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MODIFICATION OF THE SURFACE OF BIO-COMPATIBLE MATERIAL THROUGH POWDER MIXED ELECTRICAL DISCHARGE MACHINING - A REVIEW

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ABSTRACT

Bio-compatible materials are very important in many biological uses, like orthopaedic implants, oral prosthetics, and devices for the heart and blood vessels. The surface qualities of these materials significantly affect how well they work and are compatible with living things. Powder Mixed Electrical Discharge Machining (PMEDM) is a new way to change the surface of bio-compatible materials. It gives the surface better properties. This review paper gives an in-depth look at the latest study on PMEDM for changing the surface of biocompatible materials. It talks about the factors of the process, how the experiments are set up, how the surface is changed, and how that affects biocompatibility.

Keywords: PMEDM, EDM, ANNOVA, DOE

1. INTRODUCTION

In the area of biomedical engineering, it is essential to use materials that are biocompatible when making medical gadgets and implants. Ratner et al. (2004) say that some of these materials are metals, polymers, ceramics, and alloys that can safely interact with human cells. Over the years, researchers have found that the surface properties of these materials have a big effect on how well they work and if they are biocompatible (Mishra et al., 2020). Liu et al. (2017) found that surface qualities like roughness, microstructure, chemical makeup, and wettability can affect cell adhesion, growth, protein binding, and immune reaction, affecting how well implants work in the body. So, different ways of changing the surface of biocompatible materials, ranging from standard physical and chemical processes to new methods based on nanotechnology (Santos et al., 2012), have been looked into.

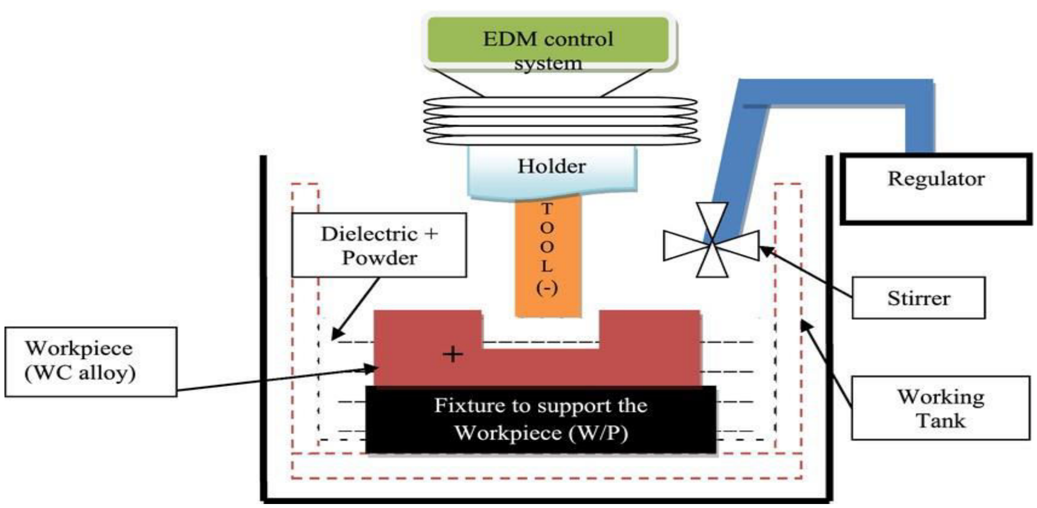

Fig 1- powder mixed electrical discharge machining process setup

Powder Mixed Electrical Discharge Machining (PMEDM) is a new way to change the surface/ Yadav et al. (2018) say that PMEDM is based on the traditional Electrical Discharge

Machining (EDM) process. In PMEDM, fine powders are added to the dielectric fluid used in EDM. (Kumar et al., 2019) have shown that this modification significantly improves the process performance and surface properties of the machined parts.

(Kumar et al., 2021) say that the way the surface of biocompatible materials is changed is a key part of how they work and how well they work overall. Once these materials are inserted into a person's body, they touch body tissues and fluids directly. Because of this, the properties of their surfaces have a big effect on how they interact with the body (Vasilev et al., 2009). Breme et al. (2006) found that modifying the surface correctly can improve characteristics like corrosion resistance, wear resistance, and dynamic strength, making the material last longer when used in medical devices and implants. It can also add or improve controlled drug release, antibiotic action, better cell attachment, growth, differentiation, and a lower inflammatory response (Bose & Bandyopadhyay, 2012). (Gittens et al., 2013) found that surface roughness, which is an important property, has a big effect on cell binding and growth, protein adsorption, and immune reaction. Santos et al. (2012) say that fine-tuning this surface roughness at the micro and nano levels could make it easier for implants to fuse with the tissues around them. Ho et al. (2004) say that Powder Mixed Electrical Discharge Machining (PMEDM) is a more advanced type of EDM. (Bhattacharya et al., 2020) say that this method is especially good for cutting hard materials that are hard to cut with standard methods. Han et al. (2017) say that sparks are made when the workpiece and electrode are put in this fluid and a change in voltage is applied between them.

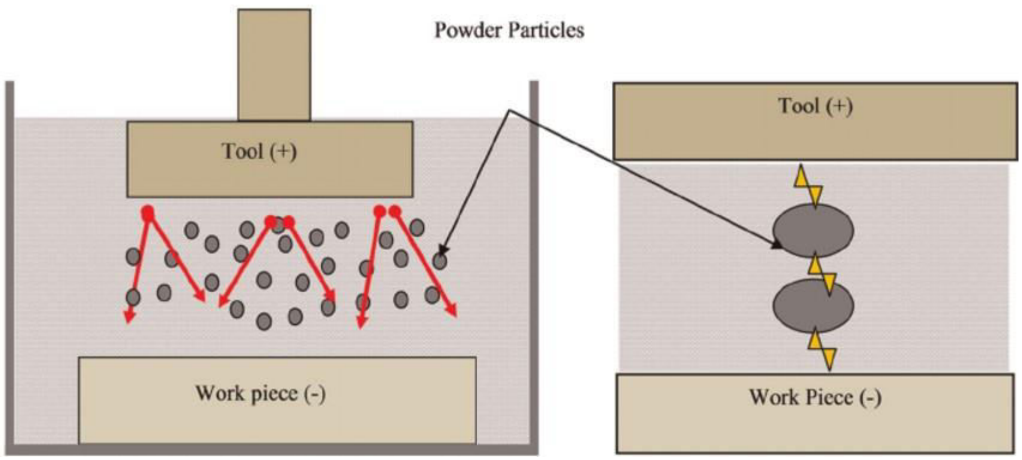

Fig 2- Schematic representation of the mechanism of the PMEDM process.

In PMEDM, the dielectric fluid is mixed with very small powders of certain materials. Mixing dielectric fluid and powders improves the EDM process, leading to better cutting in several ways (Pecas & Henriques, 2018). Singh et al. (2018) found that adding powder to the dielectric fluid can improve the surface finish, reduce the number of cracks, and change how hard the polished surface is. Gupta et al. (2019) say that the powder materials used can be different and that each powder type has its own benefits that rely on what the finished part will be used for in the end.

2. PROCESS PARAMETERS AND EXPERIMENTAL SETUPS

2.1 Pulse Generator Characteristics

The pulse generator is an essential component in the PMEDM process as it determines the energy input for sparking. The critical parameters of the pulse generator include pulse on-time (T_on), pulse off-time (T_off), peak current (I_p), and pulse voltage (V_p). The interaction of these parameters largely governs the machined surface's characteristics and the PMEDM process's overall efficiency (Jahan et al., 2016). The process parameters are mentioned below.

Pulse On-Time (T_on): This is the duration for which the voltage is applied between the tool electrode and the workpiece, and it determines the amount of material removed per spark. A longer pulse on time results in more material removal but can also increase the heat-affected zone and induce more surface defects (Bhattacharya et al., 2018).

Pulse Off-Time (T_off): This is the interval between two successive sparks, allowing for the removal of debris from the machining area and cooling of the workpiece. A shorter pulse off-time can increase the material removal rate (MRR), but at the risk of excessive heat accumulation and potential surface damage (Simao et al., 2003).

Peak Current (I_p): The peak current determines the intensity of the spark and the size of the crater formed on the workpiece surface. Higher currents lead to larger craters, higher MRR, and potentially coarser surface finishes (Ho et al., 2004).

Pulse Voltage (V_p): The voltage across the gap controls the initiation of the spark. Higher voltages can provide more energetic sparks, but can also increase electrode wear and potentially deteriorate the surface finish (Singh et al., 2018).

2.2 Powder Electrode Selection

The following powders are used in the PMEDM process to improve EDM performance.

Metallic Powders: Metallic powders like copper, aluminium, and iron have been widely used due to their high electrical and thermal conductivities. They help enhance the spark energy, reduce electrode wear, and improve the surface finish (Gupta et al., 2019).

Ceramic Powders: Ceramic powders such as aluminium oxide and silicon carbide, due to their high melting point and hardness, aid in controlling the heat-affected zone and reducing the surface defects like cracks and pits (Shabgard et al., 2011).

Composite Powders: Composite powders, including metal matrix composites (MMCs) and ceramic matrix composites (CMCs), combine properties from their constituent materials. They are often used when specific surface characteristics are desired (Pecas & Henriques, 2018).

2.3 Dielectric Fluid and its Role

In the PMEDM process, the dielectric fluid has more than one job, making it an important part of the setting. The fluid serves as an electrical insulator until a certain voltage level is reached, at this point, it becomes conductive and allows a spark to travel between the electrodes (tool and workpiece). This causes localised heating, melting, and the removal of material from the workpiece, a process called "machining." Mohan et al. (2005) say that the dielectric fluid also cools the cut area and cleans out the space between the electrodes.

When conductive powders are added to the dielectric fluid, its qualities change greatly, and so does its role in the PMEDM process. Kumar et al. (2017) found that the floating powders change the breakdown strength and conductivity of the dielectric fluid, which changes the energy and spread of the sparks. They also help spread the heat made by the process, which reduces the area of the workpiece's surface that is affected by heat. Singh et al. (2018) say that the powders also help remove trash, which lowers the chances of arcing and short circuits.

2.4 Tool Material

The selection of tool and workpiece materials is another crucial parameter in the PMEDM process. Their properties can significantly influence the process performance, including the machining rate, electrode wear, and the surface characteristics of the machined part.

Tool Material: The tool electrode material should have a high electrical conductivity and a high melting point to withstand the heat generated during the sparking process (Pecas & Henriques, 2018). Commonly used tool materials in PMEDM include copper, graphite, and tungsten due to their good electrical and thermal conductivities. Copper has been preferred for high precision applications because of its fine finish, whereas graphite, owing to its low wear rate, has been used when longer tool life is required (Rajurkar et al., 2000).

2.5 Electrical Parameters

Electrical parameters, including pulse duration (on-time and off-time), discharge current, and discharge voltage, play an essential role in the PMEDM process, as they influence the energy of the sparks and thus, the material removal rate, surface finish, and the heat-affected zone.

Pulse Duration: Pulse duration is divided into on-time, when the spark is active, and off-time, the cooling and debris removal period between successive sparks. Longer on-time usually results in higher material removal but can increase the heat-affected zone and lead to poorer surface finish due to larger craters and more recast layer (D'Urso & Maccarini, 2016). Hence, a balance must be found depending on the application requirements.

Discharge Current: The discharge current is another influential parameter, where higher current leads to greater spark energy and a higher material removal rate. However, it can also result in increased electrode wear and a rougher surface finish (Hassan et al., 2017).

Discharge Voltage: The discharge voltage affects the gap distance between the tool electrode and the workpiece, where higher voltage increases the gap and vice versa. Too high a voltage can cause unstable sparking and excessive tool wear, whereas too low a voltage can lead to an ineffective machining process (Chow et al., 2008).

2.6 Powder Mixing Techniques

Powder mixing techniques are critical in the PMEDM process to ensure a homogeneous dispersion of the powder particles within the dielectric fluid. The uniformity of the dispersion impacts the distribution of the electrical discharges, which in turn influences the machining performance and surface characteristics of the machined part.

Two primary methods are used to mix the powders into the dielectric fluid: mechanical stirring and ultrasonic vibration.

Mechanical Stirring: This method involves mechanically agitating the dielectric fluid to disperse the powder particles. It can be performed using a magnetic stirrer or an impeller. However, mechanical stirring may not always ensure a homogeneous distribution, especially with higher powder concentrations or larger particles (Singh et al., 2018).

Ultrasonic Vibration: This method employs ultrasonic waves to mix the powder into the dielectric fluid. The high-frequency vibrations cause the particles to disperse more uniformly. Compared to mechanical stirring, ultrasonic vibration can achieve better dispersion, especially for fine powders, and prevent particles from settling quickly (Yadav et al., 2019).

Both methods have their advantages and are chosen based on the specific requirements of the PMEDM process, such as the type and size of the powder particles, their concentration in the dielectric fluid, and the machining parameters. The optimal powder mixing technique is crucial for maximizing the benefits of PMEDM, such as improved surface quality and reduced tool wear.

2.7 Design of Experiments in PMEDM

The design of experiments (DoE) is a systematic and efficient method used to understand the influence of different factors and their interactions in a process such as PMEDM. The goal is to find an optimal combination of process parameters that yield the best result in terms of efficiency, surface quality, and other performance criteria. When designing experiments for PMEDM, one must consider several factors, including: The selection of independent variables (input parameters): These usually include electrical parameters (discharge current, pulse duration, and voltage), powder type and concentration, tool and workpiece material, and others as mentioned in the previous sections. The choice of response variables (output parameters): These could be the material removal rate, surface roughness, micro-hardness, surface topography, residual stress, etc. The type of experimental design: Common designs include full factorial, fractional factorial, Taguchi, response surface methodology (RSM), etc. The selection depends on the number of variables and the level of interactions one wishes to study (Montgomery, 2017).

3. SURFACE MODIFICATIONS ACHIEVED BY PMEDM

3.1 Microstructure Alterations

PMEDM is known for its ability to significantly alter the microstructure of the machined surface, which can impact the material's properties and performance in various applications, including biomedical uses. One of the significant microstructural changes that occur during PMEDM is the formation of a recast layer on the machined surface. This layer is a result of the rapid melting and solidification of the workpiece material caused by the heat of the electrical discharges (Pecas & Henriques, 2018). The recast layer can impact the hardness, wear resistance, and corrosion resistance of the machined surface. PMEDM can also lead to grain refinement in the machined surface due to the rapid solidification process. This can enhance the mechanical properties of the material, including hardness and strength (Singh et al., 2018).

3.2 Surface Roughness Improvement

Including powder particles in the dielectric fluid can significantly influence the sparks' energy distribution and the eroded particles' cooling, resulting in a more evenly distributed and less recast layer. This helps achieve a smoother surface finish (Khan et al., 2016).

The type, size, and concentration of the powder particles, as well as the electrical parameters, play a significant role in determining the surface roughness in PMEDM. For instance, fine powders can provide better surface finish than coarse powders, as they can homogenize the discharges more effectively (Prakash & Kumaresh Babu, 2016).

3.3 Grain Refinement and Recrystallization

The high thermal gradients during the PMEDM process lead to rapid solidification rates, inducing grain refinement and recrystallization in the machined surface. This is especially critical for bio-compatible materials, as refined grains can enhance mechanical properties and wear resistance, and influence the material's interaction with the biological environment. The high cooling rates in PMEDM can induce the formation of refined grains in the recast layer. These refined grains can increase the hardness and strength of the surface, which are beneficial characteristics for implant materials (Prakash & Kumaresh Babu, 2016). The high temperatures generated during PMEDM can cause the recrystallization of the material in the heat-affected zone. This can alter the crystal structure and orientation of the grains, eliminating work hardening and increasing the material's resistance to corrosion and wear (Singh et al., 2018).

The powder characteristics and the process parameters of PMEDM can be optimized to control the grain refinement and recrystallization process. Studies have shown that the use of finer powders and lower energy discharges can lead to better grain refinement (Yadav et al., 2019).

3.4 Phase Transformations and Metallurgical Changes

Phase transformations and metallurgical changes induced by the PMEDM process can significantly alter the machined bio-compatible materials' physical, chemical, and mechanical properties, impacting their performance and suitability for various applications.

Phase Transformations: The high local temperatures generated during the electrical discharges in PMEDM can lead to phase transformations in the machined material. This could include transformations from austenite to martensite in stainless steels, or the formation of non-equilibrium phases due to rapid cooling (Yadav et al., 2019). These phase transformations can alter the machined surface's hardness, toughness, and wear resistance.

Metallurgical Changes: In PMEDM, the powder particles in the dielectric fluid can melt and redeposit on the machined surface, leading to changes in the chemical and elemental composition of the surface layer. This can result in improved properties such as increased hardness, improved wear resistance, or enhanced corrosion resistance (Khan et al., 2016).

Material Transfer: The discharge energy in PMEDM can cause material transfer from the electrode to the workpiece or vice versa. The extent and direction of this material transfer depend on the process parameters, electrode material, and the type of powder used in the dielectric fluid (Prakash & Kumaresh Babu, 2016).

3.5 Surface Hardness Enhancement

Surface hardness is a vital attribute for bio-compatible materials used in biomedical applications as it can directly influence the wear resistance and longevity of the implants. PMEDM has shown considerable potential in enhancing the surface hardness of these materials.

During the PMEDM process, the high temperatures and rapid cooling rates lead to a hardened surface layer, often referred to as the recast layer. This hardened layer is typically characterized by a fine-grained microstructure, phase transformations, and the incorporation of hard phases such as carbides and oxides, all contributing to enhanced surface hardness (Yadav et al., 2019). Moreover, the introduction of specific types of powders into the dielectric fluid can lead to the formation of hard compound layers on the surface. For instance, the addition of silicon carbide (SiC) or tungsten carbide (WC) powders has shown to improve surface hardness significantly due to the formation of carbide layers (Prakash & Kumaresh Babu, 2016).

Furthermore, material transfer from the electrode to the workpiece can also enhance the hardness. For instance, using a harder electrode material can result in a harder surface layer on the workpiece (Khan et al., 2016).

3.6 Residual Stress Analysis

Residual stresses generated during the PMEDM process can significantly influence bio-compatible materials' mechanical properties, dimensional stability, and fatigue performance. Residual stress analysis is crucial for understanding and optimizing the PMEDM process to ensure the machined parts' desired surface characteristics and performance.

Residual stresses can arise due to the non-uniform heating and cooling cycles, phase transformations, and the presence of the recast layer. These stresses can be tensile or compressive in nature, depending on the specific conditions and material properties.

4. BIOCOMPATIBILITY EVALUATION

4.1 Cytotoxicity Assessment

Cytotoxicity assessment is an essential aspect of the biocompatibility evaluation of bio-compatible materials. This involves analyzing the potential toxic effects of the modified materials on the biological cells. Common methods used for cytotoxicity assessment include the MTT assay, the Trypan Blue exclusion test, or the LDH release assay, which provide quantitative measures of cell viability after exposure to the material under study (ISO 10993-5:2009).

Various studies have demonstrated the effectiveness of PMEDM in reducing cytotoxicity. For instance, introducing bioactive powders like hydroxyapatite or bio-glass in the dielectric fluid has reduced the cytotoxic effects and improved the cellular response (Yadav et al., 2019). However, it is crucial to note that the cytotoxicity of the material can also depend on the type and size of the powders used, the process parameters, and the specific cellular response to the material. Therefore, thorough cytotoxicity testing is crucial for any surface-modified bio-compatible material produced by PMEDM before they can be used for biomedical applications.

4.2 Cell Adhesion and Proliferation

Cell adhesion and proliferation are key factors in the integration of implants into the body, and both can be affected by the surface properties of bio-compatible materials. The surface modifications induced by PMEDM, such as surface roughness, grain size, and elemental composition, can influence cell adhesion and proliferation significantly.

Studies have shown that surfaces with moderate roughness can promote better cell adhesion and proliferation compared to smoother or excessively rough surfaces (Gittens et al., 2013). Furthermore, the presence of certain elements, such as calcium and phosphorous from hydroxyapatite powder, can improve cell adhesion due to their bioactivity (Yadav et al., 2019).

4.3 Hemocompatibility Evaluation

Hemocompatibility is another crucial factor in evaluating the biocompatibility of materials used for cardiovascular devices. Hemocompatibility refers to the material's interaction with blood components, including blood cells and plasma proteins.

An ideal hemocompatible material should not induce platelet activation, thrombosis, or hemolysis and should not negatively affect blood coagulation.

PMEDM has shown potential in improving the hemocompatibility of bio-compatible materials by incorporating bioactive powders, such as silicon or diamond, which can reduce platelet activation and adhesion, thus reducing the risk of thrombus formation (Khan et al., 2016).

4.4 Antibacterial Properties

The increasing concern over implant-associated infections has led to the exploration of antibacterial surface modifications. PMEDM offers a promising approach to achieving antibacterial surfaces by incorporating antibacterial agents (like silver or copper) into the dielectric fluid. The high energy discharges can cause these elements to be deposited on the surface, providing the implants with antibacterial properties.

Research has demonstrated the effectiveness of this approach in reducing bacterial adhesion and biofilm formation, thus reducing the risk of implant-associated infections (Dolatabadi et al., 2015).

It's important to note that while incorporating antibacterial elements, the overall biocompatibility and mechanical properties of the implant should not be compromised. Hence, careful consideration and testing are needed for such modifications.

5. CHALLENGES AND LIMITATIONS

5.1 Electrical Discharge-Induced Thermal Damage

One of the main challenges of PMEDM is managing the thermal damage induced by the electrical discharges. The process involves high-energy discharges in a very localized area, leading to extremely high temperatures. This could potentially result in a range of thermal damages such as micro-cracks, voids, and recast layer formation, all of which may adversely impact the mechanical properties of the bio-compatible material.

The formation of a recast layer, a layer of resolidified material on the workpiece surface, is often inevitable in the PMEDM process. While a thin recast layer can be beneficial for certain applications by providing a harder surface, a thick recast layer can be problematic. It may have a different composition and poorer mechanical properties compared to the bulk material, and it may also lead to increased surface roughness (Yadav et al., 2019).

The generation of micro-cracks is another concern, generally due to the rapid heating and cooling cycles during the PMEDM process. These cracks can act as stress concentration points and reduce the fatigue life of the bio-compatible materials, potentially leading to implant failure (Khan et al., 2016).

5.2 Surface Integrity and Microcracks

Surface integrity and the presence of microcracks are key concerns in the PMEDM process. The high energy discharges can induce rapid heating and cooling cycles, which may result in thermal stresses that can cause microcracks on the material surface (Khan et al., 2016). The presence of microcracks can lead to a reduction in mechanical strength and potentially result in premature failure of the implant.

Additionally, the process can generate a recast layer – a thin layer of molten and rapidly solidified material on the surface of the workpiece. While the recast layer can sometimes provide a harder surface, it can also contain pores and cracks that could compromise the material's structural integrity and lead to adverse effects on biocompatibility (Kumar et al., 2021). In order to ensure surface integrity and minimize microcracks, careful control and optimization of the PMEDM parameters are essential. This includes pulse energy, pulse duration, powder concentration, and tool electrode material. Advanced technologies such as real-time process monitoring and control can also be beneficial in this regard.

5.3 Uniform Powder Mixing

Achieving uniform powder mixing in PMEDM is crucial to ensure consistent and homogeneous distribution of powder particles in the dielectric fluid. However, achieving uniform powder mixing can be challenging and affect the surface modifications' quality and reliability. The powder particles' size, shape, and density can influence their suspension in the dielectric fluid. Coarser or denser particles may settle down quickly, resulting in uneven distribution (Prakash & Kumaresh Babu, 2016). Inadequate powder mixing can lead to non-uniform surface modifications, inconsistent material removal rates, and variations in surface characteristics across the machined part.

As mentioned earlier, various techniques have been proposed to address this challenge, such as ultrasonic vibration, mechanical stirring, and magnetic stirring. These techniques aim to improve powder particle dispersion and prevent sedimentation during the PMEDM process (Singh et al., 2018).

Optimizing the powder mixing technique and parameters and selecting appropriate powder characteristics are critical to achieving uniform powder distribution and improving the overall reliability and consistency of the PMEDM process.

5.4 Biocompatibility Assessment Standardization

The standardization of biocompatibility assessment is an important aspect of ensuring the consistent and reliable evaluation of the biocompatibility of bio-compatible materials modified through PMEDM. Standardization helps compare results across different studies and comprehensively understand the materials' performance in biomedical applications. International standards, such as ISO 10993 series, provide guidelines for evaluating the biocompatibility of medical devices. These standards outline various tests and procedures for assessing the cytotoxicity, sensitization, irritation, and systemic toxicity of materials (ISO 10993-1:2018).

However, it is important to note that these standards may not specifically address the unique surface modifications achieved through PMEDM. As a result, there is a need for further research and development of standardized protocols specifically tailored to evaluate the biocompatibility of bio-compatible materials modified by PMEDM (Prakash & Kumaresh Babu, 2016).

The establishment of standardized testing methods, including appropriate cell culture models and evaluation criteria, will enhance the reliability and comparability of biocompatibility assessment for PMEDM-modified materials, providing valuable insights for regulatory compliance and clinical acceptance.

6. FUTURE PERSPECTIVES AND POTENTIAL RESEARCH AREAS

6.1 Advanced Electrical Discharge Machining Techniques

In the future, the development of advanced electrical discharge machining (EDM) techniques holds great potential for further enhancing the surface modification capabilities of bio-compatible materials.

One area of research is the exploration of novel EDM methods, such as micro-EDM and electrochemical discharge machining (ECDM), which offer improved precision, finer surface finishes, and reduced thermal damage compared to traditional EDM techniques (Singh et al., 2018). These advanced EDM techniques can be further investigated and optimized for surface modification of bio-compatible materials, allowing for more controlled and precise alterations.

Additionally, the integration of EDM with other advanced manufacturing processes, such as laser processing and additive manufacturing, can offer synergistic effects and enable the fabrication of complex and customized structures with enhanced surface characteristics (Yadav et al., 2019). Moreover, advancements in process monitoring and control systems, including real-time feedback control and adaptive machining strategies, can facilitate better control over the surface modifications, leading to improved reliability and reproducibility (Kumar et al., 2021). The development of computational modeling and simulation techniques is another important area for future research. These models can help predict and optimize the effects of process parameters, powder characteristics, and material properties on surface modifications, enabling a more efficient and cost-effective approach to PMEDM (Yadav et al., 2019).

6.2 Multifunctional Surface Modifications

In the future, there is significant potential for the development of multifunctional surface modifications in bio-compatible materials through PMEDM. Multifunctional surfaces can possess a combination of desired properties such as enhanced biocompatibility, antibacterial properties, improved wear resistance, and tailored surface chemistry.

The incorporation of multiple types of powders, each with specific functionalities, into the dielectric fluid can enable the creation of surfaces with diverse properties. For example, the combination of bioactive powders like hydroxyapatite for enhanced osseointegration and antibacterial powders like silver or copper for infection prevention can lead to bio-compatible materials with multifunctional capabilities (Dolatabadi et al., 2015).

Furthermore, the introduction of hierarchical structures or micro/nano-scale surface features through PMEDM can create surfaces with enhanced biological response, such as improved cell adhesion, proliferation, and tissue integration (Gittens et al., 2014).

The optimization of powder mixing techniques and the selection of appropriate powder combinations will be crucial in achieving the desired multifunctional surface modifications. Additionally, the development of innovative powder materials and surface engineering strategies will provide further opportunities for tailoring the surface properties of bio-compatible materials

6.3 In-situ Monitoring and Control Systems

In the future, the development of in-situ monitoring and control systems for PMEDM processes can significantly enhance the efficiency, reliability, and precision of surface modifications in bio-compatible materials. Real-time monitoring of process parameters such as discharge energy, pulse duration, and powder concentration can provide valuable feedback on the actual conditions during machining. This enables the detection of any deviations or anomalies, allowing for prompt adjustments and optimization of the process parameters (Kumar et al., 2021).

Advanced sensing techniques, such as optical emission spectroscopy, thermal imaging, or acoustic emission monitoring, can be integrated into the PMEDM setup to provide continuous and accurate monitoring of the process. These in-situ monitoring systems can help in identifying thermal damage, micro-crack formation, and other potential issues, allowing for proactive intervention and control (Yadav et al., 2019). Furthermore, the integration of feedback control systems can enable adaptive machining strategies. These systems can dynamically adjust the process parameters in real-time based on the monitored data, ensuring consistent and controlled surface modifications throughout the machining process (Singh et al., 2018). The development of in-situ monitoring and control systems will contribute to better process understanding, improved repeatability, and higher quality of surface modifications in bio-compatible materials. It will also enable the optimization of the PMEDM process parameters for specific material systems and desired surface characteristics, leading to enhanced performance and reliability in biomedical applications.

6.4 Advanced Biocompatibility Evaluation Techniques

In the future, developing and implementing advanced biocompatibility evaluation techniques will enhance our understanding of the performance and safety of bio-compatible materials modified through PMEDM.

Traditional biocompatibility evaluation techniques, such as cytotoxicity assays and cell adhesion studies, provide valuable insights into the cellular response to materials. However, advanced techniques can offer more comprehensive assessments and enable a deeper understanding of the interactions between the modified surfaces and biological systems.

For example, advanced imaging techniques, such as confocal microscopy, scanning electron microscopy (SEM), and atomic force microscopy (AFM), can provide high-resolution imaging of the material surface and allow for detailed analysis of cellular interactions, surface roughness, and topographical features (Pecas & Henriques, 2018).

Moreover, techniques like X-ray photoelectron spectroscopy (XPS), Fourier-transform infrared spectroscopy (FTIR), and Raman spectroscopy can provide valuable information about the surface chemistry and chemical composition alterations induced by PMEDM (Yadav et al., 2019).

Furthermore, in vitro and in vivo studies can be complemented with advanced molecular biology techniques, such as gene expression analysis, protein profiling, and cytokine assays, to gain insights into the molecular and inflammatory responses to PMEDM-modified surfaces (Pecas & Henriques, 2018).

The integration of these advanced techniques with traditional biocompatibility assessments will provide a more comprehensive evaluation of the performance and biocompatibility of PMEDM-modified bio-compatible materials, enabling a more informed decision-making process for their application in biomedical settings.

7. CONCLUSION

7.1 Summary of Findings

This review explored the surface modification of bio-compatible materials through Powder Mixed Electrical Discharge Machining (PMEDM). The following key findings have emerged:

- PMEDM offers a promising approach for surface modification of bio-compatible materials used in various biomedical applications.
- The process parameters, including pulse generator characteristics, powder electrode selection, dielectric fluid, and electrical parameters, play a significant role in achieving desired surface modifications.
- PMEDM can induce microstructure alterations, surface roughness improvement, grain refinement, phase transformations, elemental composition alterations, and surface hardness enhancement.
- Biocompatibility evaluation of PMEDM-modified materials involves assessing cytotoxicity, cell adhesion and proliferation, hemocompatibility, osseointegration, and antibacterial properties.
- Challenges and limitations in PMEDM include electrical discharge-induced thermal damage, surface integrity, microcracks, uniform powder mixing, and standardization of biocompatibility assessment.
- Future perspectives and potential research areas include the development of advanced

EDM techniques, multifunctional surface modifications, in-situ monitoring and control systems, computational modeling and simulation, and advanced biocompatibility evaluation techniques.

In conclusion, PMEDM shows great promise in enhancing the surface characteristics of bio-compatible materials for biomedical applications. However, further research and development are needed to overcome the challenges and optimize the process parameters, while also focusing on the standardization of biocompatibility evaluation techniques. The integration of advanced technologies and multidisciplinary approaches will pave the way for the successful implementation of PMEDM in the field of bio-compatible material surface modification.

7.2 Significance of PMEDM in Bio-Compatible Material Applications

PMEDM holds significant significance in the field of bio-compatible material applications. The surface modifications achieved through PMEDM have several advantages and benefits that contribute to the improvement of bio-compatible materials and their performance in various biomedical applications. Some key points highlighting the significance of PMEDM are:

1. PMEDM allows for precise control and modification of the surface properties of bio-compatible materials. It can improve surface roughness, microstructure, grain refinement, phase transformations, elemental composition, and surface hardness. These modifications can lead to improved biocompatibility, increased osseointegration, enhanced wear resistance, and tailored surface chemistry, making the materials better suited for their intended biomedical applications.
2. PMEDM enables the incorporation of bioactive powders, antibacterial agents, and other functional materials into the dielectric fluid. This allows for the creation of multifunctional surfaces with desired properties, such as enhanced osseointegration, antibacterial properties, and improved wear resistance. By tailoring the surface functionalities, PMEDM can contribute to the development of bio-compatible materials that meet specific application requirements, such as orthopedic implants, dental prosthetics, and cardiovascular devices.
3. PMEDM offers precise and controlled surface modifications. The process parameters can be optimized to achieve the desired surface characteristics, ensuring consistency and repeatability. The use of in-situ monitoring and control systems further enhances the precision and reliability of the process, leading to high-quality and consistent results.
4. PMEDM can be adapted to various materials, allowing for customization of the surface modifications based on specific material properties and application requirements. The selection of suitable powders, process parameters, and electrode materials enables tailored surface modifications for different bio-compatible materials.

7.3 Overall Recommendations and Future Directions

Based on the findings and significance of PMEDM in bio-compatible material applications, the following recommendations and future directions can be suggested:

1. Further research should focus on optimizing the process parameters of PMEDM to achieve desired surface modifications while minimizing thermal damage and microcrack formation. Understanding the complex interactions between process parameters and material properties will help in achieving more precise and consistent surface modifications.
2. Efforts should be made to establish standardized protocols and evaluation techniques specifically tailored to assess the biocompatibility of bio-compatible materials modified through PMEDM. This will ensure consistent and reliable evaluation across different studies and facilitate regulatory compliance and clinical acceptance.
3. The integration of advanced technologies such as in-situ monitoring and control systems, computational modeling and simulation, and advanced biocompatibility evaluation techniques can enhance the efficiency, precision, and understanding of the PMEDM process. These technologies can provide real-time feedback, predictive insights, and comprehensive assessments for improved process control and optimization.
4. Collaboration between researchers from various disciplines, including materials science, engineering, biology, and medicine, is crucial for the advancement of PMEDM in bio-compatible material applications. Interdisciplinary collaboration will bring together diverse expertise and perspectives, enabling holistic approaches to address challenges, optimize surface modifications, and accelerate the translation of PMEDM into practical biomedical applications.
5. To fully realize the potential of PMEDM in bio-compatible material applications, there is a need for successful translation from the research laboratory to clinical settings. Close collaboration with clinicians and regulatory bodies is necessary to validate the safety, efficacy, and long-term performance of PMEDM-modified bio-compatible materials in real-world scenarios.

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