Vol 5, Issue 3, March 2025 www.ijesti.com E-ISSN: 2582-9734
International Journal of Engineering, Science, Technology and Innovation (IJESTI)

Experimental Investigation on Die Steel Machinability Using Powder Mixed Electric Discharge Machining (PMEDM)

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ABSTRACT

Machining serves as an essential precondition for shaping engineering components. Traditional methods rely on mechanical chip removal that becomes inefficient, costly, and detrimental to surface finish and tool life when applied to hard materials such as AISI D2 die steel. Non-conventional processes, particularly electrical discharge machining, overcome these limitations through thermal erosion via controlled sparks in a dielectric medium. Powder mixed electric discharge machining further enhances performance by suspending conductive powders in the dielectric fluid, which enlarges the spark gap, reduces breakdown voltage, promotes uniform discharge distribution, and improves debris flushing.

This study conducts a comprehensive three-phase experimental investigation on AISI D2 steel using a custom-developed PMEDM setup that incorporates a compact machining tank, lateral dynamic jet flushing, dielectric stirrer, magnetic filtration, and rotary tool attachment. Phase one evaluates aluminum, silicon, and graphite powders, establishing that aluminum powder delivers the highest material removal rate and the lowest relative wear ratio. Phase two compares copper, brass, and graphite tool materials with aluminum powder, confirming copper as the superior electrode for improved material removal rate, reduced relative wear ratio, and better surface finish. Phase three examines varying copper tool diameters, revealing their dominant influence on all performance metrics.

Taguchi L27 orthogonal arrays guide the experiments across all stages. Signal-to-noise ratio analysis and analysis of variance quantify the contributions of pulse on-time, pulse off-time, peak current, powder concentration, flushing pressure, and tool rotation speed. Grey relational analysis integrates the multiple responses of material removal rate, relative wear ratio, and surface finish to determine the optimal parametric combination. Predicted and experimental grey relational grades align closely, validating the optimization. Control charts confirm process stability with negligible arcing or short-circuiting.

The results demonstrate that aluminum powder mixed with kerosene dielectric combined with copper rotary tools significantly elevates machining efficiency, surface integrity, and productivity for AISI D2 steel in tool and die manufacturing. These findings provide practical guidelines for industrial EDM operations seeking higher metal removal rates, lower tool wear, and superior surface quality.

Keywords: *PMEDM, AISI D2 Steel, Material Removal Rate, Relative Wear Ratio, Surface Finish, Taguchi Method, Grey Relational Analysis.*

1. INTRODUCTION

1.1 Overview of Machining Processes

Machining constitutes an essential precondition for shaping all engineering components. Nearly all traditional and contemporary processes employ tools to extract material through plastic deformation and chip formation that proves more difficult than the workpiece material itself. Machining stands as an important and necessary precondition for shaping any engineering component. Nearly all well-known processes of traditional or contemporary machining use tools to extract material from the workpiece through plastic distortion with the processing of chips more difficultly than the workpiece material. The use of these traditional methods is not only time-consuming and expensive to machine new materials. Today therefore non-conventional NCM machining approaches have become a lifeline to many industries to address the demands of handling new equipment that is difficult to machine. Electric discharge machining EDM serves as one of the primary NCM processes. For the detailed machining of complicated and delicate forms EDM emerges as a very necessary tool. Limitations such as low machining performance and poor surface consistency nevertheless affect the process. In order to compete against other processing techniques attempts were reported to improve the machining efficiency and surface quality of EDM technology. The literature on EDM helps to better understand the development of processes and improvements in performance. Powder mixed EDM PMEDM stands as one of the most recent developments that demonstrates the potential for improvement in performance and good process stability. The good stability of the EDM process means that arcs or short circuits are occurring because eroded particles flush correctly. Therefore the importance of various input process parameters of PMEDM has been determined in an extensive literature review. EDM researchers hold a key interest in optimising process parameters resulting in a higher metal removal rate with excellent surface finish and low tool wear. For PMEDM process parameters applications of various optimization techniques are also reported.

1.2 Limitations of Conventional and EDM Processes

Electric discharge machining (EDM) is a prominent NCM process that converts electrical energy into thermal energy through a series of discrete sparks between the electrode and workpiece submerged in dielectric fluid. It enables machining of hard materials and complex geometries without mechanical cutting forces. However, conventional EDM suffers from low material removal rate (MRR), poor surface finish (SF), and high tool wear rate (TWR) due to its highly stochastic nature. Issues such as arcing, short-circuiting, and cavitation further reduce process stability and efficiency.

1.3 Principle and Mechanism of Powder Mixed EDM (PMEDM)

Powder mixed EDM (PMEDM) is a recent advancement where conductive powder particles are suspended in the dielectric fluid. These particles energize and form chain-like structures in the spark gap, reducing dielectric breakdown strength and enabling sparking at multiple points at lower pulse energies. This enlarges the inter-electrode gap, distributes discharge energy more uniformly, and improves debris flushing through combined mechanical and striking actions of the powder particles, leading to higher machining efficiency and better process stability.

1.4 Scope and Significance of PMEDM Research

PMEDM shows strong potential for improving surface finish in shorter times and enhancing process reliability for difficult-to-machine materials like AISI D2 die steel used in moulds, dies, and automotive components. It reduces loading and finishing time compared to standard EDM and achieves more consistent surface quality over large areas. Despite its advantages, the implementation of PMEDM in industry remains slow due to limited understanding of optimal powder-tool-material combinations and process variability.

1.5 Objectives of the Present Study

The present study aims to develop a stable PMEDM setup, conduct pilot experiments, investigate the effects of different powders (Aluminum, Silicon, Graphite), tool materials, and tool diameters on AISI D2 steel, and optimize process parameters for higher MRR, lower relative wear ratio (RWR), and better surface finish using Taguchi method and Grey Relational Analysis (GRA).

1.6 Research Methodology Overview

The research is conducted in seven phases: literature review and gap identification, development of experimental setup with pilot tests, modifications to the setup, three-stage main experimentation using Taguchi L27 orthogonal array, statistical analysis using S/N ratio and ANOVA, multi-response optimization through GRA, and drawing conclusions with future scope.

2. REVIEW OF LITERATURE

2.1 Overview

A systematic analysis of EDM and PMEDM literature reveals process developments and performance enhancements. Input parameters influence material removal rate, tool wear rate, and surface quality, yet the stochastic thermal nature complicates precise prediction.

2.2 Effect of Powders on EDM/PMEDM Performance

Erden and Bilgin first suspended copper, aluminum, iron, and carbon powders in kerosene, noting strengthened breakdown properties and increased processing rates. Jeswani achieved 60 percent higher material removal rate and 28 percent lower tool wear with 4 g/l graphite powder. Narumiya et al. and Kobayashi et al. reported superior surface finish with aluminum and graphite powders compared to silicon. Yan and Chen quantified gap expansion, higher material removal rate, and surface roughness changes with aluminum powder. Wong et al. confirmed aluminum powder effectiveness for near-mirror finishes under specific polarity and pulse conditions. Uno et al. documented reduced crater size and improved corrosion resistance with silicon powder. Chow et al. observed silicon carbide advantages in micro-slitting depth while aluminum provided better surface roughness. Later studies by Kansal et al., Singh et al., and Sharma et al. reinforced powder-specific gains in material removal rate, tool wear, and surface finish.

2.3 Influence of Tool Rotation and Non-Electrical Parameters

Yan and Chen obtained the best surface finish with rotating electrodes and aluminum-mixed dielectric. Soni and Chakraverti and Mohan et al. demonstrated that electrode rotation generates centrifugal forces for debris evacuation, improving material removal rate and surface finish.

2.4 Single-Response Optimization Techniques in PMEDM

Kansal et al. applied Taguchi methods with silicon and graphite powders to optimize material removal rate and surface finish. Response surface methodology studies by Tzeng et al. and Sharif et al. modeled interactive effects of powder concentration, peak current, and pulse durations.

2.5 Multi-Response Optimization in PMEDM

Lin et al. introduced grey relational analysis for EDM parameters. Subsequent works by Raghuraman et al., Shivakoti et al., Talla et al., and Tripathy et al. combined Taguchi with grey relational analysis or principal component analysis to balance material removal rate, tool wear rate, and surface roughness simultaneously.

2.6 Summary of Literature Findings

Aluminum powder consistently associates with elevated material removal rate and refined surfaces across diverse workpieces. Literature tables illustrate powder-specific improvements, response priorities, and parameter influences.

2.7 Identified Gaps in Existing Research

Limited data exist on process variability for specific powder-tool combinations with AISI D2 steel. Powder material properties such as density, thermal conductivity, and electrical conductivity receive insufficient attention. Rotary motion and dynamic jet flushing remain underutilized. Single-response optimization predominates while industries require simultaneous multi-response improvements.

2.8 Motivation for Current Research Work

AISI D2 steel offers high wear resistance, compressive strength, and through-hardening properties yet exhibits low machinability. No structured attempts optimize aluminum powder process variables for multiple responses on this material. The present work addresses these gaps through phased experimentation and grey relational analysis.

3. RESEARCH METHODOLOGY

3.1 Taguchi Experimental Design Method

Taguchi methodology employs orthogonal arrays to minimize experimental runs while evaluating parameter effects through signal-to-noise ratios that measure robustness against noise factors. Analysis of variance identifies significant contributors.

3.2 Selection of Process Parameters and Their Levels

Control factors include pulse on-time, pulse off-time, peak current, powder type and concentration, tool material and diameter, flushing pressure, and tool rotation speed. Levels derive from pilot experimentation and literature.

3.3 Performance Measures (MRR, RWR, SF)

Material removal rate calculates from pre- and post-machining weight difference using a 0.001 g precision balance. Relative wear ratio equals tool weight loss divided by workpiece weight loss. Surface finish measures average roughness Ra via Mitutoyo Surftest-311 stylus profilometer on dried specimens.

3.4 Pilot Experimentation

Pilot runs with 23 experiments using fixed 10 mm copper electrode and 4 g/l powder concentration establish feasible ranges and confirm aluminum powder superiority for material removal rate and relative wear ratio.

3.5 Three-Stage Main Experimentation Strategy

Stage one varies powder type with fixed copper tool. Stage two fixes aluminum powder and varies tool material. Stage three fixes aluminum powder and copper tool while varying diameter. Each stage employs L27 orthogonal array.

3.6 Grey Relational Analysis for Multi-Response Optimization

Grey relational analysis normalizes responses, computes grey relational coefficients, and aggregates them into grades to identify the single best parametric combination satisfying simultaneous maximization of material removal rate and minimization of relative wear ratio and surface roughness.

4. EXPERIMENTAL SETUP

4.1 Specifications of Base EDM Machine

The experimental work utilized a New Generation Spark Erosion Machine manufactured by Modern Machine Tools as the base platform. The work table measures 350 mm × 210 mm with linearity movement of ±0.005/100 mm and table travel of 225 mm × 125 mm, supporting job weights up to 200 kg. The dielectric tank size is 550 mm × 350 mm × 250 mm. The work head provides 150 mm vertical travel, platen-to-table distance ranging from 250 mm to 400 mm, and a platen of 125 mm × 125 mm with linearity movement of ±0.005/100 mm, accommodating electrode weights up to 3 kg. The pulse generator originally delivered an output voltage of 85 V, with pulse on-time and pulse off-time adjustable from 2 µs to 2000 µs and a maximum output current of 20 A. The dielectric system includes a 250-liter reservoir, filtration area of 3.6 m^2 per element across two filter elements, and a pump capacity of 3 m^3/hr. These specifications formed the foundation for the standard EDM operation, yet proved inadequate for consistent powder suspension and controlled dielectric circulation required in PMEDM trials.

4.2 Development of Custom PMEDM Setup

To overcome the limitations of the large 550-liter main dielectric reservoir and to enable precise powder mixing without contaminating the primary system, a dedicated custom PMEDM setup was developed in the laboratory. The core component is a 15-liter machining tank designed exclusively for powder-mixed dielectric circulation. This tank isolates the experimental dielectric volume from the main reservoir, ensuring that only 10–15 liters of mixed fluid are used per run and preventing powder waste or cross-contamination. The tank was fabricated using 3 mm thick stainless steel sheet to provide durability and corrosion resistance under repeated exposure to kerosene-based dielectric and suspended powders.

4.3 Machining Tank and Dielectric Circulation System

The machining tank adopts a hopper-shaped geometry with overall dimensions of approximately 38 cm × 26 cm × 20 cm. The inclined side walls at a 60-degree angle facilitate gravity-assisted downward flow of the powder-mixed dielectric, minimizing sedimentation at the bottom. A 0.5 horsepower pump circulates the mixed dielectric at a controlled flow rate of 2 liters per minute. The fluid is delivered through 4 mm diameter nozzles positioned strategically around the machining zone to create lateral dynamic jet flushing. This arrangement directs fresh dielectric across the spark gap from multiple angles, enhancing debris evacuation and maintaining uniform powder concentration throughout the inter-electrode gap. Two outlet branches from the pump supply—one connected directly to the tool holder and the other to the tank side—ensure balanced pressure and prevent powder accumulation on the workpiece-tool interface.

4.4 Stirrer System and Magnetic Filter Unit

Continuous suspension of powder particles is critical to PMEDM performance. Therefore, a stirrer system comprising two specially designed electric motors mounted vertically on the tank was integrated. Each motor drives plastic fan blades attached to long shafts, rotating within the dielectric to agitate the fluid and keep aluminum, silicon, or graphite powders uniformly dispersed. The stirrer assembly is clamped securely to the work table with insulated pads to eliminate any risk of sparking or electrical interference. To remove metallic debris generated during machining, a magnetic filter unit was installed in the return line. This unit consists of six permanent disc magnets arranged with central holes inside a piping chamber, creating a magnetic field that captures ferrous particles before the dielectric returns to the tank. The filter assembly connects via two end connectors and operates continuously to maintain dielectric cleanliness.

4.5 Rotary Tool Attachment and Dynamic Jet Flushing

Literature indicates that relative motion between tool and workpiece significantly improves flushing efficiency. To incorporate this benefit, a rotary tool attachment driven by a DC motor was added to the setup. The attachment imparts controlled rotational speed to the electrode, generating centrifugal forces that aid in expelling debris from the spark gap and promoting uniform discharge distribution. Combined with the lateral dynamic jet flushing from the nozzles, this rotary motion creates a synergistic effect that enhances process stability and elevates both material removal rate and surface finish. The electrode is mounted on the rotary spindle while maintaining precise alignment with the workpiece clamped inside the hopper tank.

4.6 Final Modified Setup and Validation

Several progressive modifications were implemented to achieve full PMEDM functionality. The original pulse generator was replaced with a modern unit operating at 440 V, 3-phase, 50 Hz supply, delivering a maximum output current of 25 A and output voltage of 100 V, with finer pulse on-time and off-time resolution. Independent hose connections were installed to isolate the powder-mixed dielectric circuit completely from the main 250-liter reservoir and filtration system. After assembly, the complete setup—comprising the hopper tank, pump, stirrer, magnetic filter, and rotary attachment—was validated through pilot trials. These trials confirmed consistent powder concentration, effective debris removal, stable sparking without arcing or short-circuiting, and contamination-free operation. Photographs of the progressive developments illustrate the transition from the basic EDM machine to the fully functional PMEDM system ready for the three-stage experimental program.

5. PERFORMANCE EVALUATION

5.1 Analysis of Pilot Study Results

Pilot experimentation with 23 runs validated the newly developed PMEDM setup and established feasible parameter ranges for the main study. Fixed parameters included 10 mm diameter pure copper electrode, 4 g/l powder concentration, kerosene dielectric, straight polarity, 100 V open-circuit voltage, and 15-minute machining time per trial. Performance measures were material removal rate (MRR) calculated from weight difference using a 0.001 g precision electronic balance, relative wear ratio (RWR) as the ratio of tool weight loss to workpiece weight loss, and surface finish (SF) measured as average roughness Ra via Mitutoyo Surftest-311 stylus profilometer on dried specimens. Results in Table 3.10 clearly demonstrated that powder-mixed conditions outperformed pure dielectric EDM. Aluminum powder consistently produced the highest MRR values (up to 0.1793 g/min) and the lowest RWR (down to 0.00508) across both current levels (13 A and 20 A) and pulse on-time settings (200 µs and 800 µs). Silicon and graphite powders yielded intermediate improvements in MRR and RWR but remained inferior to aluminum. Surface finish also showed moderate enhancement with all powders, particularly aluminum at lower pulse energies. Graphical trends in Figures 3.3, 3.4, and 3.5 confirmed these observations: MRR increased significantly with aluminum addition while RWR decreased markedly, and SF exhibited visible improvement under powder-mixed conditions. These findings established aluminum powder as the most promising additive and confirmed the stability and functionality of the custom setup for subsequent three-stage experimentation.

5.2 Stage-1 Results: Effect of Powder Types (Al, Si, Gr)

Stage-1 employed an L27 orthogonal array to investigate the influence of three powders—aluminum, silicon, and graphite—under varying levels of pulse on-time, pulse off-time, peak current, and flushing pressure with a fixed 10 mm copper tool. Taguchi signal-to-noise ratio analysis and analysis of variance identified aluminum powder as the dominant factor. It significantly elevated MRR while simultaneously suppressing RWR compared with silicon and graphite. The addition of aluminum powder enhanced discharge frequency and uniform energy distribution, leading to faster material erosion and reduced tool consumption. Silicon and graphite provided measurable gains over pure dielectric but produced lower MRR and higher RWR under identical conditions. Main effects plots revealed that aluminum concentration at higher levels further amplified these benefits, confirming the selection of aluminum powder for Stage-2 experimentation.

5.3 Stage-2 Results: Effect of Tool Materials

Stage-2 fixed aluminum powder concentration and compared three tool materials—copper, brass, and graphite—across the same L27 orthogonal array. Copper electrodes delivered the peak MRR, minimal RWR, and best surface finish when paired with aluminum powder. The superior electrical and thermal conductivity of copper facilitated efficient spark energy transfer and reduced electrode erosion. Brass and graphite tools exhibited higher RWR and inferior surface quality, particularly at elevated current and pulse on-time levels. Response tables ranked tool material as a highly significant factor for all three performance measures. These outcomes established copper as the optimal electrode material and guided the focus of Stage-3 on varying copper tool diameters.

5.4 Stage-3 Results: Effect of Copper Tool Diameter

Stage-3 examined three diameters of copper tools while keeping aluminum powder and optimal tool material fixed. Tool diameter exerted the strongest overall influence on MRR, RWR, and SF. Intermediate diameters balanced the discharge area with effective flushing efficiency, producing the highest MRR, lowest RWR, and smoothest surfaces. Smaller diameters restricted spark energy distribution while larger diameters led to uneven debris evacuation and increased tool wear. This stage confirmed that copper tool diameter is a critical non-electrical parameter that must be optimized alongside electrical settings for stable and productive PMEDM of AISI D2 steel.

5.5 Statistical Analysis (S/N Ratios and ANOVA)

All stages utilized Taguchi signal-to-noise ratio analysis for “higher-the-better” (MRR) and “smaller-the-better” (RWR and SF) characteristics. Response tables consistently ranked peak current as the most influential parameter for MRR, followed by pulse on-time, powder concentration, and tool diameter. Analysis of variance attributed over 50 percent contribution to peak current for both MRR and RWR, with pulse on-time and tool diameter also showing statistically significant effects at 95 percent confidence. Main effects plots illustrated that MRR increased monotonically with current and optimal pulse on-time values that balanced energy input with sufficient deionization time during pulse off-time. These statistical tools provided clear quantification of parameter contributions and guided the selection of robust levels for multi-response optimization.

5.6 Multi-Response Optimization using GRA

Grey relational analysis integrated the conflicting responses of MRR, RWR, and SF into a single grey relational grade. Normalization, grey relational coefficient calculation, and weighted aggregation identified the optimal parametric combination: moderate pulse on-time, short pulse off-time, high peak current, optimal aluminum powder concentration, selected copper tool diameter, moderate flushing pressure, and tool rotation. This setting simultaneously maximized MRR, minimized RWR, and improved SF. The GRA approach effectively handled the multi-objective nature of the PMEDM process where individual Taguchi optimization for one response often compromised others.

5.7 Process Stability Assessment via Control Charts

Process stability in Stage-3 was rigorously assessed by generating control charts for MRR, RWR, and SF across all L27 runs. All data points remained well within upper and lower control limits, indicating no out-of-control conditions. Negligible instances of arcing or short-circuiting were observed throughout the trials, confirming that the custom setup with dynamic jet flushing, stirrer, magnetic filter, and rotary tool maintained excellent process reliability.

5.8 Confirmation Experiments and Validation of Results

Confirmation runs conducted at the GRA-predicted optimal settings produced experimental grey relational grades within 5 percent of the predicted values, validating the accuracy of the model and the robustness of the optimized parameters. These results demonstrate that the three-stage Taguchi-GRA methodology reliably improves PMEDM performance for AISI D2 steel, offering higher productivity, lower tool wear, and superior surface quality for industrial tool and die manufacturing applications.

6. CONCLUSION AND FUTURE WORK

6.1 Summary of Key Findings from Stage-Wise Experiments

The experimental program was executed in three distinct stages using Taguchi L27 orthogonal arrays on AISI D2 die steel with a custom-developed PMEDM setup. Stage-1 compared three powders—aluminum, silicon, and graphite—under varying electrical and flushing parameters with a fixed copper tool. Results established aluminum powder as clearly superior, delivering the highest material removal rate (MRR) and the lowest relative wear ratio (RWR) while also improving surface finish (SF). Silicon and graphite powders produced noticeable but inferior gains compared with aluminum. Consequently, aluminum powder with varying concentrations was selected for Stage-2. Stage-2 evaluated three tool materials—copper, brass, and graphite—with fixed aluminum powder. Copper electrodes demonstrated the best overall performance, providing peak MRR, minimal RWR, and the smoothest surface finish. Brass and graphite tools exhibited higher wear and poorer surface quality. These findings directed Stage-3 toward copper tools only. Stage-3 investigated three diameters of copper tools while keeping aluminum powder concentration fixed. Tool diameter emerged as the most influential parameter, exerting major effects on MRR, RWR, and SF. Intermediate diameters optimally balanced discharge area with effective flushing. Grey relational analysis (GRA) performed after the final stage integrated the multiple responses into a single performance index, confirming the optimum combination of moderate pulse on-time, short pulse off-time, high peak current, optimal aluminum concentration, selected copper tool diameter, moderate flushing pressure, and tool rotation.

6.2 Major Conclusions

The three-stage investigation conclusively demonstrates that aluminum powder mixed with kerosene dielectric combined with copper rotary tools under optimized parameters markedly improves the machinability of AISI D2 die steel. MRR increased substantially, RWR decreased significantly, and SF improved considerably compared with conventional EDM. The custom setup incorporating lateral dynamic jet flushing, dielectric stirrer, magnetic filter, and rotary tool attachment ensured uniform powder suspension and effective debris removal, resulting in stable sparking throughout all trials. Control charts generated for Stage-3 runs showed all performance values well within control limits with negligible arcing or short-circuiting, confirming excellent process stability. Grey relational analysis proved superior to individual Taguchi signal-to-noise ratio optimization because it simultaneously satisfied the conflicting objectives of higher MRR, lower RWR, and better SF. Predicted and experimental grey relational grades matched closely (within 5 percent), validating the reliability of the optimized settings. Overall, the study establishes that PMEDM with aluminum powder and copper tools offers a practical and robust solution for enhancing productivity, tool life, and surface quality in tool-and-die manufacturing applications involving AISI D2 steel.

6.3 Contributions of the Present Study

This research makes several noteworthy contributions to PMEDM literature and industrial practice. First, a conventional EDM machine was successfully converted into a stable PMEDM system through the development of a dedicated 15-liter hopper-shaped machining tank, dynamic jet flushing, stirrer arrangement, magnetic filter unit, and rotary tool attachment. Second, the work constitutes the first structured three-phase experimental investigation of aluminum powder with copper tools specifically on AISI D2 die steel. Third, the combined effect of rotary tool motion and lateral dynamic jet flushing was systematically evaluated and demonstrated to enhance flushing efficiency and process stability. Fourth, Taguchi-based experimentation followed by GRA provided a complete multi-response optimization framework that industrial users can directly apply. The findings offer clear guidelines for selecting powder type, concentration, tool material, and tool diameter to achieve higher MRR, lower RWR, and superior SF without compromising dimensional accuracy.

6.4 Limitations and Assumptions

The study was conducted under certain controlled conditions. Commercial-grade kerosene was used as the dielectric fluid throughout all experiments. Powder particle sizes were fixed at the available average values (45 µm for aluminum, 37 µm for silicon and graphite). Machining was restricted to a small 15-liter volume of powder-mixed dielectric to prevent waste and maintain consistent concentration. Only AISI D2 steel was used as workpiece material, and experiments were limited to blind-hole machining with straight polarity. These assumptions and limitations, while necessary for focused investigation, restrict direct extrapolation to other dielectrics, powder sizes, or workpiece materials.

6.5 Scope for Future Research

Several promising avenues remain for extending the present work. Future studies could incorporate additional surface integrity metrics such as micro-hardness, white layer thickness, micro-crack density, and microstructure analysis of the machined surface. The effect of different powder particle sizes and concentrations on surface alloying mechanisms could be investigated. Extension of the PMEDM process to other tool materials, other conductive powders, or different workpiece alloys (such as H13 or D3 die steels) would broaden industrial applicability. Analysis of machining debris collected from the dielectric may reveal useful insights into material transfer and surface modification phenomena. Advanced multi-objective optimization techniques including artificial neural networks, genetic algorithms, or hybrid approaches could be applied for even finer parameter tuning. Finally, fatigue testing and wear performance evaluation of PMEDM-machined components would assess long-term service behavior in actual tool-and-die applications. These extensions would further strengthen the industrial adoption of stable and high-performance PMEDM processes.

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