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Improvement in Machining Performance using Nano Powder Particles Mixed in Bio-Degradable Oil as Dielectric in Electric Discharge Machining Process (NPMEDM): A Comprehensive Review

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Abstract: Powder mixed electric discharge machining has become a critical process for machining biomaterials used in medical implants, offering notable improvements in surface quality and machining performance. This review explores the mechanisms by which PMEDM enhances the removal rate of material and the wear rate of the electrode (tool) by adding nano- and micro-powder particles, such as aluminum (Al) and copper (Cu), to biodegradable/non-edible oils as a dielectric. This paper discusses the successful application of PMEDM in machining biomaterials such as titanium alloys, magnesium alloys, and stainless steel, emphasizing its ability to achieve superior surface finishes and enhance properties such as hardness and biocompatibility. Despite its advantages, PMEDM faces challenges, including controlling the complex interactions between process parameters and managing the environmental impact of the process. The review concludes with a discussion of the need for technological advancements, including improved process control systems and the development of environmentally friendly dielectric fluids, to further enhance PMEDM's capabilities in the biomedical field. In order to further strengthen PMEDM's capabilities in the biomedical field, the paper ends with a discussion of the necessity for technological developments, such as better machining techniques like NPMEDM with tool rotation and the creation of environmentally friendly dielectric fluids such as biodegradable/non-edible oils (castor oil, neem oil, Jatropha curcus oil, coconut oil, waste vegetable oil, bio diesels).

Keywords: nano-powder mixed electric discharge machining (NPMEDM); biodegradable oils; biomaterials; medical implants; surface morphology; material removal rate (MRR); tool wear rate (TWR); electrode wear reduction; sustainability index.

1. Introduction

Electric discharge machining is a non-traditional machining process commonly used in the aerospace industry, mold and die manufacturing, and biomedical device fabrication. Developed in the mid-20th century, EDM operates by generating electrical discharges between submerged electrodes (workpiece and tool) in a dielectric medium, typically kerosene or Deionized water. These discharges generate localized heat, melting and evaporating the material, enabling its removal without contact between electrodes [1, 2]. EDM is well-known for its ability to machine hard materials and complex geometries [3]. Despite its advantages, EDM has limitations such as low material removal rates (MRR), high tool wear rates (TWR), and the formation of microcracks on the machined surface. These issues can affect the surface morphology and performance of the machined components [4, 5]. To address these limitations, PMEDM was introduced in the 1980s. PMEDM enhances the EDM technique by suspending electrically conductive powder particles in a dielectric medium, thereby improving machining performance and surface morphology [6, 7]. The involvement of powder particles in the dielectric medium provides several benefits. The powder particles increase the gap between electrodes, enhancing debris flushing and reducing short-circuiting, resulting in more uniform and stable discharges. This significantly improves the MRR and reduces the TWR [8, 9]. Additionally, the particles facilitate the development of a composite layer on the machined surface, enhancing properties such as biocompatibility, wear resistance, and hardness. PMEDM focuses on both surface modification and material removal, making it advantageous for applications requiring high surface integrity [10, 11].

1.1. Importance of PMEDM in biomaterials.

Biomaterials such as stainless steel (SS), titanium alloys (Ti), magnesium alloys (Mg), and cobalt-chromium alloys are commonly used in the manufacturing of medical implants, including dental, orthopedic, and cardiovascular devices, due to their biocompatibility and mechanical properties [12]. However, machining these biomaterials with conventional methods poses significant challenges. Their hardness, brittleness, and heat resistance often result in poor surface quality, microcracks, and the release of toxic elements, compromising the implants' biocompatibility and performance [13, 14]. PMEDM addresses these challenges with superior machining capabilities and surface modification. Conductive powder particles in the dielectric medium enhance machining efficiency and surface characteristics. The process produces a modified surface layer with improved hardness, reduced residual stresses, and enhanced corrosion and wear resistance, which are crucial for the longevity and performance of biomedical implants [15-17].

Additionally, PMEDM can create bioactive coatings on implant surfaces, thereby promoting better integration with biological tissues and reducing the risk of implant rejection [18, 19]. The high precision and superior surface quality of PMEDM make it invaluable in biomedical engineering. It overcomes the limitations of conventional machining methods and opens new possibilities for fabricating advanced medical implants with enhanced performance and biocompatibility. For example, Ti (titanium) alloys, which are notable for their corrosion resistance and strength-to-weight ratio, are therefore ideal for load-bearing implants and have been successfully machined with PMEDM. Additionally, by decreasing surface roughness and increasing hardness, it improves the surface quality of the SS material used to make orthopedic implants and surgical tools [20-22].

1.2. Objectives of the review.

The main objective of this article is to provide a broad analysis of the advancements and applications of PMEDM in the fabrication of biomaterials. This review aims to elucidate the fundamental principles of EDM and PMEDM, including a detailed explanation of the working mechanisms of both processes and highlighting the key differences and advantages of PMEDM over traditional EDM. Understanding these principles is crucial to appreciating the improvements in machining performance and surface characteristics enabled by PMEDM [23]. The review also seeks to analyze the influence of various non-electrical and electrical parameters on the PMEDM technique. This involves discussing how parameters such as voltage (V), current (I_p), polarity, pulse duration (T_{on} and T_{off}), powder concentration (P_c), and dielectric medium affect the outcomes of the PMEDM technique [24, 25].

Furthermore, this review will evaluate the impact of different powder additives on the PMEDM technique. It will critically review the roles of various powder additives in enhancing machining performance and modifying the surface properties of commonly used biomaterials, such as cobalt-chromium alloys, titanium (Ti) alloys, stainless steel (SS), and magnesium (Mg) alloys. The effects of different types of powders and their concentrations on the performance of machining and surface integrity of these biomaterials will be considered [26, 27]. In addition, the review will discuss the applications of PMEDM in the biomedical field, focusing on its practical use in fabricating medical implants, including dental, orthopedic, and cardiovascular implants. The improvements in biocompatibility and performance achieved through PMEDM will be highlighted, supported by case studies and real-world examples [28, 29]. Moreover, the review aims to identify the current limitations and challenges of PMEDM, including the uniformity of powder distribution in the dielectric medium, control of powder concentration, and stability of the machining process. It will propose potential research directions and technological advancements to overcome these obstacles and further enhance PMEDM's capabilities [30]. Finally, the review will provide a critical overview of recent literature on PMEDM, synthesizing findings from various studies to offer a brief understanding of the modernity of PMEDM. It will identify trends, gaps, and future opportunities in the field, providing a valuable reference for researchers, engineers, and practitioners interested in PMEDM and its applications in biomaterials fabrication [31, 32]. By achieving these objectives, this review aims to contribute to the growing body of knowledge on PMEDM and its applications in biomaterials fabrication. The insights provided will be valuable for advancing development and research efforts in this area, ultimately leading to the creation of advanced medical implants with superior performance and biocompatibility [33-35].

1.3. Fundamentals of PMEDM.

Electric discharge machining (EDM) is an unconventional machining technique that removes material from a workpiece by utilizing electrical discharges. The basic EDM technique involves submerging the workpiece and tool in a dielectric medium. The electrode, which serves as the tool, is connected to a power supply that generates a series of electrical pulses. When a voltage is applied, it creates a spark gap between the electrodes. This field ionizes the dielectric fluid, creating a plasma channel through which a spark discharge occurs [36].

The heat generated by the electrical discharge is extremely localized, reaching temperatures of approximately 10,000°C. This intense heat melts and evaporates the material from the workpiece, as well as some amount of the electrode. Dielectric medium helps to cool the molten material rapidly, forming (RLT) recast layer thickness with micro holes, microcracks, and residual stresses on the machined surface. The dielectric medium also helps flush away eroded particles, maintaining a clean machining environment and preventing short circuits [37].

The EDM is a well-defined technique for machining hard and electrically conductive materials, making it ideal for applications where conventional machining methods are ineffective. It can produce complex geometries and fine details with high precision, which is particularly valuable in industries such as aerospace, automotive, and biomedical engineering. However, the EDM technique has some limitations, including high tool wear rate (TWR) and low material removal rate (MRR), which can impact efficiency and cost-effectiveness [38].

1.4. Enhanced PMEDM technique.

To reduce the limitations of traditional EDM, the PMEDM process was developed. PMEDM enhances the conventional EDM technique by introducing fine (micro and nano) powder particles into the dielectric fluid. These particles, typically made of materials like aluminum, copper, or silicon, play a crucial role in improving the machining performance and surface morphology of the workpiece [39, 40]. The presence of powder particles in the dielectric medium alters the discharge mechanism. The powder particles reduce the dielectric's insulating strength, facilitating the formation of multiple discharge channels. This results in more stable and uniform discharges, which significantly improve MRR and TWR. The powder particles also increase the spark gap between the electrodes, improving debris flushing and reducing the likelihood of short circuits [41, 42].

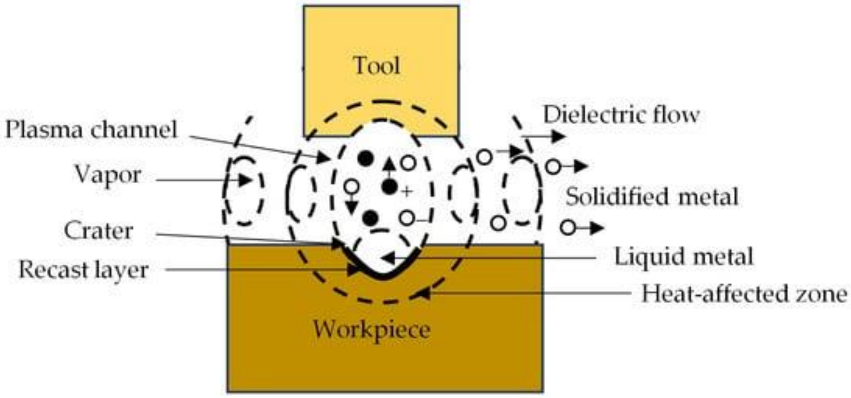


Figure 1. PMEDM technique diagram. Reproduced from[44], under the terms of the CC BY 4.0 license.

The main advantage of PMEDM is its ability to produce a modified surface layer with enhanced properties. During machining, the powder particles formed a composite layer on the workpiece surface, thereby improving surface characteristics such as wear resistance, hardness, and biocompatibility. For example, PMEDM can be used to machine titanium alloys for medical implants, resulting in surfaces with improved hardness and reduced residual stresses [43].

Figure 1 provides a schematic diagram of the proposed PMEDM technique [44]. This diagram illustrates the setup of the PMEDM system, including the tool electrode, the workpiece, and a dielectric medium containing conductive powder particles. The figure highlights the interaction between electrical discharges and powder particles, demonstrating how the particles improve machining performance and the workpiece's surface morphology.

Figure 2 presents a diagram of the EDM setup [45]. This figure shows the basic components of the EDM system, including the power supply, electrode, workpiece, and dielectric fluid.

The addition of powder particles in the PMEDM technique introduces significant enhancements over the traditional EDM technique. The particles not only improve the stability and uniformity of the discharges but also contribute to the formation of a superior surface layer on the workpiece, making PMEDM a highly effective technique for machining advanced materials and producing high-quality surfaces [46].

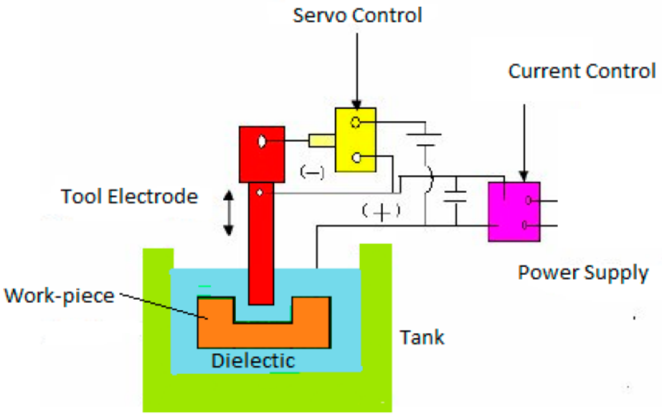


Figure 2. EDM setup diagram. Reproduced from [45], under the terms of the CC BY 4.0 license.

2. Influence of Electrical and Non-Electrical Parameters on PMEDM

2.1. Electrical factors.

The performance of PMEDM is significantly influenced by various electrical factors. These factors play an important role in determining the efficiency of material removal, tool wear rate, surface finish, and overall machining performance. Understanding and optimizing these electrical parameters are essential for achieving the desired machining outcomes.

2.1.1. Current.

Peak Current is the most critical electrical parameter in PMEDM. It influences the intensity of the electric discharges between the electrodes. Higher current levels produce more intense discharges, thereby increasing the material removal rate (MRR). However, excessively high current can also increase the tool wear rate (TWR) and surface roughness [47].

In PMEDM, the presence of powder particles in the dielectric medium can moderate the effects of current. These particles help stabilize the discharge process by creating multiple conductive paths that distribute electrical energy more evenly. This stabilization can enhance the MRR while reducing the adverse effects of high current, such as excessive tool wear and surface damage. Additionally, the particles can act as micro-electrodes, facilitating more efficient energy transfer and improving the overall machining performance [48]

Optimizing the current level is essential for balancing MRR and TWR. Lower current settings typically result in finer surface finishes and reduced tool wear, but at the cost of slower material removal. Conversely, higher current settings can significantly increase the MRR but may compromise surface quality and tool longevity. The optimal current setting in PMEDM depends on the material being machined and the required surface characteristics [4, 49].

2.1.2. Pulse duration.

Pulse duration or ON time (T_{on}) of the electrical discharge is another crucial factor in PMEDM. It determines the duration of the spark gap between the electrodes, directly affecting the thermal impact on the workpiece. Shorter pulse durations tend to produce less heat, resulting in finer surface finishes and reduced thermal damage to the workpiece. However, shorter pulses also reduced the material removed per discharge, potentially reducing the MRR [50].

In contrast, longer pulse durations allow for more energy to be transferred to the workpiece, increasing the material removal per discharge. This can improve MRR but also increases the risk of thermal damage, such as microcrack formation and recast layers. The presence of powder particles in PMEDM can help mitigate these effects by promoting a more uniform energy distribution and reducing localized overheating [51].

Optimizing pulse duration involves balancing the trade-offs between MRR and surface integrity. For applications requiring high precision and excellent surface quality, shorter pulse durations are preferable. For applications prioritizing higher MRR, longer pulse durations may be more appropriate. The ideal pulse duration settings will depend on the particulars of the machining application as well as the characteristics of the material being machined [52].

2.1.3. Voltage.

Voltage is a fundamental parameter in PMEDM that influences the formation and stability of the electrical discharge. Higher voltage levels can increase the energy per discharge, thereby enhancing the material removal rate. However, excessively high voltage can also lead to unstable discharges, increased tool wear rate, and degraded surface quality due to excessive thermal energy [53]. In PMEDM, the dielectric medium mixed with conductive powder particles helps stabilize the discharge at higher voltages. The powder particles reduce the dielectric strength, enabling more consistent and controlled discharges. This stabilization can improve machining performance and surface quality while mitigating the negative effects of high voltage [54]. Optimal voltage settings in PMEDM depend on the material being machined and the desired machining outcomes. Lower voltage settings are typically used for precision machining applications where surface quality is critical. Higher voltage settings can be used to enhance MRR but require careful management to prevent excessive tool wear and surface damage. The dielectric medium can provide greater flexibility, optimizing voltage settings by enhancing discharge stability and efficiency when powder particles are present [55].

2.1.4. Polarity.

Polarity refers to the configuration of the electrical connections between the electrodes. In PMEDM, the polarity can play a significant role in the machining performance, influencing factors such as TWR, MRR, and surface quality. There are two primary polarity configurations: positive polarity (electrode positive) and negative polarity (electrode negative) [4]. In positive polarity, the positive terminal of the power supply is connected to the tool, and the negative terminal is connected to the workpiece, resulting in improved MRR because the positive electrode tends to erode more material from the workpiece. But also lead to higher tool wear rates and poorer surface finish due to the increased thermal load on the electrode [56]. Negative polarity, in which the negative and positive terminals of the power supply are connected to the tool and workpiece, respectively, results in better surface quality and lower tool wear rate. This is because the negative electrode experiences less thermal loading, thereby reducing electrode wear and improving surface integrity. But MRR may be lower in this configuration compared to positive polarity [57].

2.2. Non-electrical factors.

2.2.1. Dielectric fluids.

Dielectric fluids are crucial non-electrical factors in the PMEDM technique, significantly influencing machining performance and surface quality. The primary purpose of dielectric fluids in the PMEDM technique is to act as an insulating medium, to prevent eroded particles, and to cool the machining zone. The choice of dielectric medium affects the stability of electrical discharges, MRR, TWR, surface roughness (SR), RLT, and microhardness of the machined surface [58].

The various types of dielectric medium used in the PMEDM technique are shown in Figure 3. The effectiveness of different types of dielectric fluids can be assessed based on their physical characteristics and their impact on EDM performance.

Table 1 presents the physical characteristics of common dielectric fluids in the PMEDM technique. The table includes vital parameters, such as breakdown strength, flash point, specific heat, and thermal conductivity, for three types of dielectric fluids: mineral oil, kerosene, and Deionized water [59-61].

Table 1. Thermo-physical properties of the applied dielectric medium in the PMEDM technique.

Dielectric fluid	Thermal conductivity (W/mK)	Specific heat (J/kg.K)	Breakdown strength (Kv/mm)	Flash point (°C)	Reference
Kerosene oil	0.140	2100.0	24.0	37.0 to 65.0	[62, 63]
Denoised water	0.623	4200.0	65.0 to 70.0	Not Applicable	[64, 65]
Mineral oil	0.130	1860.0	10.0 to 15.0	160.0	[66]

Table 2 presents the physical properties of edible/non-edible (biodegradable) oil in the PMEDM technique. The table includes various properties, such as viscosity, thermal conductivity, flash point, density, and specific heat.

Table 2. Thermo-physical properties of bio-degradable dielectric fluid.

Type	Viscosity (cm^2/S)	Thermal conductivity (W/m.K)	Flash point (°C)	Density (mg/cm^3)	Specific heat (kJ/kg K)	Reference
Waste vegetable oil (35°C)	0.402	0.22	225	0.924	1.67	[67]
Sunflower oil	0.085	0.159	250	0.92	2.24	[68, 69]
Peanut oil	0.11	0.144	283	0.914	2.05	[70]
Neem oil	4.3	0.15	214	0.868	1.962	[71, 72]
Kusum oil (40°C)	40	0.168	204	0.862	1.96	[73, 74]

Type	**Viscosity (cm^2/S)**	**Thermal conductivity (W/m.K)**	**Flash point (°C)**	**Density (mg/cm^3)**	**Specific heat (kJ/kg K)**	**Reference**
Jatropha curcas oil (40°C)	35.8	0.174	290	0.904	2.76	[75, 76]
Canola oil (40°C)	5.8	0.157	330	0.92	1.910	[77, 78]
Coconut oil	55	0.321	295	0.91	1.6	[69, 78]
Palm oil (27°C)	4.57	0.147	148	0.875	2.03	[69]
Pongamia pinnata (35°C)	40.2	0.22	225	0.924	NA	[79]
Blended used VO (35°C)	31.7	0.11	234	0.790	NA	[63]

2.2.2. Breakdown strength.

This parameter indicates the maximum voltage the dielectric medium can withstand before breaking down and allowing a discharge. Mineral oil has a breakdown strength of 15-10 kV/mm, kerosene has a breakdown strength of 24 kV/mm, and Deionized water has the highest breakdown strength of 65-70 kV/mm. Higher breakdown strength can lead to more stable and controlled discharges [80].

2.2.3. Flash point.

It is the temperature at which an ignitable combination in air can be formed by the dielectric medium vaporizing. Mineral oil has a flash point of 160°C, making it safer to handle compared to kerosene, which has a flash point range of 37-65°C. De-ionized water, being non-flammable, does not have a flash point, which is an advantage in terms of safety [81].

2.2.4. Specific heat.

This is the amount of heat needed to increase the fluid's temperature by one Kelvin. Mineral oil has a specific heat of 1860.0 J/kgK, kerosene has 2100.0 J/kgK, and De-ionized water has the highest specific heat of 4200.0 J/kgK. Higher specific heat means the fluid can absorb more heat, which is beneficial for cooling the machining zone and reducing thermal damage [82].

2.2.1.4 Thermal conductivity.

This parameter measures the ability of the dielectric medium to conduct heat. Mineral oil has a thermal conductivity of 0.130 W/mK, kerosene has 0.140 W/mK, and De-ionized water has a significantly higher thermal conductivity of 0.623 W/mK. Fluids with higher thermal conductivity can dissipate heat more efficiently, contributing to better cooling and reduced thermal stresses [83].

The selection of the dielectric medium is essential for optimizing the PMEDM technique. Mineral oil, with its moderate breakdown strength and high flash point, is often preferred for applications requiring stability and safety. Kerosene, with its higher breakdown strength and specific heat, is suitable for applications demanding efficient heat absorption and moderate stability. De-ionized water, with its superior breakdown strength, specific heat, and thermal conductivity, is ideal for applications requiring excellent cooling and minimal thermal damage. However, it requires careful handling due to its conductive nature [84].

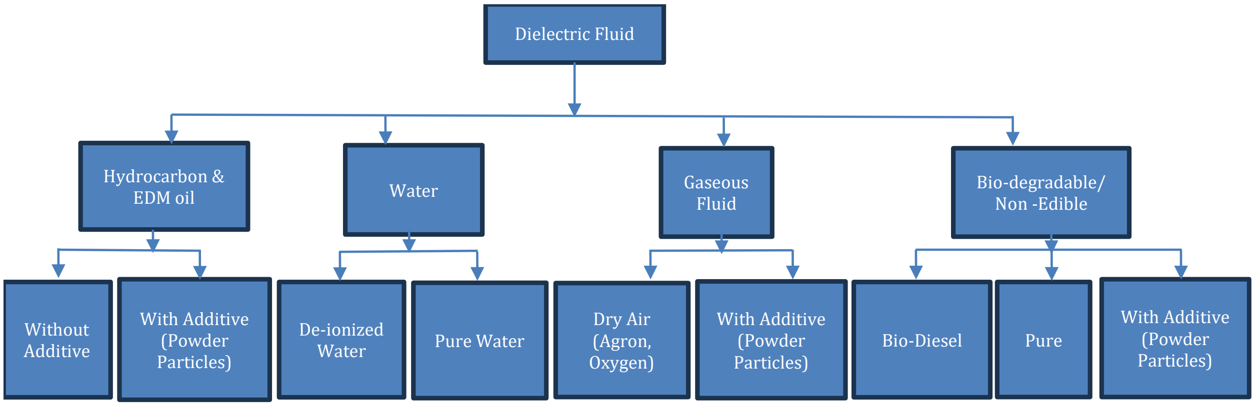


Figure 3. Various types of dielectric fluids are used in the EDM technique.

2.2.5. Powder concentration.

Powder concentration is a critical non-electrical factor in the PMEDM technique. It refers to the amount of conductive particles in the powder mixed with the dielectric medium, which can significantly influence the machining performance and surface characteristics of the workpiece. Powder particle concentration affects various aspects of the PMEDM technique, including the stability of electrical discharges, MRR, TWR, SR, and the formation of the RLT [58, 85].

In PMEDM, an optimal particle concentration is essential for efficient machining. When the concentration is too low, the particles may not adequately enhance the electrical discharge characteristics, resulting in limited improvements in MRR and TWR. Conversely, if the concentration is too high, it can lead to excessive particle agglomeration, resulting in short-circuiting and unstable discharges and negatively impacting machining performance [86]. The presence of powder particles in the dielectric medium helps to stabilize the discharge gap by creating multiple conductive paths. This stabilization results in more uniform, controlled discharges, enhancing MRR and reducing TWR. Additionally, the particles facilitate better flushing of debris from the machining surface, preventing the accumulation of eroded material and maintaining a cleaner machining environment [87].

Experimental studies have shown that various types of powder particles, such as aluminum, copper, and silicon, can have different effects on the PMEDM technique depending on their concentration. For instance, aluminum particles are known to improve surface roughness and MRR at moderate concentrations, while copper particles can enhance thermal conductivity and reduce TWR. The choice of powder type and its optimal concentration depend on the requirements of the machining application and the material being processed [11, 85, 88].

Figure 4 highlights the complex interplay among these factors and their combined impact on the PMEDM technique, and provides a detailed summary of the combined effects of electrical/non-electrical parameters on PMEDM, illustrating their impact on machining and surface properties.

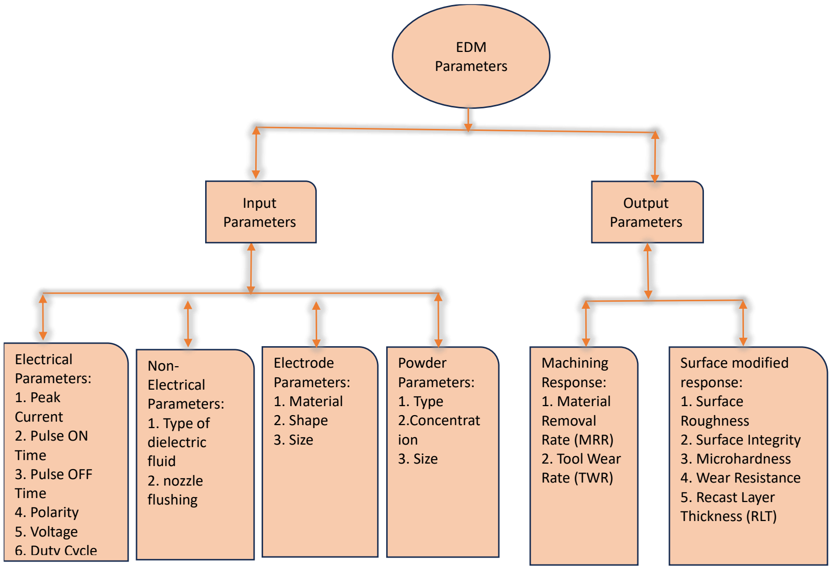


Figure 4. Expected outcomes of the PMEDM technique with various input factors.

For instance, it shows that electrical parameters like current and pulse duration directly influence the energy delivered to the workpiece, thereby affecting MRR and TWR. Similarly, non-electrical parameters, such as the type of dielectric medium and powder concentration, play a major role in stabilizing the discharge process and improving surface properties. The figure underscores the importance of optimizing both sets of factors to achieve the desired machining outcomes and surface characteristics.

3. Effect of Additional Powders on PMEDM Operation

The addition of powder particles into the dielectric medium in the PMEDM technique significantly improves the machining performance and surface quality of the work material. These powders, which can include materials such as aluminum, copper, graphite, and silicon, enhance various aspects of the machining process, including MRR, TWR, SR, and microhardness. The type and concentration of the mixed powder particles play an important role in determining the effectiveness of PMEDM, thereby improving surface quality, corrosion resistance, and wear resistance [89].

3.1. Material removal rate (MRR).

MRR is one of the most critical performance metrics in PMEDM. The addition of conductive powders to the dielectric medium can significantly enhance the MRR by improving the stability and intensity of the electrical discharges. The particles create multiple discharge channels, enabling more uniform and consistent energy transfer to the workpiece and resulting in higher MRR [90]. A thorough analysis of the effects of various materials and additive powders on MRR and TWR is given in Table 3. The table highlights how various powders impact these key performance metrics, demonstrating that certain powders, such as aluminum and copper, are particularly effective in increasing MRR due to their high thermal and electrical conductivity. These powders facilitate more efficient energy transfer during discharge, leading to higher material removal rates than in traditional EDM without powder additives [91].

Table 3. A thorough analysis of the effects of various materials and added powder particles on MRR and TWR.

Biomaterials	Additive powders	Tool (electrode) material	Outcomes	References
316L SS	Ti	Copper/ Graphite	The authors found that a long pulse-off length in conjunction with a low powder concentration reduces the quantity of sparks and, as a result, the gap's discharge energy with the tool's polarity set to negative. Moreover, Ti and SiC exhibit greater heat resistance and electrical resistivity, requiring a higher current and application for chain production. This led to a decline in MRR and TWR. The formation of TiC on the electrode and workpiece surfaces reduced the MRR and TWR. Conversely, a lower additive concentration was observed with higher TWR when using positive tool polarity settings.	[93]
	SiC	Copper	The tool's negative polarity setting lessens sparks, which lowers the gap's discharge energy. Furthermore, Ti and SiC have higher electrical resistivity and heat resistance, which means that in order to produce chains, greater current and application are required. MRR and TWR decreased as a result.	[94]
	CNT/HAp	Copper	Researchers discovered that longer pulse-on times and higher discharge currents lead to increased spark formation in the discharge gap. This accelerates the machining-induced degradation of the electrode material, raising the MRR and TWR.	[95-97]
Mg Alloy	Al	Copper	Both additives have a high conductivity. Both TWR and MRR increased suddenly as a result of an increase in the quantity of these particles and the discharge current.	[98]
	Gr	Al		[99]
Ti Alloy	Ag	WC	Given that WC is a harder and higher melting point material, the tool's TWR decreased as a result of the enhanced electrical and thermal conductivity brought on by the addition of Ag.	[100]
	HAp	Copper (Cu)	HAp is often considered to be a non-conductive material, but when it was used in an EDM process, the spark gap grew, improving the stability of the machining process. Applying HAp powder also necessitates higher applied voltage and discharge current in order to aid the process. A rise in the current led to an increase in MRR.	[101]
	CNT	Cu	Although MRR originally increased, TWR and MRR both declined. This might be because of the CNT's increased electrical and thermal conductivity, which causes it to produce heat and enlarge the discharge gap.	[102]
	Si	Cu	Copper Si increased sparks in the gap due to a long pulse-on duration produced a high MRR and a few microcracks. However, because of the production of TiC on the electrode surface, the addition of Si powder decreased TWR.	[103]
	Si	Pure Ti		[104]
	HAP	Pure Ti	As pulse duration increased, MRR and TWR first climbed before declining. This can be the result of machining that is unstable due to inadequate flushing and non-conductive material.	[105]
	HAp	Pure Ti	When HAp was applied, MRR initially decreased because of its lower conductivity, which forced the electrode to approach the workpiece in order to reduce the breakdown strength. As a result, both MRR and TWR were decreased by the unstable machining caused by microscopic gaps. Following the aforementioned conditions' resolution, additional HAp addition raised MRR and TWR.	[106]
	CNT	Graphite (Gr)	The inclusion of B4C and CNT both increased MRR, despite B4C's poorer conductivity. This could be linked to a highly conductive copper electrode.	[107]
	B_4C	Cu		[108]
	Gr	Cu	MRR increased as discharge current increased, but decreased as powder was added in greater amounts. Increased Gr addition led to erratic machining and a decrease in MRR.	[109]

3.2. Tool wear rate (TWR).

TWR is another essential factor in PMEDM, as it directly impacts the longevity and cost-effectiveness of the machining process. Adding powders to the dielectric medium can reduce TWR by stabilizing the discharge and minimizing thermal loading on the electrode. The powders act as a buffer, reducing the direct impact of discharges on the electrode and thereby decreasing the wear rate [92].

Figure 5 (a) shows the zigzag movement, and Figure 5 (b) shows powder particle bridging in the PMEM process [74]. This figure shows how the conductive powder particles interact with the electrical discharges, creating a more stable discharge environment that protects the electrode from excessive wear. The chain-like particle formations help distribute electrical energy more evenly across the machining zone, reducing localized overheating and minimizing TWR [74].

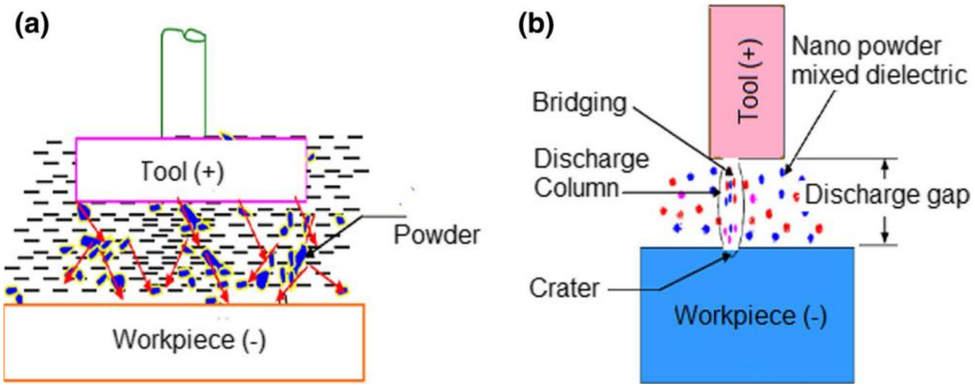


Figure 5. showing the **(a)** zigzag movement; **(b)** bridging of particles of powder in the PMEM technique. Reproduced with permission from [74], published by Springer Nature, 2020. DOI: https://doi.org/10.1007/s40430-020-02597-8.

3.3. Surface roughness (SR).

SR is a critical indicator of the surface quality achieved during PMEDM. Adding powders to the dielectric medium can significantly improve SR by facilitating smoother, more consistent discharges. The powder particles help fill micro-gaps in the spark area, facilitate uniform material removal, and produce a super surface finish [110].

A thorough analysis of the effects of different materials and mixed powder particles on surface responses is given in Table 4. The table shows that powders such as silicon and graphite are particularly effective at reducing SR, as they help smooth the discharge process and minimize the formation of microcraters on the workpiece surface.

Table 4. A thorough analysis of the effects of different materials and mixed powder particles on surface responses.

Biomaterials	Additive powders	Tool material	Key outcomes	References
Ti Alloy	Ag	WC	Ag was deposited during PMEDM, which produced a coating with a 2.49 μm thickness. While the SR decreased, the microhardness improved by 528.390 HV.	[100]
	HAp	Cu	Lower SR and an 82% increase in wear resistance were the outcomes of adding HAp. This could be connected to the surface deposition of bioceramic layer and hard carbide on Ti-Alloy.	[101]

Biomaterials	Additive powders	Tool material	Key outcomes	References
	CNT	Cu	Rich in carbon, CNT is a highly conductive material. It stabilizes the process and reduces the possibility of cracks emerging when added to the EDM fluid.	[102]
	Si	Cu	SR decreased as a result of the increased conductivity of the additional Si and the reduced discharge energy levels utilized to stabilize the machining processes.	[103]
	Si	Pure Ti	In contrast, increasing the amount of powder created a 200–500 nm nanoporous surface, a 15–20 µm RLT, increased corrosion resistance, and microhardness. Reduction of the powder addition resulted in cracks and residual stresses. Therefore, in order to create a surface devoid of cracks, it can be recommended to employ a high concentration of Si powder.	[104]
	HAp	Pure Ti	Compared to other conductive powders, HAp is unable to considerably expand the machining gap. Deeper craters indicate increased material loss. When a large concentration of HAp was applied, this produced a high SR. A 9 µm-thick covering with several microcracks was created by the powder that was deposited. Three times as much surface hardness was increased by the carbide, and the carbide formed.	[106]
	Al	W-Cu	The SR improved by 38.46%, stabilizing the EDM process by increasing the conductivity of the Al powder.	[111]
	HAp/CNT	Cu	The removal of HAp/CNT on the substrate surface results in the production of bio-compatible oxide and improves surface morphology.	[112]
	Si	Cu	The machining gap's spark rate is increased by the Si powder's strong conductivity. The heated surface was subsequently quenched by the running dielectric fluid, which caused high gas escapes, in the form of bubbles. This results in a large number of 50–200 nm nanopores on the machined surface.	[113]
	Si	Pure Ti	Due to its high conductivity, Si powder stabilizes processes when added to dielectric fluids. Moreover, it increases the machining gap for appropriate flushing. As a result, RLT, microhardness, and wear rate were all improved.	[114]
	SiC	Al	Microhardness and material migration increased with lower current and greater powder application; RLT reduced as powder concentration increased. This could have to do with using Al electrodes.	[115]
	HAp	Pure Ti	A bio-ceramic covering with exceptional microhardness, resistance to corrosion, and biocompatibility is produced by adding HAp. The coating thickness was increased to approximately 7 µm by adding more powder.	[116]
	SiC	Cu	Greater material removal is made possible by high discharge energy, which results in larger craters. However, as the current grew, the SR decreased, the RLT increased, and 630 HV microhardness was produced. Low RLT was made easier to acquire by the scouring action.	[117]
316L SS	Ti	Gr	Titanium is a very hard substance. When applied to a machined surface, it significantly increases surface microhardness and lowers surface roughness.	[93]
	HAp	Cu	The scouring effect of HAp addition lowers roughness, and its biocompatibility led to an increased production of biocompatible oxide on the machined surface.	[96]
	HAp	Cu	On the machined surface, HAp addition led to the formation of a hard, biocompatible oxide layer. The implant that was created as a result has improved microhardness and bioactivity.	[97]
	TiO_2	W	The machined surface's resistance to wear and surface hardness are improved by the formation of hard oxides and carbides.	[118]
	Si	W-C	The addition of SiC powder led to the formation of a strong carbide layer, increasing surface roughness and SR.	[119]
		Cu		[94]
Mg Alloy	HAp	Mg-Ca	HAp removal improved the wear resistance and microhardness. Furthermore, SR increased with powder concentration and decreased with lowering current.	[120]

Biomaterials	Additive powders	Tool material	Key outcomes	References
	HAp	Mg-Ca	At first, adding powder decreased SR; however, adding more mixture increased SR. Surprisingly, as additional powder was added, the deposition rate rose; initially, RLT fell, but as more HAp was added, it increased. This is because the HAp powder has extremely low conductivity, leading to an unstable machining process.	[121]
	Zn	Cu	With the addition of powder, SR and corrosion rate decreased, and cracks were observed. This could be related to the zinc powder's high conductivity, which enhances spark and machining stability.	[122]
	TiC	Cu	Particle addition increased SR, while carbide production increased wear resistance. This is because a remarkably robust carbide layer has formed on the machined surface.	[123]
	Zn	Cu	SR was reduced greatly with the high conductivity of the Zn powder by stabilizing the EDM process.	[124]
	Al	Brass, Cu, SS	Cu and Brass electrodes yielded more SR and MRR than SS electrodes, while the addition of powder particles contributed to an increase in SR and MRR. This is as a result of the Cu and brass electrodes having higher conductivities than the SS electrode.	[125]

3.4. Microhardness.

Microhardness is a measure of the workpiece surface’s hardness after machining. In PMEDM, the addition of powders can enhance microhardness by forming a composite surface layer that combines the workpiece material with the powder particles. This composite layer is typically more wear-resistant and harder than the base material alone, making it ideal for applications where surface durability is critical [126].

The increase in microhardness is particularly pronounced when using powders with high hardness and thermal stability, such as silicon carbide or tungsten. These powders contribute to the formation of a dense, hard surface layer, thereby improving the overall mechanical properties of the machined material. The improved microhardness also contributes to better wear resistance and longer component life, which are crucial for high-performance applications [127].

3.5. Corrosion resistance.

Corrosion resistance is an important mechanical property in many PMEDM applications, particularly in the fabrication of components exposed to harsh environments. Adding powders to the dielectric medium can enhance corrosion resistance by altering the surface chemistry of the workpiece. Powders such as aluminum and titanium can form protective oxide layers on their surfaces, which act as barriers against corrosive agents [128].

The formation of these protective layers is facilitated by chemical and thermal interactions between the powders and the workpiece during discharge. The result is a surface that is not only harder but also more resistant to corrosion, making it suitable for aerospace, marine, and biomedical applications. The enhanced corrosion resistance extends the service life of the components and reduces maintenance costs [82].

3.6. Wear resistance.

Wear resistance is another key performance metric influenced by the addition of powders in PMEDM. Powders that promote the formation of a hard, wear-resistant surface layer, such as tungsten carbide or chromium, can significantly improve the surface machined's wear resistance.

The composite surface layer formed during PMEDM is typically more resistant to abrasion and mechanical wear than the base material [17]. The improved wear resistance is particularly beneficial in applications where components are subjected to high mechanical stress or abrasive environments. The use of PMEDM with appropriate powders can produce components with superior wear properties, reducing the need for frequent replacements and improving the overall reliability of the machinery [85].

4. Applications of PMEDM in Biomaterials

The application of PMEDM in biomaterials has attracted significant attention due to its ability to enhance the surface quality and mechanical properties of biomedical implants. The process is particularly valuable for machining complex shapes and hard-to-cut machine materials commonly used in the medical field, such as SS, Ti alloys, Mg alloys, and cobalt-chromium alloys. The PMEDM process improves machining efficiency while enhancing the biocompatibility and longevity of medical implants [17]. Recent studies have shown that integrating nanomaterials, such as carbon nanotubes, graphene oxide, and cellulose nanofibers, into EDM and membrane-based separations can greatly improve adsorption performance and enable sustainable applications [129,130]. The use of biodegradable dielectrics in PMEDM has been gaining recognition because they generate less environmental pollution while maintaining acceptable machining performance [129].

4.1. Commonly used biomaterials.

4.1.1 Titanium alloys.

Ti alloys are commonly used in the medical industry due to their excellent biocompatibility, high strength-to-weight ratio, and superior corrosion resistance. However, the low thermal conductivity and high hardness of Ti alloys make them challenging to machine using conventional methods. PMEDM offers a solution by enabling precise machining with minimal thermal damage and improved surface characteristics. The mixing of conductive powders, such as graphite or aluminum, in PMEDM can reduce residual stresses, improve surface roughness, and increase the hardness of machined titanium implants, making them more suitable for load-absorbing applications in orthopedic and dental implants [43].

4.1.2. Magnesium alloys.

Magnesium alloys are highly used in biomedical applications due to their biodegradability and favorable mechanical characteristics. Mn alloys are particularly promising for temporary implants, such as those used in bone fixation devices, where gradual degradation is desired. Due to low melting and high reactivity, it isn't easy to machine Mn alloys. PMEDM allows for precise control of the machining process, minimizing thermal damage and improving the surface integrity of magnesium implants. The use of powder additives, such as calcium phosphate, in PMEDM can further enhance the biocompatibility and osteointegration of magnesium-based implants [15].

4.1.3. Stainless steel.

Stainless steel's mechanical strength, corrosion resistance, and affordability make it a preferred choice for a wide range of biomedical applications. It is frequently utilized in surgical equipment, cardiovascular devices, and orthopaedic implants. PMEDM is very good at machining stainless steel because it can produce intricate shapes with extreme accuracy while preserving the material's mechanical properties. Stainless steel implants can be made more wear-resistant by adding particles such as silicon carbide to the dielectric medium during PMEDM. These additions can increase hardness, improve surface polish, and decrease the production of recast layers [16].

4.1.4. Cobalt-chromium alloys.

Cobalt-chromium alloys are widely used in applications requiring high wear resistance, such as dental prosthetics and orthopedic implants. These alloys are known for their excellent biocompatibility, strength, and corrosion resistance. However, their high hardness and strength make them difficult to machine. PMEDM provides a viable solution by enabling the machining of cobalt-chromium alloys with reduced TWR and enhanced surface finishing. The use of appropriate powder additives, such as tungsten or chromium, can further enhance the wear resistance and biocompatibility of machined surfaces, thereby extending implant lifespan [43].

Table 5 compares the mechanical and physical properties of these commonly used biomaterials, highlighting differences in tensile strength, hardness, and corrosion resistance. The table highlights the challenges associated with machining these materials and the advantages of using PMEDM to overcome them, particularly in achieving superior surface finishes and enhancing the overall performance of implants [61, 101, 115, 117, 125, 131].

Table 5. Physical and mechanical properties of commonly used biomaterials.

Biomaterials	**Thermal conductivity (W/mK)**	**Fusing point (°C)**	**Electrical resistivity (μΩ-cm)**	**Young's modulus (GPa)**	**Density (mg/cm^3)**	**Tensile strength (MPa)**
Ti-6Al-4V	7.3	1933	170	113.8	4.43	950
316L SS	67	1648	81	200	7.9	490
Zr Alloy	4	644	42	95	6	1791
WE43 Alloy	51.3	540-640	4	44.2	1.8	220
NiTi Alloy	10	1300	100	75	6.45	755-960
Pure Ti	22	1940	55	105	4.72	240-360
Pure Mg	155	923	5	45	1.74	90-190
AZ31 Alloy	96	630	3	45	1.78	263
AZ91 Alloy	72	500	5	45	1.81	150

4.2. Application in orthopedic implants.

Orthopedic implants, such as knee and hip replacements, require materials that offer wear resistance, high strength, and biocompatibility. Ti alloys, SS, and cobalt-chromium alloys are commonly used for these applications. PMEDM has been effectively utilized in the machining of these materials, enabling the production of implants with complex geometries and enhanced surface characteristics. For instance, the use of PMEDM in machining titanium hip implants has been shown to improve surface roughness and hardness, thereby enhancing wear resistance and prolonging implant life. Additionally, the process allows incorporation of bioactive coatings, such as calcium phosphate, which can enhance osteointegration and reduce the risk of implant loosening [132].

4.3. Application in cardiovascular devices.

Cardiovascular devices, including heart valves and stents, require materials that are not only biocompatible but also capable of withstanding the dynamic environment of the human circulatory system. Stainless steel and cobalt-chromium alloys are frequently used in these devices due to their strength and corrosion resistance. The process also improves the material properties of the machined surfaces, such as hardness and smoothness, which are critical for reducing the risk of strokes and improving device performance. Studies have demonstrated that stents and heart valves manufactured using PMEDM exhibit superior durability and biocompatibility, contributing to better patient outcomes [133].

5. Surface Modification and Coating in PMEDM Process

Surface modification and coating are critical aspects of the PMEDM process, especially when applied to biomaterials. The ability of PMEDM to alter machined surface properties, such as biocompatibility, hardness, and wear resistance, makes it an invaluable technique for fabricating high-performance components and medical implants. This section delves into the mechanisms of surface modification, the types of coatings that can be achieved through PMEDM, and their impact on biocompatibility [134].

5.1. Mechanisms of surface modification.

Surface modification in PMEDM primarily occurs through the migration and alloying of materials during machining. When conductive powder particles are mixed with a dielectric fluid, they become energized by electrical discharges, leading to the development of a plasma channel that facilitates material migration from the electrode and the powder onto the work surface. This results in the production of the composite layer on the workpiece, which can significantly enhance its surface properties [135].

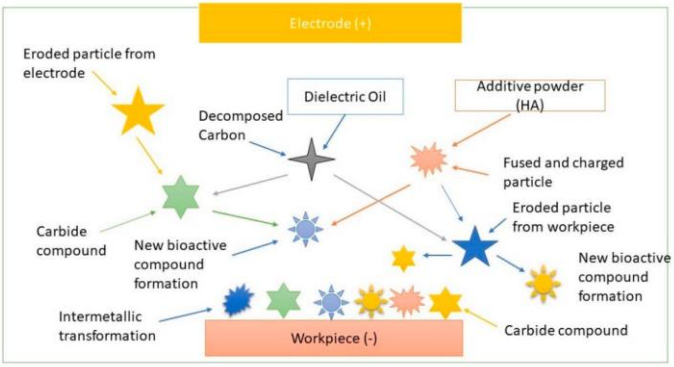


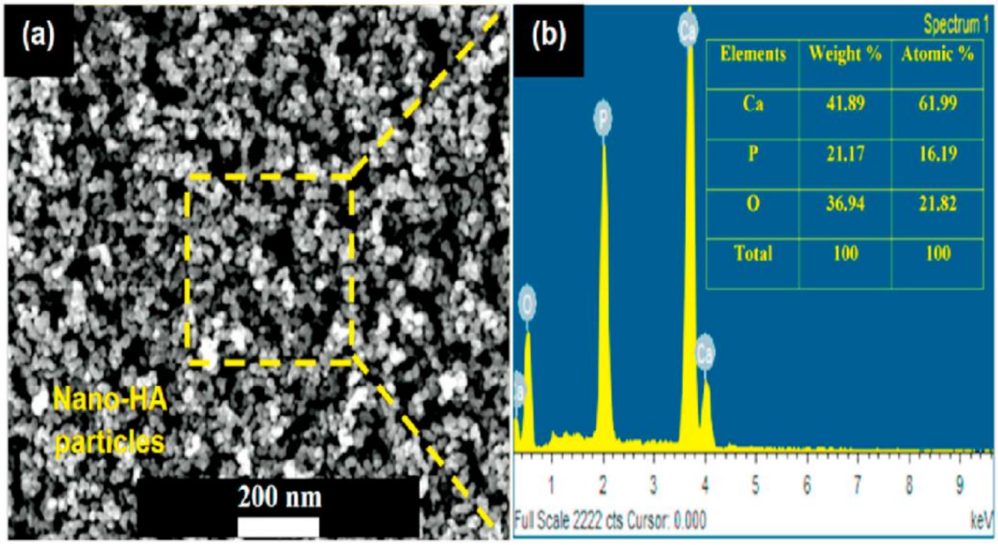
Figure 6. PMEDM technique's material scattering and alloying mechanism. Reproduced from [136], under the terms of the CC BY 4.0 license5.2. Types of coatings achieved.

Figure 6 illustrates the PMEDM technique's material-scattering and alloying mechanisms [136]. In this figure, the material from the electrode and the added powder particles are shown to be transferred to the work surface through the plasma channel created during the discharge. This migration results in a modified surface layer that incorporates elements from both the tool and the added powders. This process can enhance properties such as corrosion resistance, wear resistance, and hardness, depending on the types of powders used [11].

The types of coatings achieved through PMEDM depend on the choice of powder materials and the specific process parameters. Coatings can range from simple surface modifications to the deposition of complex, multi-layered structures with enhanced mechanical and chemical properties. The choice of powder additives, such as aluminum, magnesium, or silver, can significantly influence the nature of the coatings formed.

This coating can improve the hardness and wear resistance, making the material more suitable for applications where durability is critical. The uniform distribution of powder across the material surface also improves the overall surface finish, reducing roughness and enhancing the material's aesthetic and functional qualities [137].

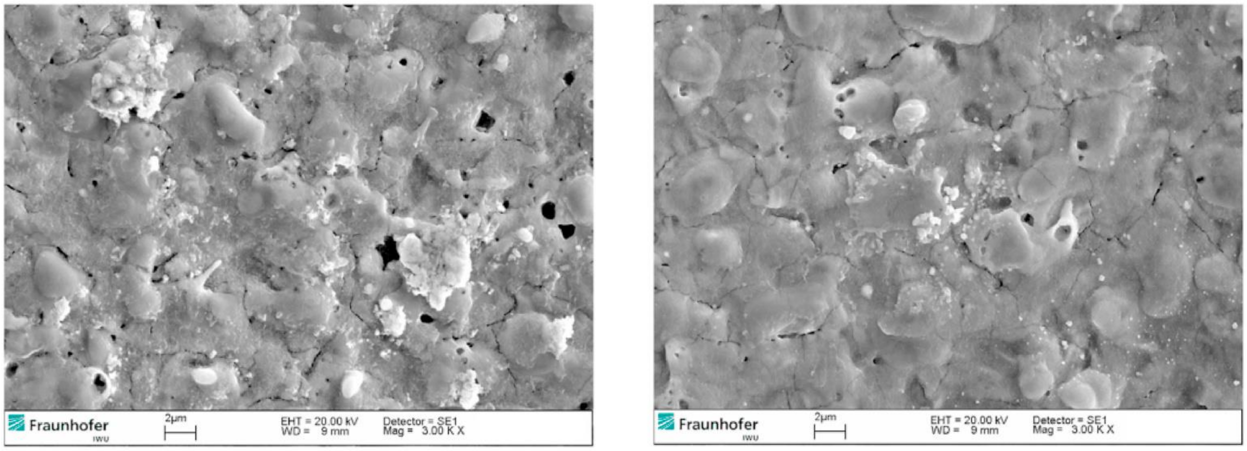
Figure 7 presents the surface morphology analysis of a magnesium-treated surface coated with nano-hydroxyapatite (nano-HAp) [120]. This figure shows the microstructural changes at the surface after PMEDM, with the magnesium substrate coated with a bioactive nano-HAp layer. This coating is particularly beneficial for biomedical applications, as it promotes bone integration and enhances the biocompatibility of the implant. The nano-HAp coating not only improves the surface roughness but also provides a suitable environment for cell attachment and growth, which is essential for successful implantation [120].



Elements	Weight %	Atomic %
Ca	41.89	61.99
P	21.17	16.19
O	36.94	21.82
Total	100	100

Figure 7. Mg synthetic surface **(a)** analysis surface morphology; **(b)** nano-Hap element analysis. Reproduced from [120], under the terms of the CC BY 4.0 license

Figure 8 illustrates the surface topography after 25 g/l of silver powder was used for machine work [138]. The figure shows the formation of a silver-rich surface layer, which significantly enhances the material's antibacterial properties. This type of coating is especially useful in medical implants, where preventing bacterial infections is critical. The silver particles are evenly distributed across the surface, providing a uniform and durable coating that offers long-term protection against microbial colonization [138].



(a) (b)

Figure 8. Surface topography was machined while using 25 mg/l of silver powder. Reproduced from [138], under the terms of the CC BY 4.0 license

5.3. Impact on biocompatibility.

The surface modifications and coatings achieved through PMEDM have a profound impact on the biocompatibility of medical implants. By carefully selecting powder types and optimizing process parameters, it is possible to create surfaces that meet the mechanical requirements of the implant, reduce the risk of adverse reactions, and promote biological integration [109].

Table 6 provides a detailed review of the influence of adding powder particles to the dielectric medium on different process outcomes, including surface finish (SF), hardness (H), and wear resistance (WR). The table highlights how different combinations of additive powders, dielectric fluids, and tool materials can be used to tailor the workpiece's surface properties to improve biocompatibility. For example, adding bioactive powders such as hydroxyapatite can improve cell adhesion and promote osteointegration, while using antibacterial powders, such as silver, can reduce the risk of infection. The ability to control these surface properties is crucial for the successful application of implants in the human body [140].

Table 6. Impact of powder particles added in the dielectric medium for PMEDM techniques on various process responses.

Input parameters					**Output responses**					**Ref.**
AP	W/P	TM	DF	PC (g/l)	TWR	MRR	H	WR	SF	
SiC	Ti64	WC	EDM3 Oil	5	D	I	-	-	-	[139]
B_4C	SS 304 plates	Cu Foils	De-ionized water	3	-	I	-	-	-	[140]
Al	Inconel 706	Cu	EDM Oil	10	I	I	-	-	I	[140]
WS_2	Ti64	W	De-ionized water	10	-	I	I	I	I	[141]
Cu	Ti64	Brass	De-ionized water	4	I	I	-	-	I	[142]
Ni	Ti64	Brass	De-ionized water	4	I	I	-	-	I	[142]
Co	Ti64	Brass	De-ionized water	4	I	I	-	-	I	[142]
Gr	Ti	W	Kerosene	15	-	I	-	-	I	[143]
MoS_2	Inconel 718	W	Kerosene	5	-	I	-	-	I	[144]

6. Challenges and Future Directions

6.1. Limitations in PMEDM.

Despite the numerous advantages of Powder Mixed Electric Discharge Machining (PMEDM), several limitations continue to pose challenges to its widespread adoption in industrial applications, particularly in the field of biomaterials. One of the primary limitations is the complexity of controlling the process factors. The conductive powders mixed into the dielectric medium introduce variables, such as powder concentration, particle size, and type, which can significantly affect machining performance. Achieving optimal conditions requires precise control and a deep understanding of the interactions between these variables and the electrical parameters, which is often challenging in a production environment [145].

Another significant limitation is electrode wear during PMEDM. Although the use of powders can reduce tool wear to some extent, excessive wear still occurs, particularly when machining hard materials. This affects the accuracy of the machined components and increases operational costs due to frequent electrode replacement or redressing. Moreover, the generation of RLT, which often contains microcracks and residual stresses, remains a concern, especially in applications where high surface integrity is critical, such as in biomedical implants [137]. The environmental impact of PMEDM is another area of concern. The use of dielectric fluids mixed with conductive powders can generate hazardous waste, requiring careful disposal and treatment to prevent environmental contamination. Additionally, the process is energy-intensive, requiring significant power to maintain the necessary discharge conditions, which can contribute to higher operational costs and a larger carbon footprint [11].

6.2. Use of biodegradable oils as dielectric.

Biodegradable/non-edible oils are a good alternative to EDM oil as dielectric fluids, improving operator health, energy efficiency, and environmental impact. Table 7 related to research in the EDM process using biodegradable/ non-edible oils.

Table 7. Research work in the field of EDM/PMEDM using non-edible/biodegradable oil as a dielectric medium.

Dielectric used	Process	Finding	References
Canola bio-dielectric (BD), sunflower (SF) BD	EDM	Canola and Sunflower BD improve the MRR by 137% and 114% respectively, as compared to Kerosene.	[146]
Jatropha curcas oil (JCO) based BD	EDM	Increased the MRR, reduced the SR, and improved the micro-hardness as compared to Kerosene.	[147]
Vegetable oil-based BD	EDM	MRR increased by 165% and there is an improvement in sustainability as compared to Kerosene.	[148]
Palm oil-based BD	EDM	Improvement in the sustainability index and MRR by 38% as compared to Kerosene.	[149]
Waste vegetable oil-based BD	EDM	Shown better MRR and Sustainability Index as compared to Kerosene.	[150]
Pongamia pinnata seed oil-based BD	EDM	Significant improvement in MRR as compared to Kerosene.	[151]
Neem oil, canola oil, JCO-based BD	EDM	Shows better MRR and lower SR as compared to Kerosene, JCO BD provides the best results.	[152]
SF, peanut seed, and rapeseed (RS) oil	EDM	Significant improvement in machining performance and sustainability compared to Kerosene.	[153]
SF, RS, and soybean (SB) oil	EDM	RS provides better machining performance due to good thermophysical characteristics as compared to Kerosene oil, SF, and SB oil.	[154]

Dielectric used	Process	Finding	References
JCO	PMEDM-TR	Improvement in MRR, SR, and a better sustainability Index as compared to EDM oil.	[38]
Kusum oil	PMEDM-TR	Improvement in MRR and SR as compared to EDM oil.	[74]
WVO	PMEDM-TR	Significant improvement in the sustainability index MRR and SR as compared to EDM oil.	[76]
Neem oil	EDM	Shows better improvement in MRR, SR, and machining time as compared to EDM oil.	[155, 156]
Coconut oil	EDM	Observed the better machining rate, EWR, MRR, and SR with less debris produced as compared to EDM oil.	[157]

Very few studies have reported on pure biodegradable/non-edible oils due to the fluids' high viscosity. Machining with EDM/PMEDM techniques using pure biodegradable/non-edible oils is a scope for the future to improve MRR, SR, and the sustainability index. Divya et al. [158] found that MRR increases with increasing pulse current.

6.3. Technological advancements needed.

To address these limitations, several technological advancements are needed in PMEDM. One area that requires improvement is the development of advanced control systems capable of real-time monitoring and adjustment of process parameters. Implementing artificial intelligence (AI) and machine learning (ML) algorithms could significantly improve the ability to predict and optimize machining conditions, resulting in more consistent, high-quality results. Such advancements would also reduce the reliance on trial-and-error approaches, making the process more efficient and cost-effective [11].

Another critical advancement is the development of more wear-resistant electrode materials. Research into new electrode materials, such as composite or coated electrodes, could help to reduce tool wear and extend electrode life, thereby improving the overall efficiency of the PMEDM technique. Additionally, advancements in environmentally friendly dielectric fluids that enhance machining performance are essential. The development of biodegradable or recyclable dielectric fluids could mitigate the environmental impact of PMEDM while maintaining, or even improving, machining capabilities [82].

Enhancing the understanding of interactions between work materials and powders at the micro- and nanoscales is also crucial. This could lead to the development of new powder formulations specifically designed to improve surface properties, reduce recast layer formation, and enhance biocompatibility for medical applications. Advances in nanotechnology could also enable the use of nanosized powders, further improving the mechanical properties and SF of the machined components [43].

7. Conclusion

This review has explored the significant advancements and applications of Powder Mixed Electric Discharge Machining (PMEDM), particularly in the context of machining biomaterials for medical implants and other high-performance components. PMEDM has the potential to overcome the limitations of traditional EDM by incorporating conductive powder particles into the dielectric medium, thereby improving machining performance and surface characteristics and enabling surface tailoring for specific applications, particularly in the biomedical field.

One key finding is that PMEDM provides substantial improvements in material removal rate (MRR) and tool wear rate (TWR), which are critical to the economic viability and efficiency of the machining process. The addition of powders such as aluminum, copper, and graphite has been shown to significantly improve these parameters, resulting in faster machining times and reduced electrode wear. Additionally, PMEDM's ability to produce superior surface finishes with reduced surface roughness (SR) and increased Microhardness is of paramount importance in applications requiring high surface integrity, such as the fabrication of medical implants. The formation of a composite surface layer through the migration and alloying of powder materials with the workpiece contributes to these enhanced properties.

However, the paper also identifies several limitations of PMEDM, including the complexity of controlling process parameters, the persistence of tool wear, and the environmental impact associated with the use of dielectric fluids and conductive powders. Addressing these challenges will require technological advancements in control systems, electrode materials, and environmentally friendly dielectric fluids. Moreover, integrating PMEDM with other machining technologies, such as laser or ultrasonic machining, represents a promising area for future research, potentially leading to hybrid processes that offer even greater precision and efficiency.

The potential research areas identified in this review underscore the need for continued innovation in PMEDM. The exploration of new powder materials, such as graphene and carbon nanotubes, could open up opportunities to enhance surface properties and develop novel coatings with unique characteristics. Additionally, the review emphasizes the importance of sustainable practices in PMEDM, particularly in reducing the environmental impact of the process through the development of biodegradable or recyclable dielectric media.

Author Contributions

Conceptualization, V.K.S. and H.P.; methodology, V.K.S.; software, R.B.; validation, V.K.S. and R.B.; formal analysis, H.P.; investigation, V.K.S. and R.B.; resources, V.K.S.; data curation, R.B.; writing—original draft preparation, V.K.S.; writing—review and editing, V.K.S. and H.P.; visualization, H.P.; supervision, H.P. and R.B.; project administration, V.K.S. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

References

1. Equbal, A.; Sood, A.K. Electrical discharge machining: an overview on various areas of research. *Manuf. Ind. Eng.* **2014**, *13*, 1-6, https://doi.org/10.12776/mie.v13i1-2.339.
2. Shahri, H.R.; Mahdavinejad, R.; Ashjaee, M.; Abdullah, A. A comparative investigation on temperature distribution in electric discharge machining process through analytical, numerical and experimental methods. *Int. J. Mach. Tools Manuf.* **2017**, *114*, 35-53, https://doi.org/10.1016/j.ijmachtools.2016.12.005.
3. Ho, K.H.; Newman, S.T. State of the art electrical discharge machining (EDM). *Int. J. Mach. Tools Manuf.* **2003**, *43*, 1287-1300, https://doi.org/10.1016/S0890-6955(03)00162-7.
4. Qudeiri, J.E.; Zaiout, A.; Mourad, A.H.; Abidi, M.H.; Elkaseer, A. Principles and characteristics of different EDM processes in machining tool and die steels. *Appl. Sci.* **2020**, *10*, 2082, https://doi.org/10.3390/app10062082.
5. Tao, L.V. The influence of additive powder on machinability and surface integrity of SKD61 steel by EDM process. *Mater. Manuf. Process.* **2021**, *36*, 1084-1098, https://doi.org/10.1080/10426914.2021.1885710.
6. Kansal, H.K.; Singh, S; Kumar, P. Effect of silicon powder mixed EDM on machining rate of AISI D2 die steel. *J. Manuf. Process*, **2007**, *9*, 13-22, https://doi.org/10.1016/S1526-6125(07)70104-4.
7. Pecas, P.; Henriques, E. Influence of silicon powder-mixed dielectric on conventional electrical discharge machining. *Int. J. Mach. Tools Manuf.* **2003**, *43*, 1465-1471, https://doi.org/10.1016/S0890-6955(03)00169-X.
8. Jeswani, M.L. Effect of the addition of graphite powder to kerosene used as the dielectric fluid in electrical discharge machining. *Wear.* **1981**, *70*, 133-139, https://doi.org/10.1016/0043-1648(81)90148-4.
9. Kansal, H.; Singh, S.; Kumar, P. Parametric optimization of powder mixed electrical discharge machining by response surface methodology. *J. Mater. Process. Technol.* **2005**, *169*, 427-436, https://doi.org/10.1016/j.jmatprotec.2005.03.028.
10. Kiran, P.; Mohanty, S.; Das, A.K. Surface modification through sustainable micro-EDM process using powder mixed bio-dielectrics. *Mater. Manuf.* **2022**, *37*, 640-651, https://doi.org/10.1080/10426914.2021.1967976.
11. Abdudeen, A.; Abu Qudeiri, J.E.; Kareem, A.; Ahammed, T.; Ziout, A. Recent advances and perceptive insights into powder-mixed dielectric fluid of EDM. *Micromachines* **2020**, *11*, 754, https://doi.org/10.3390/mi11080754.
12. Khan, W.; Muntimadugu, E.; Jaffe, M.; Domb, A.J. Implantable Medical Devices. In Focal Controlled Drug Delivery, Domb, A.J., Khan, W., Eds.; Springer US: Boston, MA, **2014**; pp. 33-59, https://doi.org/10.1007/978-1-4614-9434-8_2.
13. Duraccio, D.; Mussano, F.; Faga, M.G. Biomaterials for dental implants: current and future trends. *J. Mater. Sci*, **2015**, *50*, 4779-4812, https://doi.org/10.1007/s10853-015-9056-3.
14. Nikolova, M.P.; Apostolova, M.D. Advances in multifunctional bioactive coatings for metallic bone implants. *Materials* **2022**, *16*, 183, https://doi.org/10.3390/ma16010183.

15. Al-Amin, M.; Abdul Rani, A.M.; Abdu Aliyu, A.A.; Bryant, M.G.; Danish, M.; Ahmad, A. Bio-ceramic coatings adhesion and roughness of biomaterials through PM-EDM: a comprehensive review. *Mater. Manuf. Process.* **2020**, *35*, 1157-1180, https://doi.org/10.1080/10426914.2020.1772483.
16. Aliyu, A.A.; Abdul-Rani, A.M.; Ginta, T.L.; Prakash, C.; Axinte, E.; Razak, M.A.; Ali, S. A Review of Additive Mixed-Electric Discharge Machining: Current Status and Future Perspectives for Surface Modification of Biomedical Implants. *Adv. Mater. Sci. Eng.* **2017**, *2017*, 8723239, https://doi.org/10.1155/2017/8723239.
17. Al-Amin, M.; Abdul-Rani, A.M.; Danish, M.; Thompson, H.M.; Aliyu, A.A.; Hastuty, S.; Zohura, F.T.; Bryant, M.G.; Rubaiee, S.; Rao, T.V. Assessment of PM-EDM cycle factors influence on machining responses and surface properties of biomaterials: A comprehensive review. *Precis. Eng.* **2020**, *66*, 531-549, https://doi.org/10.1016/j.precisioneng.2020.09.002.
18. Singh, H.; Singh, S.; Prakash, C. Current Trends in Biomaterials and Bio-manufacturing. In Biomanufacturing, Prakash, C., Singh, S., Singh, R., Ramakrishna, S., Pabla, B.S., Puri, S., Uddin, M.S., Eds.; Springer International Publishing: Cham, **2019**; pp. 1-34, https://doi.org/10.1007/978-3-030-13951-3_1.
19. Davis, R.; Singh, A.; Jackson, M.J.; Coelho, R.T.; Prakash, D.; Charalambous, C.P.; Ahmed, W.; Da Silva, L.R.; Lawrence, A.A. A comprehensive review on metallic implant biomaterials and their subtractive manufacturing. *Int. J. Adv. Manuf. Technol.* **2022**, *120*, 1473-1530, https://doi.org/10.1007/s00170-022-08770-8.
20. Godbole, N.; Yadav, S.; Ramachandran, M.; Belemkar, S. A review on surface treatment of stainless steel orthopedic implants. *Int. J. Pharm. Sci. Rev. Res.* **2016**, *36*, 190-194.
21. Bekmurzayeva, A.; Duncanson, W.J.; Azevedo, H.S.; Kanayeva, D. Surface modification of stainless steel for biomedical applications: Revisiting a century-old material. *Mater. Sci. Eng.* **2018**, *93*, 1073-1089, https://doi.org/10.1016/j.msec.2018.08.049.
22. Resnik, M.; Benčina, M.; Levičnik, E.; Rawat, N.; Iglič, A.; Junkar, I. Strategies for improving antimicrobial properties of stainless steel. *Mater.* **2020**, *13*, 2944, https://doi.org/10.3390/ma13132944.
23. Xuanyu, M.A. Research on electrical discharge machining with stepped electrodes considering the effects of dielectric fluid field. Doctoral Thesis, College of Science, Technology, Engineering and Maths, RMIT University, Melbourne, Australia, **December 2022**.
24. Pourasl, H.H. Theoretical and Experimental Investigation of the Material Removal Rate, Surface Roughness and Tool Wear Ratio in Electrical Discharge Machining. Doctoral Thesis, Eastern Mediterranean University, Gazimağusa, North Cyprus, **January 2019**.
25. Kumar, R.; Channi, A.S.; Kaur, R.; Sharma, S.; Grewal, J.S.; Singh, S.; Verma, A.; Haber, R. Exploring the intricacies of machine learning-based optimization of electric discharge machining on squeeze cast TiB2/AA6061 composites: Insights from morphological, and microstructural aspects in the surface structure analysis of recast layer formation and worn-out analysis. *J. Mater. Res. Technol.* **2023**, *26*, 8569-8603, https://doi.org/10.1016/j.jmrt.2023.09.127.
26. Yaşar, H.; Ekmekci, B. The effect of micro and nano hydroxyapatite powder on biocompatibility and surface integrity of Ti6Al4V (ELI) in powder mixed electrical discharge machining. *Surf. Topogr.: Metrol. Prop.* **2021**, *9*, 015015, https://doi.org/10.1088/2051-672X/abdda2.
27. Mahajan, A.; Sidhu, S.S. Surface modification of metallic biomaterials for enhanced functionality: a review. *Adv. Mater. Technol*. **2018**, *33*, 93-105, https://doi.org/10.1080/10667857.2017.1377971.
28. Dutta, S.; Singh, A.K.; Paul, B.; Paswan, M.K. Machining of shape-memory alloys using electrical discharge machining with an elaborate study of optimization approaches: a review. *J. Braz. Soc. Mech. Sci. Eng.* **2022**, *44*, 557, https://doi.org/10.1007/s40430-022-03826-y.
29. Korgal, A.; Shettigar, A.K; Karanth, P.N.; Prabhakar, D.A. Advances in micro electro discharge machining of biomaterials: a review on processes, industrial applications, and current challenges. *Mater. Sci. Eng. C.* **2024**, *28*, 215-65, https://doi.org/10.1080/10910344.2024.2311376.
30. Choudhary, S.K.; Jadoun, R.S. Current advanced research development of electric discharge machining (EDM): a review. *Int. J. Res. Adv. Technol.* **2014**, *2*, 273-297.
31. Prakash C.; Kansal H.K;, Pabla B.S.; Puri S.; Aggarwal A. Electric discharge machining–A potential choice for surface modification of metallic implants for orthopedic applications: A review. *Acad. J. Manuf. Eng.* **2016**, *230*, 331-353, https://doi.org/10.1177/0954405415579113.

32. Singh, R.; Singh, R.P.; Trehan, R. State of the art in processing of shape memory alloys with electrical discharge machining: a review. *Acad. J. Manuf. Eng.* **2021**, *235*, 333-366, https://doi.org/10.1177/0954405420958771.
33. Bauer, S.; Schmuki, P.; Von Der Mark, K.; Park, J. Engineering biocompatible implant surfaces: Part I: Materials and surfaces. *Prog. Mater. Sci.* **2013**, *58*, 261-326, https://doi.org/10.1016/j.pmatsci.2012.09.001.
34. Losic, D. Advancing of titanium medical implants by surface engineering: Recent progress and challenges, Expert Opin. *Drug Deliv.* **2021**, *18*, 1355-1378, https://doi.org/10.1080/17425247.2021.1928071.
35. Kutner, N.; Kunduru, K.R.; Rizik, L.; Farah, S. Recent advances for improving functionality, biocompatibility, and longevity of implantable medical devices and deliverable drug delivery systems. *Adv. Funct. Mater.* **2021**, *31*, 2010929, https://doi.org/10.1002/adfm.202010929.
36. Bajaj, R.; Dixit, A.R.; Tiwari, A.K.; Chauhan, N.K. Machining performance enhancement of EN-31 diesteel using MWCNT mixed rotary EDM. *Indian J. Eng. Mater. Sci.* **2021**, *27*, 309-319, https://doi.org/10.56042/ijems.v27i2.45944.
37. Alting, L.; Boothroyd, G. Nontraditional manufacturing processes. In Manufacturing Engineering Processes, Second Edition; Alting, L., Ed.; CRC Press: Boca Raton, Florida, USA, **2020**; pp. 363-416, http://dx.doi.org/10.1201/9781003067177-12.
38. Bajaj, R.; Tiwari, A.K.; Pramanik, A.; Srivastava, A.K.; Dixit, A.R. Machining performance and sustainability analysis of PMEDM process using green dielectric fluid. *J. Braz. Soc. Mech. Sci. Eng.* **2022**, *44*, 563, https://doi.org/10.1007/s40430-022-03878-0.
39. Songmene, V.; Khettabi, R.; Zaghbani, I.; Kouam, J.; Djebara, A. Machining and Machinability of Aluminum Alloys. In Aluminium Alloys - Theory and Applications, Kvackaj, T., Ed.; IntechOpen: Rijeka, **2011**; https://doi.org/10.5772/14888.
40. Hakami, F.; Pramanik, A.; Basak, A.K. Tool wear and surface quality of metal matrix composites due to machining: A review. *Proc. Inst. Mech. Eng. Pt. B J. Eng. Manufact.* **2017**, *231*, 739-752, https://doi.org/10.1177/0954405416667402.
41. Pecas, P.; Henriques, E. Electrical discharge machining using simple and powder-mixed dielectric: the effect of the electrode area in the surface roughness and topography. *J. Mater. Process. Technol.* **2008**, *200*, 250-258, https://doi.org/10.1016/j.jmatprotec.2007.09.051.
42. Davis, R.; Singh, A.; Debnath, K.; Jackson, M.J.; Soares, P.; Amorim, F.L.; Dutta, H. Effect of powder particle concentration and tool electrode material amid zinc powder-mixed μEDM of biocompatible Mg alloy AZ91D. *J. Mater. Eng. Perform.* **2021**, *30*, 5704-5718, https://doi.org/10.1007/s11665-021-05788-z.
43. Al-Amin, M.; Abdul Rani, A.M.; Abdu Aliyu, A.A.; Abdul Razak, M.A.; Hastuty, S.; Bryant, M.G. Powder mixed-EDM for potential biomedical applications: A critical review. *Mater. Manuf. Process.* **2020**, *35*, 1789-1811, https://doi.org/10.1080/10426914.2020.1779939.
44. Kamenskikh, A.A.; Muratov, K.R.; Shlykov, E.S.; Sidhu, S.S.; Mahajan, A.; Kuznetsova, Y.S.; Ablyaz, T.R. Recent trends and developments in the electrical discharge machining industry: a review. *J. Manuf. Mater. Process.* **2023**, *7*, 204, https://doi.org/10.3390/jmmp7060204.
45. Abbas, A.T.; Sharma, N.; Alsuhaibani, Z.A.; Sharma, V.S.; Soliman, M.S.; Sharma, R.C. Processing of Al/SiC/Gr hybrid composite on EDM by different electrode materials using RSM-COPRAS approach. *J. Met.* **2023**, *13*, 1125, https://doi.org/10.3390/met13061125.
46. Srivastava, S.; Vishnoi, M.; Gangadhar, M.T.; Kukshal, V. An insight on Powder Mixed Electric Discharge Machining: A state of the art review. *Proc. Inst. Mech. Eng. Part B.* **2023**, *237*, 657-690, https://doi.org/10.1177/09544054221111896.
47. Sharma, D.; Hiremath, S.S. Review on tools and tool wear in EDM. *Int. J. Adv. Manuf. Technol.* **2021**, *25*, 802-873, https://doi.org/10.1080/10910344.2021.1971711.
48. Ma, Z.; Wang, W.; Xiong, Y.; Long, Y.; Shao, Q.; Wu, L.; Wang, J.; Tian, P.; Khan, A.U.; Yang, W.; Dong, Y. Carbon Micro/Nano Machining toward Miniaturized Device: Structural Engineering, Large-Scale Fabrication, and Performance Optimization. *Small.* **2024**, *19*, 2400179, https://doi.org/10.1002/smll.202400179.
49. Surani, K.; Patel, S.; Alrubaie, A.J.; Oza, A.; Panchal, H.; Kumar, S.; Zahmatkesh, S. Performance comparison of powder mixed EDM and traditional EDM on TZM-molybdenum super alloy using response surface methodology. *Int. J. Interact. Des. Manuf.* **2023**, *17*, 2647-2658, https://doi.org/10.1007/s12008-022-01088-5.

50. Haddad, M.J.; Tehrani, A.F. Material removal rate (MRR) study in the cylindrical wire electrical discharge turning (CWEDT) process. *J. Mater. Process. Technol.* **2008**, *199*, 369-378, https://doi.org/10.1016/j.jmatprotec.2007.08.020.
51. Kumar, S.; Singh, R.; Singh, T.P.; Sethi, B.L. Surface modification by electrical discharge machining: A review. *J. Mater. Process. Technol.* **2009**, *209*, 3675-3687, https://doi.org/10.1016/j.jmatprotec.2008.09.032.
52. Barron, C.C. Optimization of resonant modulators and photodetectors for optical interconnection and communications applications. Doctoral Thesis, University of California, Santa Barbara, **January 1994**.
53. Bian, J.; Ma, B.; Liu, X.; Qi, L. Experimental study of tool wear in electrochemical discharge machining. *Appl. Sci.* **2020**, *10*, 5039, https://doi.org/10.3390/app10155039.
54. Singh Yadav, H.N.; Krishna, E.; Kombath, S.; Dev, D.S.; Das, M. Investigation of MRR and surface characterization using plasma process. *Mater. Manuf. Process.* **2023**, *38*, 1716-1728, https://doi.org/10.1080/10426914.2023.2176873.
55. Bhattacharyya, B.; Munda, J. Experimental investigation on the influence of electrochemical machining parameters on machining rate and accuracy in micromachining domain. *Int. J. Mach. Tools Manuf.* **2003**. *43*, 1301-1310, https://doi.org/10.1016/S0890-6955(03)00161-5.
56. Shrivastava, S.M.; Sarathe, A. Influence of process parameters and electrode shape configuration on material removal rate, surface roughness and electrode wear in die sinking EDM: a review. *Int. J. Emerging Technol. Adv. Eng.* **2014**, *4*, 138-145.
57. Gill, A.S.; Kumar, S.; Singh, J.; Aggarwal, V.; Sharma, S. A review of recent methods for tool wear reduction in electrical discharge machining. *Surf. Rev. Lett.* **2020**, *27*, 2030002, https://doi.org/10.1142/S0218625X20300026.
58. Rouniyar, A.K.; Shandilya, P. Experimental investigation on recast layer and surface roughness on aluminum 6061 alloy during magnetic field assisted powder mixed electrical discharge machining. *J. Mater. Eng. Perform.* **2020**, *29*, 7981-7992, https://doi.org/10.1007/s11665-020-05244-4.
59. Etter, T.; Papakyriacou, M.; Schulz, P.; Uggowitzer, P.J. Physical properties of graphite/aluminium composites produced by gas pressure infiltration method. *Carbon*. **2003**, *41*, 1017-1024, https://doi.org/10.1016/S0008-6223(02)00448-7.
60. Guu, Y.H.; Hocheng, H. Effects of workpiece rotation on machinability during electrical-discharge machining. *Mater. Manuf. Process.* **2001**, *16*, 91-101, https://doi.org/10.1081/AMP-100103699.
61. D'Urso, G.; Maccarini, G.; Ravasio, C. Influence of electrode material in micro-EDM drilling of stainless steel and tungsten carbide. *Int. J. Adv. Manuf. Technol.* **2016**, *85*, 2013-2025, https://doi.org/10.1007/s00170-015-7010-9.
62. Sarmadi, M.S.; Zohrevand, P.; Rezaee, M. Effect of kerosene contamination on the physical and mechanical properties of sandy soil. *Innov. Infrastruct. Solut.* **2019**, *4*, 7, https://doi.org/10.1007/s41062-019-0196-1.
63. Sethy, S.; Behera, R.K.; Rana, J.; Muduli, K. Experimental investigation on the performance variations of three different work piece materials in EDM with variation of thermo-physical properties. *Int. J. Process Manag. Benchmarking*. **2023**, *15*, 46-72, https://doi.org/10.1504/IJPMB.2023.132659.
64. Intartaglia, R.; Bagga, K.; Brandi, F.; Das, G.; Genovese, A.; Di Fabrizio, E.; Diaspro, A. Optical properties of femtosecond laser-synthesized silicon nanoparticles in deionized water. *J. Phys. Chem. C.* **2011**, *115*, 5102-5107, https://doi.org/10.1021/jp109351t.
65. Sethy, S.; Behera, R.K.; Davim, J.P.; Rana, J. Effect of thermo-physical properties of the tool materials on the electro-discharge machining performance of Ti-6Al-4V and SS316 work piece materials. *J. Manuf. Mater. Process.* **2022**, *6*, 96, https://doi.org/10.3390/jmmp6050096.
66. Amanullah, M.; Islam, S.M.; Chami, S.; Ienco, G. Analyses of physical characteristics of vegetable oils as an alternative source to mineral oil-based dielectric fluid. In Proceedings of the IEEE International Conference on Dielectric Liquids, 2005. ICDL 2005, 26 June-1 July 2005, IEEE: **2005**; pp. 397-400, https://doi.org/10.1109/ICDL.2005.1490109.
67. Valente, O.S.; Pasa, V.M.; Belchior, C.R.; Sodré, J.R. Physical–chemical properties of waste cooking oil biodiesel and castor oil biodiesel blends. *Fuel* **2011**, *90*, 1700-1702, https://doi.org/10.1016/j.fuel.2010.10.045.

68. Guinda, A.; Dobarganes, M.C.; Ruiz-Mendez, M.V.; Mancha, M. Chemical and physical properties of a sunflower oil with high levels of oleic and palmitic acids. *Eur. J. Lipid Sci. Technol.* **2003**, *105*, 130-137, https://doi.org/10.1002/ejlt.200390028.
69. Danish, M.; Gupta, M.K.; Rubaiee, S.; Ahmed, A.; Sarikaya, M. Influence of graphene reinforced sunflower oil on thermo-physical, tribological and machining characteristics of inconel 718. *J. Mater. Res. Technol.* **2021**, *15*, 135-150, https://doi.org/10.1016/j.jmrt.2021.07.161.
70. Davis, J.P.; Price, K.; Dean, L.L.; Sweigart, D.S.; Cottonaro, J.; Sanders, T.H. Peanut oil stability and physical properties across a range of industrially relevant oleic acid/linoleic acid ratios. *Peanut Sci.* **2016**, *43*, 1-11, https://doi.org/10.3146/PS14-17.1.
71. Atta, N.M.; Ismaiel, G.H.; Hashish, A.E.M.S.; Mohamed, E.S. Physical and chemical characteristics of neem oils extracted from seed, whole fruit and flesh. *Egypt. J. Agric. Res.* **2015**, *93*, 887-899, https://doi.org/10.21608/ejar.2015.155469.
72. Adedeji, M.A.; Owolarafe, O.K. Some Physical Properties of Neem Seeds & Kernels (Azandirachta indica) as a Function of moisture Content. *Int. J. Sci. Eng. Res.* **2015**, *6*, 812-820.
73. Kumar, N.; Pali, H.S. Kusum oil as a potential fuel for ci engines. In Proceedings of the International Conference on Alternative Fuels for IC Engines (ICAFICE), Jaipur, Rajasthan, India, 6-8 February 2013; Priya Tech Publication Private Ltd, Jaipur, India: **2013**; http://dx.doi.org/10.13140/2.1.3313.6966.
74. Bajaj, R.; Dixit, A.R.; Tiwari, A.K. Machining performance enhancement of powder mixed electric discharge machining using Green dielectric fluid. *J. Braz. Soc. Mech. Sci. Eng.* **2020**, *42*, 512, https://doi.org/10.1007/s40430-020-02597-8.
75. Das, S.; Paul, S.; Doloi. B. Feasibility assessment of some alternative dielectric mediums for sustainable electrical discharge machining: a review work. *J. Braz. Soc. Mech. Sci. Eng.* **2020**, *42*, 148, https://doi.org/10.1007/s40430-020-2238-1.
76. Bajaj, R.; Mardi, K.B.; Srivastava, A.K.; Dixit, A.R. Feasibility and sustainability analysis of waste vegetable oil as a dielectric fluid for powder mixed EDM process. *Int. J. Adv. Manuf. Technol.* **2024**, *134*, 3531-3549, https://doi.org/10.1007/s00170-024-14321-0.
77. Niranjan, T.; Singaravel, B.; Chakradhar, B.; Kumar, D.S. Investigation of vegetable oil as dielectric fluid in electric discharge machining. *Mater. Today Proc.* **2023**, https://doi.org/10.1016/j.matpr.2023.02.142.
78. Ishfaq, K.; Sana, M.; Rehman, M.; Anwar, S.; Alfaify, A.Y.; Zia. A.W. Role of biodegradable dielectrics toward tool wear and dimensional accuracy in Cu-mixed die sinking EDM of Inconel 600 for sustainable machining. *J. Braz. Soc. Mech. Sci. Eng.* **2023**, *45*, 235, https://doi.org/10.1007/s40430-023-04126-9.
79. Gupta, V.; Singh, P.; Singh, B.; Mishra, R.K. Vegetable oil based dielectric fluids for electrical discharge Machining Process: Advancements and challenges. *Mater. Today Proc.* **2022**, *62*, 3129-3132, https://doi.org/10.1016/j.matpr.2022.03.395.
80. Mason, J.H. The deterioration and breakdown of dielectrics resulting from internal discharges. *Proc. IEE-Part I.* **1951**, *98*, 44-59, https://doi.org/10.1049/pi-1.1951.0019.
81. Diallo, A.O., Len, C.; Morgan, A.B.; Marlair, G. Revisiting physico-chemical hazards of ionic liquids. *Sep. Purif. Technol.* **2012**, *97*, 228-234, https://doi.org/10.1016/j.seppur.2012.02.016.
82. Philip, J.T.; Mathew, J.; Kuriachen, B. Transition from EDM to PMEDM–impact of suspended particulates in the dielectric on Ti6Al4V and other distinct material surfaces: a review. *J. Manuf. Process.* **2021**, *64*, 1105-1142, https://doi.org/10.1016/j.jmapro.2021.01.056.
83. Ahmed, A.; Fardin, A.; Tanjilul, M.; Wong, Y.S.; Rahman, M.; Senthil Kumar, A. A comparative study on the modelling of EDM and hybrid electrical discharge and arc machining considering latent heat and temperature-dependent properties of Inconel 718. *Int. J. Adv. Manuf. Technol.* **2018**, *94*, 2729-2737, https://doi.org/10.1007/s00170-017-1100-9.
84. Lokanathan, M.; Acharya, P.V.; Ouroua, A.; Strank, S.M.; Hebner, R.E.; Bahadur, V. Review of nanocomposite dielectric materials with high thermal conductivity. *Proc. IEEE.* **2021**, *109*, 1364-1397, https://doi.org/10.1109/JPROC.2021.3085836.
85. Choudhary SK, Jadoun RS. Current Research Issue, Trend & Applications of Powder Mixed Dielectric Electric Discharge Machining (PM-EDM): A Review. *Int. J. Eng. Sci. Res. Technol.* **2014**, *3*, 335-358.

86. Kumar, D.; Bajpai, V.; Singh, N.K. Nano electrical discharge machining–the outlook, challenges, and opportunities. *Mater. Manuf. Process.* **2021**, *36*, 1099-1133, https://doi.org/10.1080/10426914.2021.1905832.
87. Chandan, P.B.; Manoj, A.; Gajrani, K.K.; Dhaka, S.; Sankar, M.R. Sustainability issues in advanced machining processes. In Advanced Machining Science, 1st Edition; Jain, V.K., Ed.; CRC Press: Boca Raton, Florida, USA, **2022**; pp. 425-468.
88. Razak, M.A.; Abdul-Rani, A.M.; Nanimina, A.M. Improving EDM efficiency with silicon carbide powder-mixed dielectric fluid. *Int. J. Mater. Mech. Manuf.* **2015**, *3*, 40-43, https://doi.org/10.7763/IJMMM.2015.V3.163.
89. Singh, G.; Ablyaz, T.R.; Shlykov, E.S.; Muratov, K.R.; Bhui, A.S.; Sidhu, S.S. Enhancing corrosion and wear resistance of Ti_6Al_4V alloy using CNTs mixed electro-discharge process. *Micromachines* **2020**, *11*, 850, https://doi.org/10.3390/mi11090850.
90. Sahoo, R.; Singh, N.K.; Bajpai, V. A novel approach for modeling MRR in EDM process using utilized discharge energy. *Mech. Syst. Signal Process.* **2023**, *185*, 109811, https://doi.org/10.1016/j.ymssp.2022.109811.
91. Talla, G.; Gangopadhayay, S.; Biswas, C.K. State of the art in powder-mixed electric discharge machining: a review. *Proc. Inst. Mech. Eng. B.* **2017**, *231*, 2511-2526, https://doi.org/10.1177/0954405416634265.
92. Mahajan, A.; Devgan, S.; Sidhu, S.S. Surface alteration of biomedical alloys by electrical discharge treatment for enhancing the electrochemical corrosion, tribological and biological performances. *Surf. Coat. Technol.* **2021**, *405*, 126583, https://doi.org/10.1016/j.surfcoat.2020.126583.
93. Banh, T.L.; Nguyen, H.P.; Ngo, C.; Nguyen, D.T. Characteristics optimization of powder mixed electric discharge machining using titanium powder for die steel materials. J. *Proc. Inst. Mech. Eng.* **2018**, *232*, 281-98, https://doi.org/10.1177/0954408917693661.
94. Gudur, S.; Potdar, V. Effect of silicon carbide powder mixed EDM on machining characteristics of SS 316L material. *Int. J. Innov. Res. Sci. Eng. Technol.* **2015**, *4*, 8131-8141, https://doi.org/10.15680/IJIRSET.2015.0404027.
95. Khan, A.A.; Mohiuddin, A.K.; Faizi, M.H.; Norhamzan, N.H. Enhancement of machining performance during electrical discharge machining of stainless steel with carbon nanotube powder added dielectric fluid. *Int. J. Appl. Eng. Res.* **2018**, *13*, 7076-7080.
96. Lamichhane, Y.; Singh, G.; Bhui, A.S.; Mukhiya, P.; Kumar, P.; Thapa, B. Surface modification of 316L SS with HAp nano-particles using PMEDM for enhanced biocompatibility. *Mater. Today: Proc.* **2019**, *15*, 336-343, https://doi.org/10.1016/j.matpr.2019.05.014.
97. Singh, G.; Lamichhane, Y.; Bhui, A.S.; Sidhu, S.S.; Bains, P.S.; Mukhiya, P. Surface morphology and microhardness behavior of 316L in HAp-PMEDM. *Facta Univ.* **2019**, *17*, 445-454, https://doi.org/10.22190/FUME190510040S.
98. Hourmand, M.; Sarhan, A.A.; Farahany, S.; Sayuti, M. Microstructure characterization and maximization of the material removal rate in nano-powder mixed EDM of Al-Mg 2 Si metal matrix composite—ANFIS and RSM approaches. *Int. J. Adv. Manuf. Tech.* **2019**, *101*, 2723-2737, https://doi.org/10.1007/s00170-018-3130-3.
99. Santosh, S.; Javed, S.I.S.; Saravanamuthukumar, P.; Rajkumar, K.; Harikrishna, K.L. Nano graphite powder assisted electric discharge machining characteristics of ZM21 Magnesium alloy. *Appl. Mech. Mater.* **2015**, *787*, 406-410, https://doi.org/10.4028/www.scientific.net/AMM.787.406.
100. Bui, V.D.; Mwangi, J.W.; Meinshausen, A.K.; Mueller, A.J.; Bertrand, J.; Schubert, A. Antibacterial coating of Ti-6Al-4V surfaces using silver nano-powder mixed electrical discharge machining. *Surf. Coat. Technol.* **2020**, *383*, 125254, https://doi.org/10.1016/j.surfcoat.2019.125254.
101. Bains, P.S.; Bahraminasab, M.; Sidhu, S.S.; Singh, G. On the machinability and properties of Ti–6Al–4V biomaterial with n-HAp powder–mixed ED machining. *Proc. Inst. Mech. Eng. H* **2020**, *234*, 232-42, https://doi.org/10.1177/0954411919891887.
102. Shabgard, M.; Khosrozadeh, B. Investigation of carbon nanotube added dielectric on the surface characteristics and machining performance of Ti–6Al–4V alloy in EDM process. *J. Manuf. Process.* **2017**, *25*, 212-219, https://doi.org/10.1016/j.jmapro.2016.11.016.

103. Gosai, N.D.; Joshi, A.Y. 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.* **2016**, *16*, 21-32, https://doi.org/10.1515/jmsp-2015-0013.
104. Prakash, C.; Kansal, H.K.; Pabla, B.S.; Puri, S. Experimental investigations in powder mixed electric discharge machining of Ti–35Nb–7Ta–5Zrβ-titanium alloy. *Mater. Manuf. Process.* **2017**, *32*, 274-285, https://doi.org/10.1080/10426914.2016.1198018.
105. Ou, S.F.; Wang, C.Y. Fabrication of a hydroxyapatite-containing coating on Ti–Ta alloy by electrical discharge coating and hydrothermal treatment. *Surf. Coat. Technol.* **2016**, *302*, 238-243, https://doi.org/10.1016/j.surfcoat.2016.06.013.
106. Ou, S.F.; Wang, C.Y. Effects of bioceramic particles in dielectric of powder-mixed electrical discharge machining on machining and surface characteristics of titanium alloys. *J. Mater. Process. Technol.* **2017**, *245*, 70-79, https://doi.org/10.1016/j.jmatprotec.2017.02.018.
107. Bhui, A.S.; Bains, P.S.; Sidhu, S.S.; Singh, G. Parametric optimization of ED machining of Ti-6Al-4V in CNTs mixed dielectric medium. *Mater. Today: Proc.* **2019**, *18*, 1532-1539, https://doi.org/10.1016/j.matpr.2019.06.623.
108. Kolli, M, Kumar, A. Assessing the influence of surfactant and B4C powder mixed in dielectric fluid on EDM of titanium alloy. *Silicon* **2019**, *11*, 1731-1743, https://doi.org/10.1007/s12633-017-9701-3.
109. Gugulothu, B.; Rao, G.K.; Rao, D.H. Influence of drinking water and graphite powder concentration on electrical discharge machining of Ti-6Al-4V alloy. *Mater. Today: Proc.* **2020**, *27*, 294-300, https://doi.org/10.1016/j.matpr.2019.11.035.
110. Kumar, N.; Mandal, N.; Das, A.K. Micro-machining through electrochemical discharge processes: a review. *Mater. Manuf. Process.* **2020**, *35*, 363-404, https://doi.org/10.1080/10426914.2020.1711922.
111. Abdul-Rani, A.M.; Nanimina, A.M.; Ginta, T.L.; Razak, M.A. Machined surface quality in nano aluminum mixed electrical discharge machining. *Procedia Manuf.* **2017**, *7*, 510-517, https://doi.org/10.1016/j.promfg.2016.12.061.
112. Devgan, S.; Sidhu, S.S. Surface modification of β-type titanium with multi-walled CNTs/µ-HAp powder mixed Electro Discharge Treatment process. *Mater. Chem. Phys.* **2020**, *239*, 122005, https://doi.org/10.1016/j.matchemphys.2019.122005.
113. Umar, F.M.; Pervez, M.M.; Ahmed, N.; Ahmad, M.N.; Al-Ahmari, A.M.; He, Y. On the investigation of surface integrity of Ti6Al4V ELI using Si-mixed electric discharge machining. *Materials.* **2020**, *13*, 1549, https://doi.org/10.3390/ma13071549.
114. Prakash, C.; Kansal, H.K.; Pabla, B.S.; Puri, S. Potential of silicon powder-mixed electro spark alloying for surface modification of β-phase titanium alloy for orthopedic applications. *Mater. Today: Proc.* **2017**, *4*, 10080-10083, https://doi.org/10.1016/j.matpr.2017.06.324.
115. Öpöz, T.T.; Yaşar, H.; Ekmekci, N.; Ekmekci, B. Particle migration and surface modification on Ti6Al4V in SiC powder mixed electrical discharge machining. *J. Manuf. Process.* **2018**, *31*, 744-758, https://doi.org/10.1016/j.jmapro.2018.01.002.
116. Prakash, C.; Uddin, M.S. Surface modification of β-phase Ti implant by hydroaxyapatite mixed electric discharge machining to enhance the corrosion resistance and in-vitro bioactivity. *Surf. Coat. Technol.* **2017**, *326*, 134-145, https://doi.org/10.1016/j.surfcoat.2017.07.040.
117. Li, L.; Zhao, L.; Li, Z.Y.; Feng, L.; Bai, X. Surface characteristics of Ti-6Al-4V by SiC abrasive-mixed EDM with magnetic stirring. *Mater. Manuf. Process.* **2017**, *32*, 83-86, https://doi.org/10.1080/10426914.2016.1151043.
118. Singh, G.; Sidhu, S.S.; Bains, P.S.; Bhui, A.S. Improving microhardness and wear resistance of 316L by TiO2 powder mixed electro-discharge treatment. *Mater. Res. Express.* **2019**, *6*, 086501, https://doi.org/10.1088/2053-1591/ab1bab.
119. Bhaumik, M.; Maity, K. Effect of machining parameter on the surface roughness of AISI 304 in silicon carbide powder mixed EDM. *Decis. Sci. Lett.* **2017**, *6*, 261-268, https://doi.org/10.5267/j.dsl.2016.12.004.
120. Prakash, C.; Singh, S.; Pabla, B.S.; Uddin, M.S. Synthesis, characterization, corrosion and bioactivity investigation of nano-HA coating deposited on biodegradable Mg-Zn-Mn alloy. *Surf. Coat. Technol.* **2018**, *346*, 9-18, https://doi.org/10.1016/j.surfcoat.2018.04.035.

121. Prakash, C.; Singh, S.; Singh, M.; Verma, K.; Chaudhary, B.; Singh, S. Multi-objective particle swarm optimization of EDM parameters to deposit HA-coating on biodegradable Mg-alloy. *Vacuum* **2018**, *158*, 180-190, https://doi.org/10.1016/j.vacuum.2018.09.050.
122. Razak, M.A.; Rani, A.M.; Saad, N.M.; Littlefair, G.; Aliyu, A.A. Controlling corrosion rate of Magnesium alloy using powder mixed electrical discharge machining. *Mater. Sci. Eng. C* **2018**, *344*, 012010, https://doi.org/10.1088/1757-899X/344/1/012010.
123. Chen, Y.F.; Lin, Y.C. Surface modifications of Al–Zn–Mg alloy using combined EDM with ultrasonic machining and addition of TiC particles into the dielectric. *J. Mater. Process. Technol.* **2009**, *209*, 4343-4350, https://doi.org/10.1016/j.jmatprotec.2008.11.013.
124. Abdul-Rani, A.M.; Razak, M.A.; Littlefair, G.; Gibson, I.; Nanimina, A.M. Improving EDM process on AZ31 magnesium alloy towards sustainable biodegradable implant manufacturing. *Procedia Manuf.* **2017**, *7*, 504-509, https://doi.org/10.1016/j.promfg.2016.12.057.
125. Rout, P.K.; Surekha, B.; Jena, P.C.; Arko, G.N. Experimental studies on aluminum powder mixed electro discharge machining of ultra-light weight Mg-6Al alloy. *Mater. Today: Proc.* **2020**, *26*, 2379-2387, https://doi.org/10.1016/j.matpr.2020.02.510.
126. Al-Amin, M.; Abdul-Rani, A.M.; Danish, M.; Rubaiee, S.; Mahfouz, A.B.; Thompson, H.M.; Ali, S.; Unune, D.R.; Sulaiman, M.H. Investigation of coatings, corrosion and wear characteristics of machined biomaterials through hydroxyapatite mixed-EDM process: a review. *Materials* **2021**, *14*, 3597, https://doi.org/10.3390/ma14133597.
127. Zain, Z.M.; Ndaliman, M.B.; Khan, A.A.; Ali, M.Y. Improving micro-hardness of stainless steel through powder-mixed electrical discharge machining. *J. Mech. Eng. Sci.* **2014**, *228*, 3374-3380, https://doi.org/10.1177/0954406214530872.
128. Prakash, C.; Kansal, H.K.; Pabla, B.S.; Puri, S. Processing and characterization of novel biomimetic nanoporous bioceramic surface on β-Ti implant by powder mixed electric discharge machining. *J. Mater. Eng. Perform.* **2015**, *24*, 3622-33, https://doi.org/10.1007/s11665-015-1619-6.
129. Shukla, B.K.; Sharma, P.K.; Yadav, H.; Singh, S.; Tyagi, K.; Yadav, Y.; Rajpoot, N.K.; Rawat, S.; Verma, S. Advanced membrane technologies for water treatment: utilization of nanomaterials and nanoparticles in membranes fabrication. *J. Nanopart. Res.* **2024**, *26*, 222, https://doi.org/10.1007/s11051-024-06117-w.
130. Shukla, B.K.; Singh, R.D.; Singh, N.; Singh, S.; Burman, Y.K.; Singh, R. Application of Nanomaterials in Water Purification: A Thematic Review. In Emerging Materials and Technologies in Water Remediation and Sensing. ICWT 2022. Lecture Notes in Civil Engineering; Saxena, S., Shukla, S., Mural, P.K.S., Eds.; Springer, Singapore, **2024**; Volume 439, pp. 97-113, https://doi.org/10.1007/978-981-99-6762-9_6.
131. Aliyu, A.A.A.; Abdul-Rani, A.M.; Ginta, T.L.; Rao, T.; Selvamurugan, N.; Roy, S. Hydroxyapatite mixed-electro discharge formation of bioceramic Lakargiite (CaZrO3) on Zr–Cu–Ni–Ti–Be for orthopedic application. *Mater. Manuf. Process.* **2018**, *33*, 1734-1744, https://doi.org/10.1080/10426914.2018.1512122.
132. Marin, E.; Lanzutti, A. Biomedical applications of titanium alloys: a comprehensive review. *Materials* **2023**, *17*, 114, https://doi.org/10.3390/ma17010114.
133. Oveissi, F.; Naficy, S.; Lee, A.; Winlaw, D.S.; Dehghani, F. Materials and manufacturing perspectives in engineering heart valves: a review. *Mater. Today Bio.* **2020**, *5*, 100038, https://doi.org/10.1016/j.mtbio.2019.100038.
134. Gul, I.A.; Abdul-Rani AM, Al-Amin M, Garba E. Elucidating powder-mixed electric discharge machining process, applicability, trends and futuristic perspectives. *Machines.* **2023**, *11*, 381, https://doi.org/10.3390/machines11030381.
135. Simao, J.; Lee, H.G.; Aspinwall, D.K.; Dewes, R.C.; Aspinwall, E.M. Workpiece surface modification using electrical discharge machining. *Int. J. Mach. Tools Manuf.* **2003**, *43*, 121-128, https://doi.org/10.1016/S0890-6955(02)00187-6.
136. Laghari, R.A.; Li, J.; Wu, Y. Study of machining process of SiCp/Al particle reinforced metal matrix composite using finite element analysis and experimental verification. *Materials* **2020**, *13*, 5524, https://doi.org/10.3390/ma13235524.
137. Joshi, A.Y.; Joshi, A.Y. A systematic review on powder mixed electrical discharge machining. *Heliyon* **2019**, *5*, e02963, https://doi.org/10.1016/j.heliyon.2019.e02963.

138. Bui, V.D.; Mwangi, J.W.; Schubert, A. Powder mixed electrical discharge machining for antibacterial coating on titanium implant surfaces. *J. Manuf. Process.* **2019**, *44*, 261-270, https://doi.org/10.1016/j.jmapro.2019.05.032.
139. Kuriachen, B.; Mathew, J. Effect of powder mixed dielectric on material removal and surface modification in microelectric discharge machining of Ti-6Al-4V. *Mater. Manuf. Process.* **2016**, *31*, 439-446, https://doi.org/10.1080/10426914.2015.1004705.
140. Wu, Z.Z.; Luo, F.; Guo, DJ.; Wu, X.Y.; Xu, B.; Lei, J.G.; Liang, X.; Diao, D.F. Micro-EDM by using laminated 3D microelectrodes with deionized water containing B 4 C powder. *Int. J. Adv. Manuf. Tech.* **2018**, *99*, 2893-2902, https://doi.org/10.1007/s00170-018-2581-x.
141. Mohanty, S.; Kumar, V.; Tyagi, R.; Kumar, S.; Bhushan, B.; Das, A.K.; Dixit, A.R. Surface alloying using tungsten disulphide powder mixed in dielectric in micro-EDM on Ti6Al4V. *Mater. Sci. Eng. C.* **2018**, *377*, 012040, https://doi.org/10.1088/1757-899X/377/1/012040.
142. Tiwary, A.P.; Pradhan, B.B.; Bhattacharyya, B. Influence of various metal powder mixed dielectric on micro-EDM characteristics of Ti-6Al-4V. *Mater. Manuf. Process.* **2019**, *34*, 1103-1119, https://doi.org/10.1080/10426914.2019.1628265.
143. Prihandana, G.S.; Mahardika, M.; Hamdi, M.; Wong, Y.S.; Miki, N.; Mitsui, K. Study of workpiece vibration in powder-suspended dielectric fluid in micro-EDM processes. *Int. J. Precis. Eng. Manuf.* **2013**, *14*, 1817-1822, https://doi.org/10.1007/s12541-013-0243-3.
144. Prihandana, G.S.; Mahardika, M.; Hamdi, M.; Wong, Y.S.; Mitsui, K. Effect of micro-powder suspension and ultrasonic vibration of dielectric fluid in micro-EDM processes—Taguchi approach. *Int. J. Mach. Tools Manuf.* **2009**, *49*, 1035-1041, https://doi.org/10.1016/j.ijmachtools.2009.06.014.
145. Kumar, D.; Singh, N.K.; Bajpai, V. Recent trends, opportunities and other aspects of micro-EDM for advanced manufacturing: a comprehensive review. *J. Braz. Soc. Mech. Sci. Eng.* **2020**, *42*, 222, https://doi.org/10.1007/s40430-020-02296-4.
146. Ng, P.S.; Kong, S.A.; Yeo, S.H. Investigation of biodiesel dielectric in sustainable electrical discharge machining. *Int. J. Adv. Manuf. Tech.* **2017**, *90*, 2549-2556, https://doi.org/10.1007/s00170-016-9572-6.
147. Valaki, J.B.; Rathod, P.P.; Sankhavara, C.D. Investigations on technical feasibility of Jatropha curcas oil based bio dielectric fluid for sustainable electric discharge machining (EDM). *J. Manuf. Process.* **2016**, *22*, 151-160, https://doi.org/10.1016/j.jmapro.2016.03.004.
148. Valaki, J.B.; Rathod, P.P. Investigating feasibility through performance analysis of green dielectrics for sustainable electric discharge machining. *Mater. Manuf. Process.* **2016**, *31*, 541-549, https://doi.org/10.1080/10426914.2015.1070430.
149. Ahmad, S.; Chendang, R.N.; Lajis, M.A.; Supawi, A.; Rahim, E.A. Machinability Performance of RBD Palm Oil as a Bio Degradable Dielectric Fluid on Sustainable Electrical Discharge Machining (EDM) of AISI D2 Steel. In Proceedings of the Advances in Material Sciences and Engineering, Singapore, 2020//; Awang, M., Emamian, S., Yusof, F., Eds.; Springer, Singapore, **2020**; pp. 509-517, https://doi.org/10.1007/978-981-13-8297-0_53.
150. Valaki, J.B.; Rathod, P.P. Assessment of operational feasibility of waste vegetable oil based bio-dielectric fluid for sustainable electric discharge machining (EDM). *Int. J. Adv. Manuf. Tech.* **2016**, *87*, 1509-1518, https://doi.org/10.1007/s00170-015-7169-0.
151. Chaudhury, P.; Samantaray, S. A comparative study of different dielectric medium for sustainable EDM of non-conductive material by electro-thermal modelling. *Mater. Today: Proc.* **2021**, *41*, 437-444, https://doi.org/10.1016/j.matpr.2020.10.162.
152. Das, S.; Paul, S.; Doloi, B. An experimental and computational study on the feasibility of bio-dielectrics for sustainable electrical discharge machining. *J. Manuf. Process.* **2019**, *41*, 284-296, https://doi.org/10.1016/j.jmapro.2019.04.005.
153. Ming, W.; Cao, C.; Xie, Z.; Liu, X.; Xu, Y.; Jiang, Z.; Li, X.; Liu, K.; Guo, X.; Yuan, J.; Li, L. Green manufacturing: a comparative study of renewable dielectrics in the EDM process. *J. Braz. Soc. Mech. Sci. Eng.* **2022**, *44*, 580, https://doi.org/10.1007/s40430-022-03867-3.

154. Ming, W.; Guo, X.; Zhang, G.; Hu, S.; Liu, Z.; Xie, Z.; Zhang, S.; Duan, L. Optimization of process parameters and performance for machining Inconel 718 in renewable dielectrics. *Alex. Eng. J.* **2023**, *79*, 164-179, https://doi.org/10.1016/j.aej.2023.07.075.
155. Das, S.; Paul, S.; Doloi, B. Feasibility investigation of neem oil as a dielectric for electrical discharge machining. *Int. J. Adv. Manuf. Tech.* **2020**, *106*, 1179-1189, https://doi.org/10.1007/s00170-019-04736-5.
156. Das, S.; Paul, S.; Doloi, B. Investigation of the machining performance of neem oil as a dielectric medium of EDM: a sustainable approach. *Mater. Sci. Eng. C.* **2019**, *653*, 012017, https://doi.org/10.1088/1757-899X/653/1/012017.
157. Ramasubbu, N.; Ramabalan, S. Experimental feasibility study of coconut oil for sustainable electrical discharge machining on Hastelloy B2. *Sadhana.* **2023**, *48*, 137, https://doi.org/10.1007/s12046-023-02211-2.
158. Chandra, D.; Chauhan, N.R.; Rajesha, S. Process Optimization of EDM Parameters Using TAGUCHI while Machining Aluminium Metal Matrix Composite. In Optimization of Industrial Systems; Panchal, D., Tyagi, M., Sachdeva, A., Pamucar, D., Eds.; Scrivener Publishing LLC: **2022**; pp. 533-543, https://doi.org/10.1002/9781119755074.ch41.

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