, and SR [19].

Kanwal Jit Singh, et al (2019) presented the use of grey rational analysis (GRA) for determining the optional parameters setting of powder mixed EDM process to the machining of high-speed steel T1 grade. The results showed that copper tool material gives maximum MRR and least TWR [20]. Chenxue Wang, et al (2019) experimented with or without Al powder mixture based micro-EDM for the manufacturing of Inconel-706 and found out that Al mixed EDM oil increase MRR and tool wear rate (TWR) is higher than conventional EDM process due to the conductivity of the suspended Al powder. Also stated that using Al powder to EDM oil is to decrease the surface roughness of Inconel-706 in EDM [21]. Bidyut Kumar Panda, et al (2019) used manganese powder mixed dielectric oil to machine AISI D3 high carbon high chromium die steel with negative polarity. Results indicated that using manganese powder mixed EDM with graphite electrode the microhardness of material is obtained as high as 2815HV due to surface alloying [22].

Preetkanwal Singh, et al (2019) studied silicon carbide particulates (SiCp) mixed hybrid EDM on Ti-6Al-4V to optimize process parameters. Experiments were conducted to analyze various eminent responses namely MRR, TWR, and SR with or without abrasive jet flushing. Results indicated that the enhancement of surface hardness due to the oxides (SiO2) formation on the machined surface with abrasive mixed dielectric and its reduce MRR [23]. Arun Kumar Rouniyar, et al (2019) magnetic field-assisted powder mixed electrical discharge machining was used to machine Aluminum-6061 alloy. The experimental research has noted that increased MRR and decreased TWR with an increase in the magnetic field [24]. Van Tao Le, et al (2019) used tungsten carbide powder mixed kerosene as dielectric fluid to machine SKD61 steel. Results indicated that the surface roughness and the microhardness of surface obtained by PMEDM are generally better than by normal EDM [25]. V. Srinivasa Sai, et al (2019) conducted experiments for machining of EN-19 using graphite powder in paraffin as dielectric fluid. Experimental results revealed that the increase in the value of peak current - powder concentration the value of MRR is increased and the value of TWR is increased up to a certain extent and then starts decreasing [26].

L. Tang, et al (2019) established the thermo-electrical coupling simulation model of powder mixed electrical discharge machining (PMEDM) for machining SiC/Al FGM. Results stated that under the condition of 5wt% SiC/Al FGM, peak current 14A, powder concentration 4g/L, compared with conventional EDM, the efficiency of PMEDM is improved by 16.34% and surface roughness is decreased by 29.42% [27]. B. Surekha et al (2019) studied the effect of aluminum powder added PMEDM for machining of EN-19 alloy steel. Response surface methodology was used to model the experiments and the effect of change in various parameters was studied on material removal rate (MRR) and tool wear rate (TWR). The fuzzy gray rational analysis optimizes the parameters to fulfill the multi-response characteristics of the PMEDM process. They stated that the addition of powder leads to improve the surface roughness [28]. R. Rajeswari, et al (2019) experiments were conducted on ultrasonic-assisted and graphite powder added EDM to machine D3 die steel workpiece. Experimental results stated that the powder added and ultrasonic-assisted both finish EDM processes perfume better than conventional finish EDM. They stated that by using ultrasonic vibration and powder added dielectric medium is reduced roughness and Ra value [29].

A. P. Tiwary, et al (2019) compared three different types of powders (copper, nickel, and cobalt) in studying the effect of powder concentration on material removal rate. They found that copper powder mixed deionized water with a concentration of 4g/L obtained the highest material removal rate due to its superior electrical and thermal conductivity in improving the electrical and thermal energy distribution uniformly in the machining zone [30]. Mukund V. Kavade, et al (2019) determined the influence of suspending fine Aluminum (Al) powder into Electra oil and achieved high MRR. They observed that the peak current and powder concentration are significantly affecting MRR by the use of ANOVA [31].

Deepti Ranjan Sahu, et al (2019) studied the influence of pulse duration, peak current, and gap voltage on MRR, TWR, and SR by mixing Al_2O_3 nanopowder in EDM oil while machining Inconel 825 using the copper electrode. Considerable increment in MRR and reduction in SR has been found in the case of PMEDM as compared to conventional EDM. A reduction in microcracks, microholes, uneven deposits, and recast layer thickness (RLT) has been observed [32].

Mohsen Asghari Ilani, et al (2019) used the fused deposition modeling (FDM) method of rapid prototyping (RP) to improve the conductivity of the electrode tools for the PMEDM. They indicated that RP electrodes enhance MRR, TWR, and SR by 33%, 31%, and 77% with using the Aluminum powder in dielectric oil [33]. K. V. Arun Pillai, et al (2019) investigates the combined effects of powder mixed dielectric fluid at three different regimes of discharge energies for MRR and TWR while micro-electric discharge milling of Ti-6Al-4A using cryo-treated tungsten carbide (WC) electrode. The result indicated that the addition of powder in the dielectric reduced creater diameter and increased 3D roughness of surface [34]. Tahsin T. Opoz, et al (2018) studied PMEDM for Ti-6Al-4A ELI material for the influence of silicon carbide (SiC) powder concentration on particle deposition and surface topography. Based on the experiment results, low pulse current and high powder concentration improve the material removal rate [35]. Vinay Kumar, et al (2018), Inconel 825 is machined using aluminum oxide (Al_2O_3) micro-powder suspension in dielectric EDM oil. Process parameters were varied and the effect is measured on SR, MRR, and surface integrity. From the results, it was found that peak current, gap voltage, and pulse on time are major affecting parameters on MRR and SR. The addition of Al_2O_3 powder improves surface roughness [36]. Ramesh S., et al (2018) analyzed aluminum (Al), silicon carbide (SiC), and aluminum oxide (Al_2O_3) powder-based PMEDM for machining of AISI P20 steel with different electrode materials like copper, brass, and tungsten. Results stated that maximum MRR was achieved by the copper tool with Al powder. The researcher reported that the tool wear rate of the tungsten electrode is very low [37]. S. Ramesh, et al (2018), PMEDM experiments used three different electrode materials like copper, brass, and tungsten to machining Nimonic 75 by adding Al powder in the dielectric fluid. Copper combined with Al powder has to produce maximum MRR. Similarly, in combination with the tungsten tool, the Al powder led in less TWR [38].Kanwal Jit Singh, et al (2018) Grey rational analysis (GRA) technique was implemented to assess the efficacy of various process parameters using powder mixed EDM in the machining of high carbon high steel (D2 steel). It is observed from the experimental results that the addition of perfect sized particles in proper concentration improves MRR, TWR, and SR [39]. S. Tripathy, et al (2018) implemented Technique for an order of preference by similarity to ideal solution (TOPSIS) and Grey relational analysis (GRA) to assess the efficiency of various process parameters using chromium powder mixed EDM for machining of H-11 hot work tool steel with a copper electrode. It is concluded from the experimental results that the addition of properly sized particles in proper concentration improves surface finish [40]. Chandar Prakash, et al (2018) studied multi walled carbon nanotube mixed electric discharge machining of Al-SiCp. The addition of MWCNT powder improves SR and MRR both. A combination of high powder concentration and high peak current delivers improvement in MRR and reduction in SR [41]. Munmun Bhaumik, et al (2018) experiments were conducted on SiC powder mixed EDM to machine AISI 304 workpiece with a cryo treated tungsten carbide electrode. Experimental results stated that the addition of SiC powder concentration and the use of cryo treated electrode improve the machining efficiency. SiC powder increased MRR by 23.2%, decreased TWR and SR by about 25% and 14.2% respectively [42]. S. Vijayabhaskar, et al (2018) used silicon carbide (SiC) nanoparticles mixed deionized water as dielectric during the WEDM of magnesium matrix composites. The results show that the pulse on-time and voltage has significant effects on MRR [43]. Shalini Mohanty, et al (2017) investigated the effect of using Al_2O_3 powder mixed dielectric fluid PMEDM for the machining of AlSiCp. Results revealed that the powder enhances the machining rate and surface finish. It means MRR increases as well as surface roughness decreases [44]. Munmun Bhaumik, et al (2017) used silicon carbide (SiC) powder mixed kerosene as dielectric fluid to machine AISI 304 stainless steel. Results indicated that the increase in peak current and powder concentration decreases surface crack density (SCD) [45]. Jagdeep Singh, et al (2017) Taguchi parameter design approach was used to investigate the powder concentration effect in graphite powder mixed PMEDM for machining of Tungsten carbide (WC) alloy. MRR and TWR are measured to analyze the effect of change in various process parameters. Experimental results revealed that as the peak current increases MRR also increases [46]. A. M. Abdul-Rani, et al (2017) investigates surface morphology and corrosion rate of titanium alloy during the process of powder mixed electric discharge machining (PMEDM). The experiments have been carried out in the optimal combination of electrical machining parameters like peak current, gap voltage, on time and off time through aluminum powder, the improvement in surface morphology, and enhance the corrosion rate observed by mixing powders into dielectric media [47]. Nagwa Mejid Elisti, et al (2017) experimented with Iron oxide nano-powders (Fe_2O_3) based PMEDM for the manufacturing of cobalt-chromium-molybdenum (Co-Cr-Mo). Results, in particular, showed that for powder concentration of 2 g/L provided higher MRR in comparison with 4 g/L and without powder cases [48]. Satish Kumar, et al (2017) studied the effect of three micro powder particles (i.e. tungsten carbide, cobalt, and boron carbide) added PMEDM for machining of Inconel 800.

Response surface methodology was used to model the experiments and the effect of change in various parameters was studied on MRR and TWR. The analysis of the experimental observation highlights that the current, pulse on time and tool materials are the most decisive factor for MRR, while current intensity, pulse on time, tool material, and powder particles for TWR [49].

S. Tripathy, et al (2017) performed a hybrid multi-response optimization using TOPSIS and GRA during the EDM of H-11 die steel using SiC powder mixed dielectric. A current of 3A, a duty cycle of 80%, and a gap voltage of 30V with added SiC powder (6 g/L) in dielectric resulted in maximum MRR [50]. Vinod Kumar, et al (2017) observed the suspension of Si and Al powders in dielectric for a WC-Co alloy in wire-cut EDM. The results show that silicon powder improves more surface quality as compared to aluminum powder. The addition of powders reduces cracks formation on the work surface [51].

Amit Kumar, et al (2017) analyzed material removal rate and surface roughness with Al_2O_3 powder suspended deionized water as a dielectric for the machining Inconel 825 material. Experimental results concluded that surface topography of the machined surface improved by adding nano-powder mixed EDM [52]. Sagar Patel, et al (2017) investigated the potential of powder mixed rotary EDM for enhancing material removal rate (MRR) of Inconel 718 with aluminum suspended kerosene as a dielectric fluid. ANOVA technique was adopted to analyze the experimental results. Experimental results indicated that the peak current and duty cycle significantly affect MRR [53]. Mohammad Yeakub Ali, et al (2017) compared the average surface roughness (Ra) in micro Electrical Discharge Machining (EDM) of zirconium oxide (ZrO2) ceramic using tantalum carbide (TaC) nanopowder mixed kerosene dielectric fluid and without powder mixed dielectric.

The gap voltage, capacitance, and powder concentration consider as the process parameters for the investigation of machined surface roughness. Experimental results stated that 5 g/L to 7 g/L TaC powder in kerosene dielectric fluid produced better surface finish [54]. A Muttamara, et al (2016) experimented using a copper electrode and titanium nitride (TiN) powder mixed dielectric fluid for machining of AISI 316L steel. The PMEDM surfaces were observed by a scanning electron microscope (SEM). The experimental results revealed that the hardness of the modified surface with TiN mixed kerosene is higher than conventional EDM with pure kerosene [55]. Jagdeep Singh, et al (2016) utilized a Taguchi method for machining Tungsten carbide (WC) alloy by dispersing nano and micro-sized graphite powder particles in the dielectric of EDM process. They observed that the graphite powder is more suitable for improvement in surface characteristics of WC-Co. Results show the pulse on time is the most affecting parameter compares to other input parameters [56]. Chetan Roy, et al (2016) used a response surface methodology to optimize the process parameters pulse on time, pulse current, and concentration of the aluminum powder in kerosene dielectric. The researcher reported that the addition of Al powder improves the surface roughness to a value of 3.31μm [57]. A. Agrawal, et al (2016) analyzed material removal rate and tool wear rate with graphite powder suspended dielectric for machining copper-iron-graphite MMC material. Experimental results concluded that an increase in powder concentration increases MRR [58].

Jagdeep Singh, et al (2016) studied graphite powder mixed EDM on cobalt bonded tungsten carbide (WC-Co) with three different dielectric fluids for machining as well as environmental aspects. They conduct hazard and operability analysis (HAZOP), by that minimize machining waste, cost, and environmental pollution related to the EDM process [59].

Chandar Prakash, et al (2016) followed the Taguchi method and used silicon powder in the dielectric to machining β-Ti alloy. Experimental results revealed that peak current and powder concentration have a more significant effect on surface roughness and surface microhardness [60]. Saeed Daneshmand, et al (2016) examined PMEDM of NiTi60 material for the influence of Al_2O_3 powder concentration and tool rotational. It was observed from experimental results that current intensity, pulse on time, and voltage are major affecting parameters on MRR. Rotation of the tool increases the material removal rate [61].

L. Li, et al (2016), EDM was used to improve surface characteristics of Ti-6Al-4V work material by adding SiC abrasive to the dielectric. The results show that a continuous strengthened layer formed during the SiC powder mixed-EDM process. They also stated that the addition of SiC powder improves the hardness of work material [62]. Chandar Prakash, et al (2016) used silicon (Si) powder in hydrocarbon oil as dielectric fluid during machining on Ti-35Nb-7Ta-5Zr β-titanium alloy. The results show that the silicon as powder additive in the dielectric fluid of PMEDM significantly improved the surface quality by reducing surface defects like micro-cracks, craters/pit size, recast layer thickness. The 4 g/L Si powder concentration is the optimum level at which the surface characteristics and machining efficiency are most desirable [63].

Mr. Cyril Pilligrin J, et al (2016) analyzed aluminum, graphite, and silicon carbide powders based PMEDM for machining of 316L stainless steel. Result revealed that the addition of powders tends to increase the MRR and reduce the TWR [64]. Sachin Mohal, et al (2016) studied multiwall carbon nanotubes (MWCNTs) mixed PMEDM on Al-10%SiCp MMC to achieve the best surface finish. Experiments were conducted to analyze the effect of peak current, duty cycle, CNTs concentration, and pulse on time on work piece's surface topography. Results indicated that the MRR and surface finish has improved by 38.22% and 46.6% respectively by mixing the MWCNTs into the dielectric fluid [65].

Ryota Toshimitsu, et al (2016) researched the influence of chromium powder mixed EDM. They observed the Vicker hardness, water repellency, and corrosion resistance of alloy tool steel SKD11. The finished surface increased by using chromium powder mixed EDM oil [66]. Gangadharudu Talla, et al (2015) utilized aluminum powder mixed kerosene dielectric to enhance the efficiency of machining of aluminum metal matrix composite. The results showed that increases in MRR and decreases in SR compared to conventional EDM [67]. Chander Prakash, et al (2015) performed simultaneous optimization of multi objectives using a Non-dominated sorting genetic algorithm (NSGA) -II to predict the optimal condition of PMEDM. They reported that the best optimal condition 13A peak current, 5µs pulse duration, 8% duty cycle, and 8 g/L silicon powder concentration for a required low SR and high surface microhardness (SMH) [68].

Murahari Kolli, et al (2015) observed the material removal rate, surface roughness, recast layer thickness, and surface topography of titanium alloy using surfactant and graphite powder mixed EDM oil on Ti-6Al-4V. Researchers found that the addition of surfactant to dielectric fluid improved the material removal rate and surface roughness. The experimental result showed that the RLT reduced by mixing surfactant to the dielectric fluid [69]. Abdus Sabur, et al (2015) studied the effect of tantalum carbide (TaC) powder added micro-EDM for machining of zirconium oxide (ZrO_2) ceramic. Response surface methodology used to model the experiments and the effect of powder concentration on surface roughness (Ra). The addition of tantalum carbide powder improves surface roughness [70].

B. Kuriachen, et al (2015) experimented by adding silicon carbide (SiC) powder into deionized water as a dielectric on Ti-6Al-4V. The results show that to achieve the maximum MRR, at 5g/L of powder concentration with middle levels of capacitance and voltage, to be used as the machining parameters [71].

Gangadharudu Talla, et al (2014) performed grey rational analysis during the powder mixed EDM of Al-Al_2O_3 using the aluminum powder in kerosene dielectric. The results show that the addition of aluminum powder increased the MRR and decreases the SR. Powder concentration of 6g/L gives a minimum value of SR [72].

In the dielectric fluid, Harmesh Kumar, et al (2014) made use of carbon nano tubes (CNTs) to enhance the efficiency of machining of AISI-D2 die steel. They stated that the appropriate addition of CNTs into the dielectric fluid of EDM increases MRR and decreases SR. The experimental results further indicate that the CNTs concentration and peak current are the most influential parameters [73]. Ajay Batish, et al (2014) investigated surface optimization and powder dielectric migration (silicon, graphite, and W) on three different die-steels (H11, HCHCr and AISI 1045). The addition of powders in dielectric improved the surface finish via migrating into the machined surface and to improve the micro-hardness. Results showed that the brass electrode and tungsten powder improve surface finish in H11 and AISI 1045 wheres W-Cu electrode, and tungsten powder gave higher microhardness in HCHCr [74].

Sarbjeet Singh Sidhu, et al (2014) investigated surface properties of different types of metal matrix composites (MMCs) 65Vol%SiC/A356.2, 10Vol%Sic-5Vol% quartz/Al and 30Vol%Sic/A359 using graphite powder mixed EDM process. They found that an increase in the density of reinforced particles in the metal matrix increased microhardness [75]. Balbir Singh, et al (2014) experimented on the addition of tungsten powder into dielectric on 6061/10%SiC aluminum alloy. The results show that the addition of tungsten particles in kerosene improves 48.43% MRR [76].

V. Vikram Reddy, et al (2014) machined the PH17-4 stainless steel with the PMEDM process and studied the influence of input parameters on MRR, SR, White layer thickness (WLT), and surface crack density (SCD) of the machined surface. Improvement in MRR was observed with the use of surfactant added EDM oil. The experimental research has shown that the peak current is the most significant parameter affecting MRR, SR, and WLT [77].

Sanjeev Kumar, et al (2011) investigated the influence of tungsten powder mixed electro-discharge machining of OHNS O2 die steel, (HC-HCr) type D2 die steel, hot work type H13 die steel on the microhardness. The authors indicated that surface alloying with tungsten has a significant effect on its properties as observed from the increase in microhardness by more than 100% for all the three work material [78].

Harmesh Kumar, et al (2011) investigated the influence of silicon powder in powder mixed EDM process for the Machining of Al-10%Sicp Metal Matrix Composites. Researchers concluded that concentration of the silicon added powder and peak current are the most influential on MRR and SR. There is a significant increase in MRR when 4 g/L is added in dielectric fluid and lowers the SR by 33% [79]. A. Bhattacharya, et al (2011) performed a multi-objective optimization of MRR, TWR, and SR during powder mixed EDM of various steels (HCHCr, EN31, and hot die steel) using the analytic hierarchy process (AHP) which eliminates subjectively in the selection of response weight. Results concluded that the addition of powder in the dielectric improved the MRR as the electrical conductivity of powder reduces the dielectric insulating strength [80]

VI. CONCLUSION

Electrical discharge machining is a machining method primarily used for hard metals or those that would be very difficult to machine with traditional techniques. PMEDM is an upgraded technique, which holds a bright promise and overcomes the drawbacks of the conventional EDM process. Many researchers have experimented with different powder materials suspended in various dielectrics combinations to machine different work materials. This paper presents a review of published research work based on the experimental study on PMEDM. Some conclusions extracted from the present review are;

A. PMEDM is a hybrid technique process where powder suspended dielectric is used to improve machining efficiency as well as surface characteristics. The review state that the use of powder in dielectric enhanced performance efficiency means increasing MRR and decreasing surface roughness.

B. Among the process parameters, peak current, pulse on time, gap voltage, powder material, and powder concentration have significantly affected the performance measure in PMEDM.

C. Most of the researchers used Taguchi, gray rational analysis, and response surface methodology for designing the experiments as well as analysis and optimization of experimental results.

D. This methodology has also significantly reduced the requirement of dielectric fluid, unlike the conventional EDM process.

VII. FUTURE SCOPE

A. Very few researcher literatures are available on powder mixed EDM of superalloys such as molybdenum, Haynes-25, columbium C-103, and electrically Non-conductive materials, etc.

B. Effect of powder particle shape & size, powder type, and powder concentration on properties like microhardness, surface morphology, overcut size, the thickness of the strengthened layer and dimension accuracy needs a thorough study.

C. Polymer powders were very rarely used as additives in the dielectric. So the investigation of PMEDM responses using polymer powder materials would be an emerging area of research.

D. Most of the researchers focused on the experimental study of PMEDM. Very few researchers have done the numerical simulation of PMEDM using FEM or any other tools for optimal achievement of all process measures taken together.

E. Some organic liquid or other environment-friendly dielectric fluid can be tried as a dielectric medium.

F. In further, for optimization of experimental results neural network, fuzzy logic, genetic algorithm, and particle swarm optimization, etc can be used.

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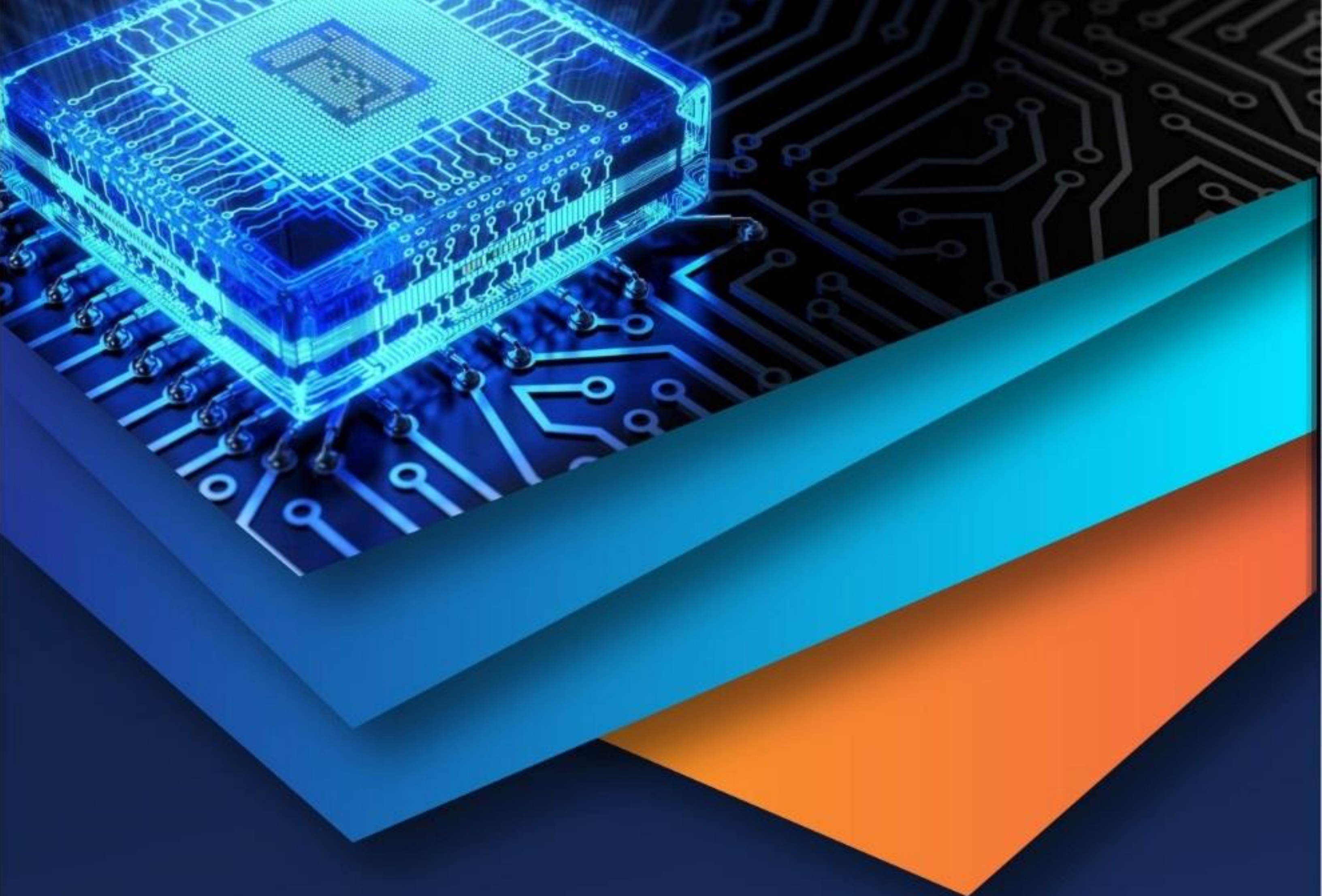

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