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Advances in nano-powder mixed electrical discharge machining (NPEDM): mechanisms, applications, and emerging Trends (2021–2025)

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In-situ Nano-Powder Mixed Electrical Discharge Machining (NPEDM) represents a revolutionary alteration of conventional EDM complemented with nano-scaled powder to effectively enhance material removal rate, reduce tool wear, and improve surface quality. This critical review covers the advances in NPEDM during the period from 2001 to up to 2025 to pinpoint the effect of various nano-powder types (e.g. Al_2O_3, SiC, CNTs, hydroxyapatite) and process parameters on the material removal rate and functional surface properties. This work differs from earlier reviews by a predictable categorization of past studies, identifying deficiencies in our current understanding of powder–dielectric interactions, and discussing the potential of developing industrial and biomedical applications. The challenges in powder agglomeration, control of recast layer and care of standardized operating parameters are summarized, while ranges of opportunities in the development of the process, such as AI-based optimization of process parameters and application of eco-friendly dielectric fluid, are explored. This study synthesizes two decades of research and offers a holistic view of NPEDM as a sustainable high precision machining technology with significant relevance towards industry.

Keywords: Electrical discharge; Nano-powder; Material removal rate; Tool wear rate.

1. INTRODUCTION

Electrical discharge machining (EDM) is one of the most popular non–conventional machining processes for machining hard and difficult–to–cut conductive materials. Due to its unique capacity to produce complex geometries with a high degree of precision, EDM is now an important technology for aerospace, automotive, tool and die manufacturing and bioscience applications [1-3]. However, EDM has intrinsic limitations caused by disadvantages such as low MRR, high tool wear and poor surface properties (micro-cracks, recast layer) [4-6]. As a remedy, Powder-Mixed EDM (PMEDM) was developed, wherein micro- or nano-powders are suspended in the dielectric fluid to ameliorate discharge behaviour and allow for process stabilization [7,8]. The presence of nano-powders in the work fluid, referred to as Nano-Powder Mixed EDM (NPEDM), has been very attractive in recent decades. NPEDM utilizes the special characteristics of nanoparticle to develop discharge stability and uniformity in spark gap, as well as increasing flushing efficiency [9,10]. This opens up opportunities for improved surface integrity, corrosion resistance/biocompatibility, and functional performance beyond a few options and to address more demanding industrial and biomedical applications [11,12]. Nevertheless, the existing research on NPEDM is still quite fragmented to date. Concerning continuity, most studies tend to either focus on specific powders, process parameters, or isolated applications, resulting in an absence of standardized guidelines and inadequate comparative assessments [13-15]. Moreover, issues like powder agglomeration, cost of operation, and Control of the recast layer are still avaluable wrestled with [16-20]. The purpose of this review is to address these gaps by systematically synthesizing and analyzing information about NPEDM from 2001 to 2025, and discuss mechanisms as well as future NPEDM applications, challenges, and directions [21-25].

2. FUNDAMENTALS OF EDM AND NPEDM

Electrical Discharge Machining Process (EDMP) is greatly utilized amongst non-conventional machining utilized for treatment tool mould, such as injector nozzles, medical devices and die for industries [26, 27]. Therefore, the ability of the machine's complex shapes and hard materials to generate geometrically increased the number of applications for this process [28-30]. The removal of material in EDM is complicated and not defined easily [31]. Still, the conversion of electric energy into thermal by means of electric discharge is most effortlessly understood and accepted by researchers around the world [32,33]. There is the movement of fast-moving electrons from the tool cathode to the anode workpiece when the required voltage is applied across the tool and workpiece [34, 35]. The discharged electrons collide on the dielectric medium, dividing into electrons and ions [36]. A discrete column of dielectric molecules is established between the tool and the workpiece, which leads to the creation of sparks [37-40]. A wave is created with a high-temperature range of 8000 to 12000 degrees Celsius [41,42]. This high temperature causes the melting of the workpiece and tool. Lastly, the tiny chips are removed from the workpiece to form craters [43, 44]. Tiny debris is removed by flushing the dielectric fluid. The accuracy of machining is highly dependent on the flushing [6,45,46].

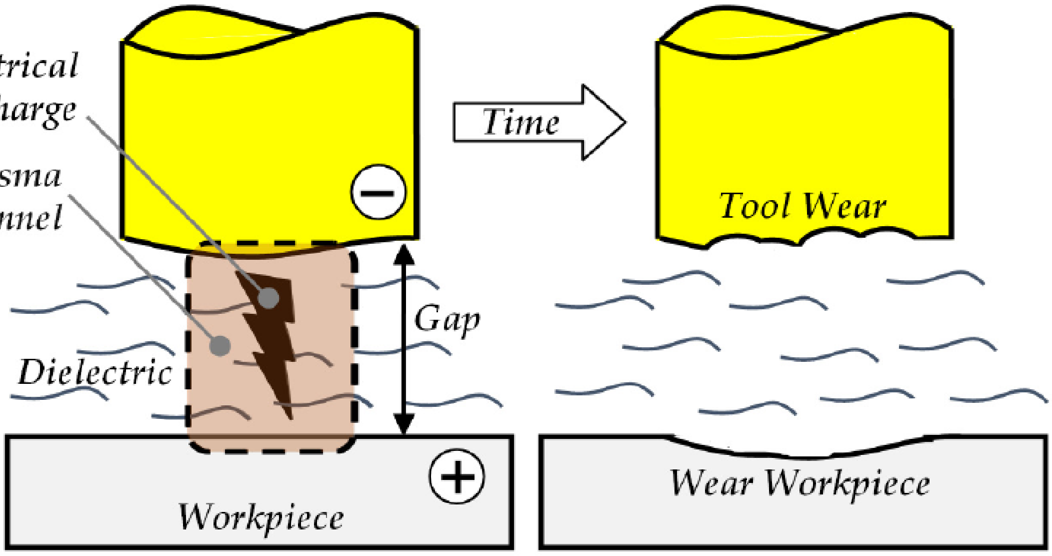

Figure 1 Schematic represents the basic principle and working of the EDM technology [7].

The conductive powder particles are incorporated into dielectric fluid [Fig. Discouraging insulation by passing easy current between electrodes [2, 47-50], increasing inter-electrode space. Therefore, this PMEDM is another kind of hybrid material especially removal process [51]. Die steel as an industrial material has taken a prominent role, thus, in experimental work, copper electrode over die steel was used, EDM oil used as dielectric medium [52]. High number of parameters dictate its efficacious reactions in PMEDM as a result of its physiological complexity [53]. Abstract This studyeither possible to maximize the material The purpose of this studymaximal material removal rate minimal tool wear rate (TWR) with the minimum surface roughness (SR) of Die Steels using PMEDM [8,54].

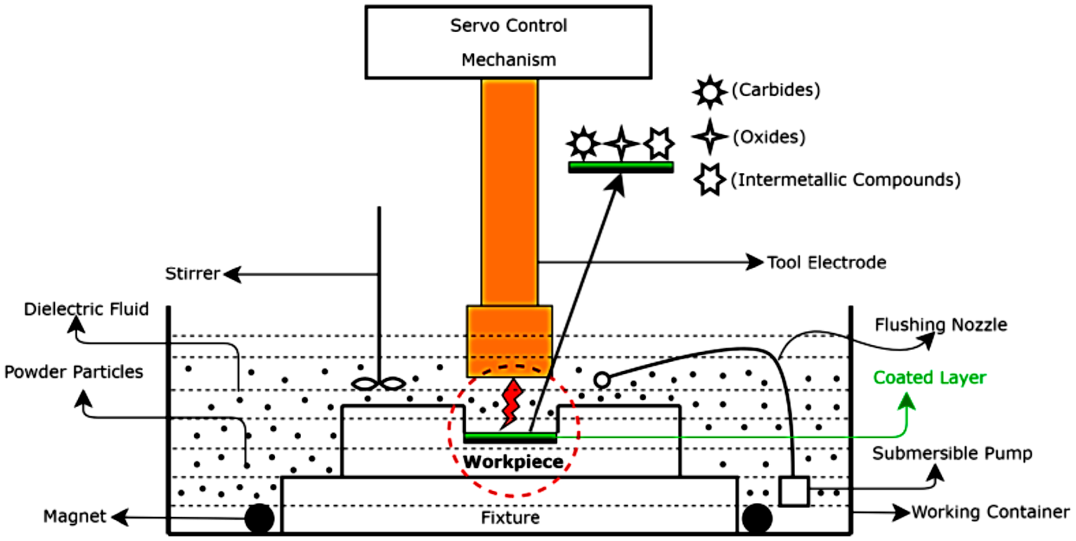

Figure 2 Typical arrangement of PMEDM system [9].

The appropriate amount of fine abrasive powder is blended with the dielectric fluid. The process of removing the hybrid material is called Powder Mixed EDM (PMEDM) in which the minimum pulse energy is constantly working and the efficiency of the EDM method is considerably affected [55]. The insulation resistance of the dielectric fluid gets decreases due to electrically conductive powders and increases the gap between the tool and the work-piece [56]. The EDM method becomes much more stable and facilitates the machining process. Productivity, MRR, SR. However, most of the research was conducted to estimate the surface finish of the process. It would provide a mirror-like surface finish that becomes a challenge in the EDM. The parameters of the powder, such as size, type, and concentration, affect the dielectric performance [8].

3. INFLUENCE OF NANO-POWDERS ON MACHINING PERFORMANCE

The impact of various nano-powders (Al_2O_3, SiC, CNTs, HA, etc.) on surface integrity, tool wear, and process efficiency [57]. The effect of some different powders on surface quality in PMEDM as follows

3.1. Graphite powder

The addition of graphite powder to the dielectric fluid significantly enhanced surface quality due to its high electrical conductivity and its ability to form a thin carbon layer, which reduces tool wear and improves smoothness. However, excessive use may increase the thickness of the recast layer [58].

3.2. Silicon carbide (SiC) powder

SiC powder, with its high hardness and good thermal conductivity, contributed to producing harder and smoother surfaces, in addition to reducing recast layer formation. Nevertheless, high concentrations may lead to unstable discharges.

3.3. Aluminum oxide (Al_2O_3) powder

The use of Al_2O_3 powder showed favorable results in enhancing surface accuracy and reducing roughness, as it acts as an additional insulating medium that ensures uniform spark distribution. The oxide layer formed on the surface also provides improved corrosion resistance.

3.4. Aluminum and copper powders

The addition of aluminum and copper powders improved discharge efficiency and enhanced surface quality, though it slightly increased tool wear. Despite this, these powders helped achieve more uniform surfaces.

3.5. Multi-walled carbon nanotubes (MWCNTs)

Carbon nanotube particles contributed to the formation of a stable plasma channel during discharge, leading to a remarkable improvement in surface roughness and a reduction in surface defects. These improvements were more pronounced compared to conventional powders [59].

3.6. Other oxides or compounds (e.g., Cr, Ni, etc.)

Some studies employed powders such as chromium and nickel, which enhanced surface hardness and provided high corrosion resistance [60]. However, these powders sometimes resulted in thicker recast layers, requiring additional post-processing in certain applications [10]. Therefore, based on previous research, we conclude that each powder type used in PMEDM leaves a distinct impact on surface quality [61]. While graphite and alumina improve smoothness and precision, SiC and chromium enhance surface hardness, whereas nano materials such as carbon nanotubes provide better control of surface morphology and minimize defects [62]. It should also be noted that these types of powders are part of those used in previous research, and the effect of many different types on the quality of the resulting surface can be observed in the table. Figure 3 shows the different types of powders as well as the ones most commonly used in various studies [63].

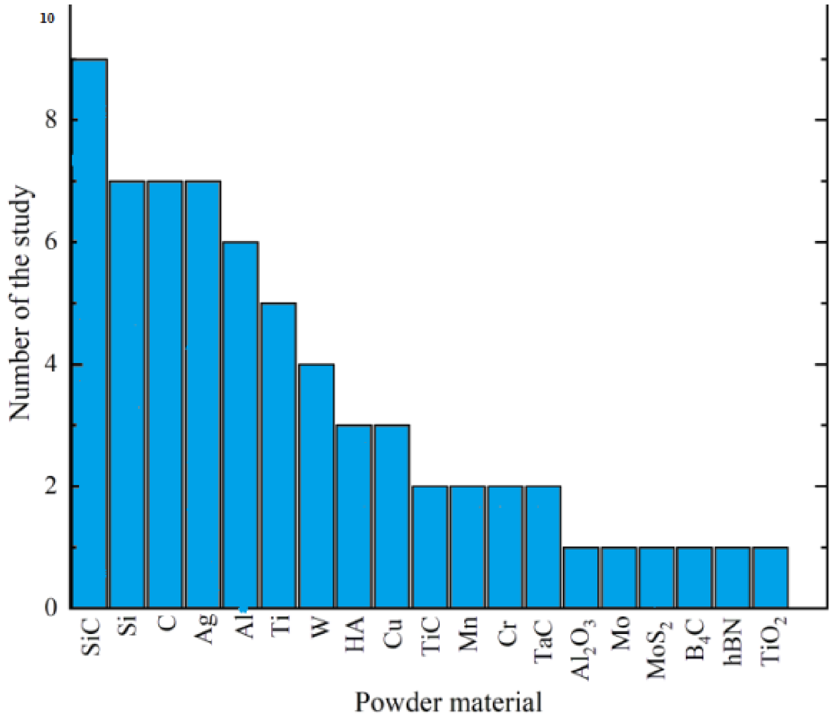

Figure 3 Popularity of powder materials utilized in the studies of PMEDM surface modification (C: graphite; HA: hydroxyapatite; hBN: hexagonal boron nitride) [11].

Table 1 display the Summary of Selected NPEDM Studies (2001–2025) about type of powders and important parameters for Nano powder electrical discharge machining process.

Table 1 Summary of selected NPEDM studies (2001–2025).

No.	Author(s) & Year	Workpiece	Powder(s) Used	Key Process Parameters	Key Findings	Refs
1	Yan et al., 2001	SKD 61	Al, Graphene	Current, Ton, duty cycle	Improved MRR, reduced TWR	[12]
2	Unses & Cogun, 2015	Ti6Al4V	Graphite	Ip, Ton, Toff	Reduced surface roughness	[13]
3	Aliyu et al., 2017	Zr-based BMG	HA	Current, polarity	Enhanced nano-porosity	[14]
4	Abdul-Rani et al., 2017	Ti6Al4V	Nano-Al	Current, voltage	Improved surface morphology	[15]
5	Bui et al., 2019	Ti6Al4V	Ag	Powder concentration, polarity	Improved biocompatibility	[16]
6	Kumari et al., 2019	Inconel 825	Al, C, Si	Ton, pulse time, current	Better Ra, ROC, MRR	[17]
7	Opoz et al., 2019	Ti6Al4V	HA	Pulse duration, concentration., current	Better corrosion, hardness	[18]
8	Jadam et al., 2020	Inconel 718	CNT	Powder concentration current	Enhanced surface integrity	[19]
9	Farooq et al., 2020	Ti6Al4V ELI	Si	Pulse duration, current	Reduced recast layer	[20]
10	Ashok et al., 2020	P20 Steel	Nano-Al_2O_3	Ton, Toff, current	Better MRR, TWR, Ra	[21]
11	Bhaumik & Maity, 2020	AISI 304	SiC	Ton, peak current	Better radial overcut (ROC), SR	[22]
12	Ibrahim & mohamed, 2021	AL6061	γ-Fe_2O_3	Voltage, Ton, concentration.	Increased MRR	[23]
13	Yaşar & Ekmekci, 2021	Ti6Al4V ELI	Micro & Nano HA	Pulse current, concentration.	Better Ra, biocompatibility	[24]
14	Ishfaq et al., 2022	Ti6Al4V	Nano-Graphene	Voltage, flushing, pulse	Improved dimensional accuracy	[25]
15	Farooq et al., 2022	Ti6Al4V ELI	Si, SiC	Voltage, Ton, concentration.	Better surface integrity	[26]
16	Chaudhari et al., 2022	Nitinol SMA	Al_2O_3	Ton, Toff, current	Better Ra, TWR, MRR	[27]
17	Ishfaq et al., 2022	Ti6Al4V	Nano-Graphene	Ton, current	Improved surface roughness	[28]
18	Barot et al., 2022	Incoloy 800	Al	Current, pulse time	Better MRR, Ra	[29]
19	Bhowmick et al., 2022	Inconel 718	Ti, Gr	Pulse current, powder type	Higher microhardness	[30]
20	Nauryz et al., 2023	Ti6Al4V	HA	Voltage, concentration.	Antibacterial properties	[31]

21	Chaudhari et al., 2023	Ti6Al4V	Al_2O_3, Graphene	Pulse timing, conc.	Improved MRR and Ra	[32]
22	Hayyawi et al., 2024	Ti-35Nb-7Zr-5Ta	Ag	Pulse current, Ton, polarity	Better corrosion and hardness	[33]
23	Sana et al., 2024	Al6061	Al_2O_3	Peak current, Ton, concentration.	Improved MRR, EWR, Ra	[34]
24	Gul et al., 2024	316 Steel	CNT	Discharge time, current	Corrosion resistance, biocompatibility	[35]
25	Nguyen et al., 2025	90CrSi Tool Steel	Si	Ton, Toff, voltage	Better Ra, MRR, EWR	[36]
26	Sachit & Tawfiq, 2025	304L SS	SiO_2, Graphite	Pulse duration, concentration.	Improved Ra, MRR, EWR	[37]

4. PROCESS PARAMETERS AND OPTIMIZATION STRATEGIES OF THE (PMEDM)

The performance of PMEDM depends upon electrical parameters, non-electrical parameters, powder concentration and its type, material and size of electrode, workpiece material and their properties. The process parameters in EDM are used to regulate the performance methods of the machining process. Process parameters are generally well-disciplined machining input factors that decide the conditions in which machining is carried out [64]. These machining situations will affect the process performance result, which are gauged using various performance methods [65]. There are two types of process parameters i:e electrical parameters like peak current, voltage, duty cycle, pulse on, pulse off etc and non-electrical parameters like flushing, powder mixed dielectric, tool rotation etc. Fig. 2 shows the cause and effect on PMEDM process performance like MRR, TWR, SR [38].

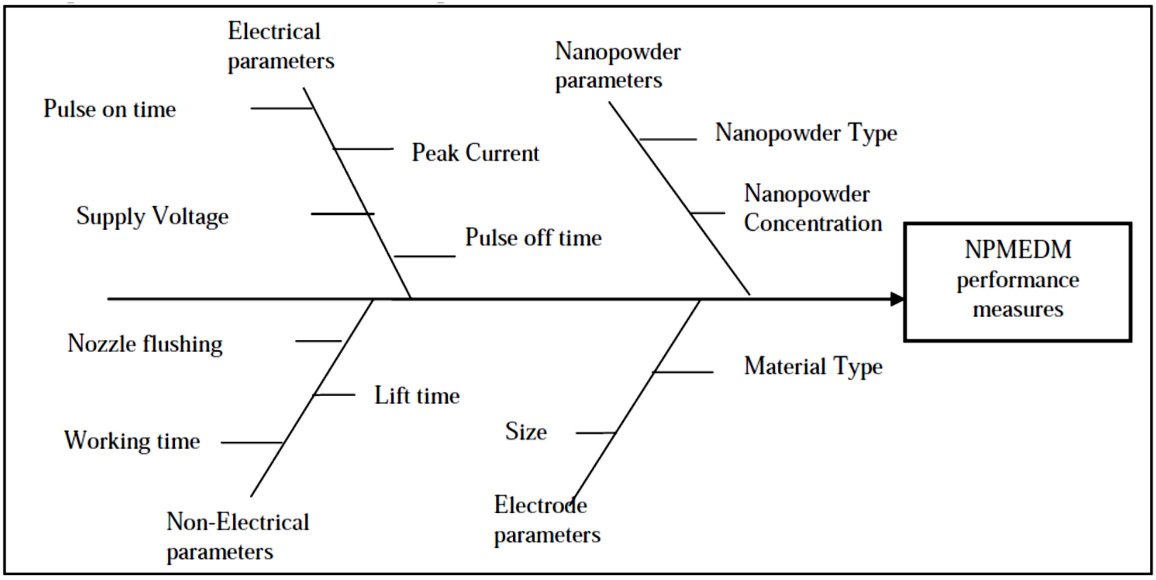

Figure 4 Process parameters of NPMEDM [39].

5. EVALUATION OF PMEDM PERFORMANCE

The various machining characteristics used to evaluate the performance of PMEDM are: MRR, tool wears rate (TWR), relative wear ratio (WR) and surface roughness (SR). The MRR is expressed as the weight of material removed from workpiece over a period of machining time in minutes [66-70].

$$\text{MRR (mm}^3\text{/ min)} = \frac{Workpiece\ weight\ loss\ (g) \times 1000}{density\ (g/cm3) \times machining\ time\ (min)} \tag{1}$$

The TWR is calculated by using the weight loss from the tool divided by the time of machining.

$$\text{TWR (mm}^3\text{/min)} = \frac{Tool\ weight\ loss\ (g) \times 1000}{density\ (g/cm3) \times machining\ time\ (min)} \tag{2}$$

The relative wear ratio of the workpiece and tool is expressed as:

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

The SR of the workpiece can be expressed in different ways like, arithmetic average (*R*a), average peak to valley height (*RZ*), or peak roughness (*R*P), etc. [40].

6. APPLICATIONS OF PMEDM

Applications in industrial sectors (aerospace, die manufacturing) and biomedical engineering (implants, surface functionalization) will be analyzed and can be illustrate [71-73]:

a) PMEDM is applicable in machining of advance materials like metal matrix composite materials are perceived promising.
b) It can be used where rough machining is required.
c) Powder mixed electrical discharge machining can be used in the improve the surface properties of biomedical implants
d) PMEDM can be used in high precision instruments where large area with fine surface finish is required to be machined.

e) Complex 3-D shapes, complex profiles and fragile components can also be machined successfully using the PMEDM process regardless of their strength and hardness [41].

7. CHALLENGES AND RESEARCH GAPS

The Key challenges such as powder agglomeration, recast layer formation, cost, and lack of parameter standardization will be critically evaluated [74].

Although Powder Mixed Electrical Discharge Machining (PMEDM) has proven its effectiveness in enhancing the Metal Removal Rate (MRR), reducing the Tool Wear Rate (TWR), and improving surface quality, it still faces several challenges that limit its widespread industrial implementation. The main challenges can be summarized as follows [75-77]:

1. Powder distribution in the dielectric fluid: Maintaining a uniform suspension of nano- or micro-particles in the dielectric fluid is a major challenge. Particle agglomeration or sedimentation leads to process instability and deteriorated surface quality [78-80].
2. Control of powder concentration: While increasing powder concentration improves MRR and surface finish, exceeding the optimal level results in short-circuit discharges and unstable machining [81].
3. Limited studies on the effect of different powders: There remains a knowledge gap regarding the influence of various powders (e.g., carbon, ZrO_2, MgO) on surface characteristics such as corrosion resistance, residual stresses, microhardness, and fatigue performance [82].
4. Unpredictable tool wear effects: In certain cases, variations in polarity or the use of specific powders increase tool wear, reducing machining accuracy and raising production costs [83].
5. Thermal effects and recast layer formation: Discharge sparks produce a resolidified layer (recast layer) on the machined surface, which can negatively affect mechanical properties such as ductility and fatigue resistance. Controlling this layer remains a significant challenge [84].
6. Lack of standardized operating parameters: Most existing studies are based on specific experimental setups using different materials and powders, with no standardized machining parameters. This makes it difficult to compare results and directly transfer them into industrial applications [85].
7. Cost and time considerations: Despite its advantages over conventional EDM, PMEDM can still be more time-consuming in certain applications. Additionally, the high cost of preparing and dispersing nano-powders increases the overall machining expense [86-90].

8. FUTURE RESEARCH DIRECTIONS

Promising directions include AI-driven parameter optimization, eco-friendly dielectric development, and multi-functional coatings for biomedical use. The most important to study are [91-94]

- Study of the effects of nanopowder shapes on the quality of the resulting surface in terms of metal removal rate, electrode tool wear, and white layer thickness.
- Study the effect of adding surfactants to the dielectric fluid on the surface resulting from PMEDM.
- Study and comparison of dielectric fluids that is less harmful to the environment and the resulting surface.
- Comparing the best methods for mixing powders with dielectric fluid and the results of the mixing method on the microstructure of the surface.
- Integrating artificial intelligence with (PMEDM) to improve machining processes.

9. CONCLUSIONS

Nano-Powder Mixed EDM (NPEDM) has demonstrated substantial promise as a sustainable, high-precision machining technology. Through the integration of nano-powders into dielectric fluids, it enables significant improvements in machining efficiency, surface quality, and functional performance. Nevertheless, persistent challenges—including particle agglomeration, recast layer control, and absence of standardized operational frameworks—continue to hinder widespread industrial adoption. Future research should emphasize holistic optimization strategies, environmentally benign dielectrics, and interdisciplinary integration with artificial intelligence to establish NPEDM as a transformative technology for both industrial and biomedical applications. This review has provided a comprehensive overview of the latest developments in this field, focusing on:

1. Additive powder mixed dielectric used in Powder-Mixed EDM (PMEDM) plays a significant role in improving material removal rate and reducing tool wear rate compared to conventional Electrical Discharge Machining (EDM) process.
2. Use of powder mixed dielectric helps to attain mirror-like surface finish, suspended additive powder particle alloying helps to modify Surface characteristics, Totally Burr free & no stresses produced in the workpiece.
3. The impact of various process parameters on performance.

a. Tangible improvements in surface quality and treated layer properties.
b. Diverse industrial applications benefiting from this technology.
c. Technical and research challenges facing future development.

This field represents a promising opportunity to develop more precise and efficient manufacturing techniques, with a continuous need for research to overcome current challenges and fully exploit the underlying potentials.

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