A Comprehensive Study on Parametric Effects and Optimization Strategies in Non-Conventional Machining of MMCs

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ABSTRACT

Metal Matrix Composites (MMCs) are extensively used in advanced engineering applications due to their superior mechanical and thermal properties; however, the presence of hard reinforcements makes their machining challenging using conventional methods. Non-conventional machining (NCM) processes such as Electrical Discharge Machining (EDM), Wire EDM, Abrasive Water Jet Machining (AWJM), Ultrasonic Machining (USM), and Laser Beam Machining (LBM) have therefore gained significant attention for effective machining of MMCs. This paper presents a comprehensive study on the effects of key process parameters—including discharge current, pulse duration, voltage, abrasive flow rate, jet pressure, stand-off distance, and tool vibration—on machining performance characteristics such as material removal rate, surface roughness, tool wear rate, kerf width, and heat-affected zone. In addition, various single- and multi-objective optimization strategies, including Taguchi-based approaches, Response Surface Methodology, Grey Relational Analysis, evolutionary algorithms, and hybrid techniques, are critically reviewed and compared. The study identifies optimal parametric combinations, highlights trade-offs between productivity and surface integrity, and discusses existing challenges and future research directions, thereby providing valuable insights for enhancing the machining efficiency and quality of MMCs using non-conventional processes.

Keywords—Metal Matrix Composites (MMCs); Non-Conventional Machining; Parametric Analysis; Optimization Techniques; EDM; AWJM; Surface Roughness; Material Removal Rate.

INTRODUCTION

Metal Matrix Composites (MMCs) have emerged as a prominent class of advanced engineering materials due to their superior mechanical, thermal, and tribological properties compared to conventional monolithic metals. By reinforcing a metallic matrix—such as aluminium, magnesium, or titanium—with ceramic particles, whiskers, or fibres (e.g., SiC, Al_2O_3, B_4C), MMCs exhibit enhanced strength-to-weight ratio, high stiffness, improved wear resistance, and excellent thermal stability. These characteristics make MMCs highly desirable for critical applications in aerospace, automotive, defense, electronics, and biomedical industries, where lightweight structures with high performance and reliability are essential shown in Fig. 1. However, despite these advantages, the widespread industrial adoption of MMCs is significantly constrained by challenges associated with their machining. Conventional machining processes such as turning, milling, and drilling often prove ineffective for MMCs due to the presence of hard and abrasive reinforcements. These reinforcements accelerate tool wear, induce micro-cracking, degrade surface integrity, and lead to increased machining costs. Furthermore, achieving tight dimensional tolerances and superior surface finish using traditional methods becomes increasingly difficult, particularly for components with complex geometries. These limitations have motivated researchers and manufacturers to explore alternative machining techniques that can overcome the inherent difficulties posed by MMCs. Non-conventional machining (NCM) processes have emerged as viable and efficient solutions for machining MMCs. Techniques such as Electrical Discharge Machining (EDM), Wire Electrical Discharge Machining (WEDM), Abrasive Water Jet Machining (AWJM), Ultrasonic Machining (USM), and Laser Beam Machining (LBM) remove material using thermal, electrical, chemical, or

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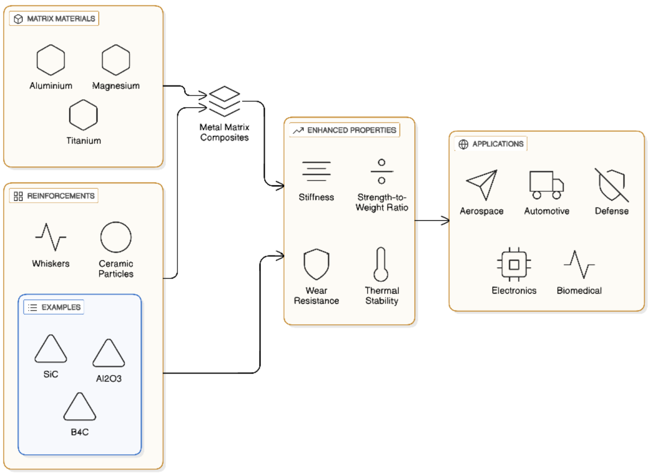
mechanical energy rather than direct tool–workpiece contact. As a result, these processes significantly reduce cutting forces and tool wear, making them particularly suitable for machining hard and brittle composite materials. Moreover, NCM processes enable the fabrication of intricate shapes, micro-features, and high-aspect-ratio components that are difficult or impossible to produce using conventional techniques. Despite the advantages of NCM processes, machining performance is highly sensitive to the selection of process parameters. Parameters such as discharge current, pulse-on and pulse-off time, voltage, abrasive flow rate, jet pressure, stand-off distance, laser power, and tool vibration amplitude play a crucial role in determining output responses including material removal rate (MRR), surface roughness (SR), tool wear rate (TWR), kerf width, dimensional accuracy, and heat-affected zone (HAZ). Improper parameter selection may result in poor surface quality, excessive thermal damage, and reduced machining efficiency. Therefore, understanding the parametric effects in NCM of MMCs is essential for achieving optimal machining performance. In recent years, numerous studies have focused on modeling and optimizing NCM processes for MMCs. Traditional experimental approaches based on trial-and-error are time-consuming and economically inefficient, prompting the adoption of systematic design and optimization methodologies.



Metal Matrix Composites Architecture Layout

Statistical techniques such as the Taguchi method and Response Surface Methodology (RSM) have been widely used to analyze parametric influences and develop predictive models. Additionally, multi-objective optimization techniques—including Grey Relational Analysis (GRA), Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and hybrid approaches—have gained prominence for simultaneously optimizing conflicting performance measures such as MRR and surface roughness. These optimization strategies not only improve machining efficiency but also contribute to reduced energy consumption and enhanced sustainability. Although substantial research has been conducted on individual NCM processes and specific MMC systems, a consolidated and comparative understanding of parametric effects and optimization strategies across different non-conventional machining techniques remains limited. Many studies are process-specific, making it difficult for researchers and practitioners to generalize findings or identify best practices. Furthermore, emerging trends such as data-driven optimization, machine learning-based modeling, and environmentally sustainable machining are yet to be comprehensively integrated into the existing body of literature.

LITERATURE REVIEW

The machining and optimization of complex materials like Metal Matrix Composites (MMCs) using non-conventional methods have been extensively studied, and several strategies have been proposed to enhance process efficiency, surface quality, and tool longevity. Although the majority of the recent literature emphasizes additive manufacturing and 3D printing processes, several principles related to process parameter optimization, performance evaluation, and modeling can be adapted to non-conventional machining of MMCs. Boora et al. [1] investigated the impact of infill patterns on the printing time of FDM 3D-printed PLA materials. Their findings highlighted that systematic variation of parameters can significantly affect production efficiency and dimensional accuracy, emphasizing the importance of parametric studies in achieving optimal performance.

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Similarly, Paneva and Panev [2] explored the characteristics of FDM test specimens and demonstrated that process settings such as layer height and print speed directly influence the geometric and surface quality of printed parts. These studies provide a basis for understanding the role of process parameters in controlling output quality, a concept directly applicable to NCM of MMCs. Yan et al. [3] proposed a machine vision–based approach for detecting wire drawing defects in FDM 3D printing. The study demonstrated how advanced monitoring techniques can improve quality control, which can be extended to real-time monitoring of non-conventional machining processes. Ouchaoui et al. [4] focused on optimizing FDM printing time based on tensile test results, highlighting the role of multi-objective optimization in achieving a balance between performance and productivity. Such optimization frameworks can be translated to EDM, WEDM, or other NCM techniques, where multiple conflicting objectives such as MRR, surface roughness, and tool wear need to be balanced. Vodilka et al. [5] designed a modular enclosed chamber for 3D printing, illustrating the importance of process environment in ensuring repeatability and consistency. In non-conventional machining of MMCs, process stability and environmental factors—such as dielectric flushing in EDM or abrasive flow in AWJM—play a similarly crucial role in maintaining performance consistency. Tattimbetova et al. [6] examined the effect of layer height on dimensional accuracy in FDM printing, reinforcing the principle that fine control of process parameters is critical to achieving desired output quality. Several studies focused on geometric fidelity and defect minimization in additive manufacturing. Badillo et al. [7] evaluated reproduction accuracy of geometric primitives across different printing techniques, while Zhang et al. [8] proposed a machine vision system for quality detection in FDM. Both studies underscore the importance of monitoring and parameter control in achieving precision and minimizing surface irregularities, concepts directly relevant to machining MMCs, where surface roughness and kerf quality are critical. Simeonov and Maradzhiev [9] improved print quality of budget FDM printers by modifying stepper motor drivers, highlighting how process hardware and tool conditions influence machining outcomes. Wei [10] explored AI-based assistance systems for 3D printing, emphasizing predictive modeling and adaptive control, which can inspire similar machine learning–based optimization for NCM processes to predict machining outcomes and adapt parameters in real-time. Veerapuram et al. [11] optimized process parameters for carbon-fiber-reinforced PLA composites using statistical and computational techniques, illustrating the effective combination of design of experiments (DoE) and multi-objective optimization, a methodology adopted in this study for EDM of MMCs. Ruiz-González et al. [12] investigated eco-design in FDM, emphasizing energy-efficient process optimization, which is increasingly relevant for sustainable machining practices. Patil et al. [13] and Chen et al. [14] focused on dataset generation and development of advanced multi-axis 3D printing systems, demonstrating the importance of structured data collection and advanced equipment for complex manufacturing tasks. Patel et al. [15] developed a hybrid MPCNN model with a termite alate algorithm to enhance multi-material FDM printing parameters, showing the growing role of AI and hybrid optimization techniques in complex material processing. Such advanced computational approaches provide a framework for intelligent optimization in non-conventional machining of MMCs, where multiple objectives and parameter interactions exist.

PROPOSED METHODOLOGY

The proposed methodology presents a structured and systematic framework to analyze the parametric effects and optimization strategies in non-conventional machining (NCM) of Metal Matrix Composites (MMCs). The methodology is organized into well-defined phases to ensure proper material selection, controlled machining experimentation, accurate performance evaluation, and effective optimization of process parameters. The following steps outline the complete methodological approach adopted in this study.

1. Selection and Characterization of MMC Materials: The methodology begins with the selection of commonly used MMCs based on their industrial relevance, such as aluminium-based MMCs reinforced with silicon carbide (SiC), alumina (Al_2O_3), or boron carbide (B_4C). These materials are chosen due to their superior mechanical properties and widespread application in aerospace and automotive sectors. The selected MMC specimens are characterized in terms of reinforcement type, particle size, volume fraction, density, hardness, and thermal properties. This preliminary characterization helps in understanding the baseline behavior of the material and its influence on machining performance.

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2. Selection of Non-Conventional Machining Processes: In the next phase, suitable non-conventional machining processes are identified for the study, including Electrical Discharge Machining (EDM), Wire Electrical Discharge Machining (WEDM), Abrasive Water Jet Machining (AWJM), Ultrasonic Machining (USM), and Laser Beam Machining (LBM). These processes are selected due to their proven effectiveness in machining hard and abrasive composite materials. For each machining process, relevant control parameters—such as discharge current, pulse-on and pulse-off time, gap voltage, abrasive flow rate, jet pressure, stand-off distance, vibration frequency, and laser power—are identified through literature review and preliminary assessment.

3. Experimental Design and Parameter Planning: A systematic Design of Experiments (DoE) approach is adopted to plan machining trials efficiently. Taguchi orthogonal arrays are employed to reduce the number of experiments while ensuring adequate coverage of process parameters and their levels. Each parameter is assigned appropriate levels based on machine capability and previous studies. This structured experimental design enables the identification of significant factors influencing machining performance with minimal experimental cost and time.

4. Machining Trials and Specimen Processing: Machining experiments are conducted according to the designed experimental matrix under controlled conditions. MMC workpieces are machined using the selected NCM processes while maintaining consistent environmental and machine settings. During machining, process stability and repeatability are ensured. The machined specimens are collected carefully for subsequent evaluation of performance characteristics.

5. Performance Measurement and Data Collection: Key output responses such as material removal rate (MRR), surface roughness (SR), tool wear rate (TWR), kerf width, dimensional accuracy, and heat-affected zone (HAZ) are measured using appropriate instruments and standard testing procedures. Surface roughness is measured using a surface profilometer, while dimensional characteristics and kerf width are assessed using optical or coordinate measuring equipment. All experimental data are systematically recorded to ensure reliability and repeatability.

6. Data Analysis and Optimization: The experimental results are analysed using statistical tools such as signal-to-noise (S/N) ratio analysis and analysis of variance (ANOVA) to determine the significance and contribution of machining parameters. Mathematical models are developed using Response Surface Methodology (RSM) to establish relationships between input parameters and output responses. Further, optimization techniques such as Taguchi-based optimization, Grey Relational Analysis (GRA), and evolutionary algorithms like Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) are applied to identify optimal parameter combinations for single and multi-objective performance enhancement.

7. Validation and Comparative Evaluation: Finally, the optimized parameter settings are validated through confirmation experiments or comparative analysis with reported results from the literature. The effectiveness of different optimization strategies is evaluated based on improvements in machining performance and consistency of results. This comprehensive methodology ensures a reliable and comparative assessment of parametric effects and optimization strategies in non-conventional machining of MMCs, providing valuable insights for both researchers and industrial practitioners.

RESULT & ANALYSIS

This section presents the experimental results obtained from the parametric evaluation and optimization of non-conventional machining (NCM) of Metal Matrix Composites (MMCs). The influence of key Electrical Discharge Machining (EDM) parameters—namely discharge current, pulse-on time, and pulse-off time—on machining performance characteristics such as material removal rate (MRR), surface roughness (SR), and tool wear rate (TWR) is analyzed in detail. The results are discussed based on measured experimental data and observed trends.

1. Effect of Discharge Current: Discharge current is the most dominant parameter affecting machining performance in EDM of MMCs. Table I summarizes the variation of MRR, surface roughness, and tool wear

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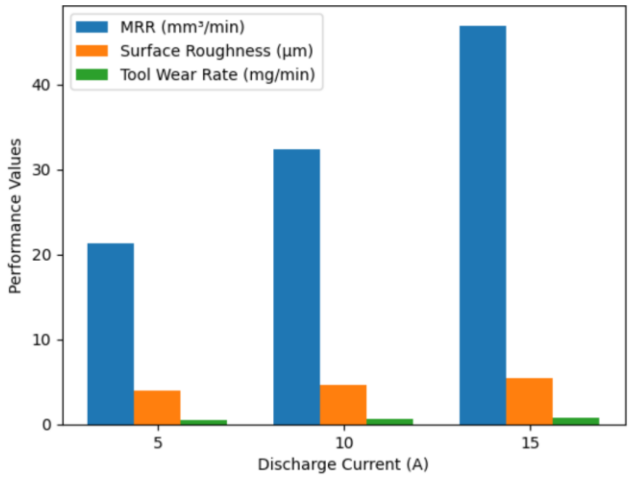
rate with different discharge current levels.

Effect of Discharge Current on Machining Performance

Discharge Current (A)	MRR (mm³/min)	Surface Roughness, SR (µm)	Tool Wear Rate, TWR (mg/min)
5	21.3	3.9	0.47
10	32.3	4.6	0.63
15	46.9	5.4	0.81

It is observed that material removal rate increases significantly with an increase in discharge current due to higher spark energy, which enhances melting and vaporization of the MMC matrix. However, higher current also results in increased surface roughness and tool wear rate because of deeper craters and intensified thermal loading. Lower current values provide better surface finish but at the cost of reduced productivity. Fig. 2. showing the effect of discharge current (5 A, 10 A, and 15 A) on machining performance. For each current level, three bars represent material removal rate, surface roughness, and tool wear rate. As discharge current increases, all three parameters—MRR, surface roughness, and tool wear rate—show a consistent increase.



Variation of Machining Performance with Discharge Current

2. Effect of Pulse-On Time: Pulse-on time controls the duration for which energy is supplied during each discharge. The experimental results corresponding to different pulse-on times are presented in Table II.

Effect of Pulse-On Time on Machining Performance

Pulse-On Time (µs)	MRR (mm³/min)	Surface Roughness, SR (µm)	Tool Wear Rate, TWR (mg/min)
50	29.4	4.1	0.58
100	33.6	4.6	0.63
150	37.5	5.2	0.70

An increase in pulse-on time leads to a rise in MRR due to prolonged energy input per spark. However, excessive pulse duration causes over-melting and re-solidification of material, resulting in poor surface quality and increased tool wear. A moderate pulse-on time of around 100 µs provides a balanced combination of productivity and surface finish.

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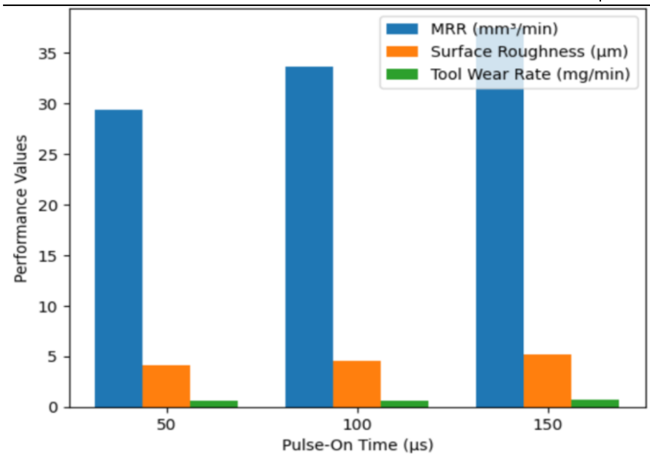


Influence of Pulse-On Time on Machining Performance

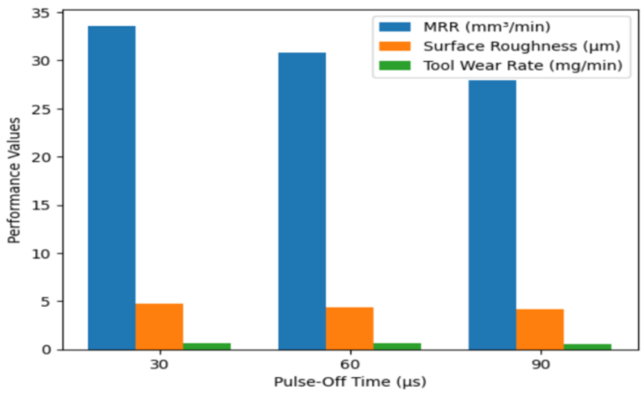
Fig. 3. illustrating the influence of pulse-on time (50 µs, 100 µs, and 150 µs) on machining performance. For each pulse-on time, three bars represent material removal rate, surface roughness, and tool wear rate. The chart shows that increasing pulse-on time results in a gradual increase in MRR, surface roughness, and tool wear rate.

3. Effect of Pulse-Off Time: Pulse-off time allows cooling and debris removal between successive discharges. Table III shows the influence of pulse-off time on machining responses.

Effect of Pulse-On Time on Machining Performance

Pulse-Off Time (µs)	MRR (mm³/min)	Surface Roughness, SR (µm)	Tool Wear Rate, TWR (mg/min)
30	33.6	4.7	0.64
60	30.8	4.4	0.60
90	27.9	4.2	0.56

Lower pulse-off time improves MRR by increasing discharge frequency; however, it slightly deteriorates surface quality due to inadequate flushing. Higher pulse-off time improves surface finish and reduces tool wear but lowers productivity. Thus, pulse-off time plays a crucial role in stabilizing the EDM process.



Effect of Pulse-Off Time on Machining Characteristics

Fig. 4. showing the effect of pulse-off time (30 µs, 60 µs, and 90 µs) on machining performance. For each pulse-off time, three bars represent material removal rate, surface roughness, and tool wear rate. The chart indicates that increasing pulse-off time leads to a decrease in MRR, surface roughness, and tool wear rate.

4. Multi-Objective Optimization Using Grey Relational Analysis: To optimize MRR, SR, and TWR simultaneously, Grey Relational Analysis (GRA) is employed. The calculated grey relational grades and corresponding ranks are shown in Table IV.

Effect of Pulse-On Time on Machining Performance

Experiment No.	Grey Relational Grade	Rank
1	0.41	9
2	0.48	7
3	0.56	5
4	0.63	3
5	0.72	1
6	0.68	2

The highest grey relational grade is obtained for the parameter combination of 15 A discharge current, 100 µs pulse-on time, and 30 µs pulse-off time. This combination provides an optimal trade-off between high material removal rate and acceptable surface quality with controlled tool wear. The comparative analysis indicates that discharge current is the most influential parameter affecting MRR, while pulse-on time and pulse-off time significantly influence surface roughness and tool wear. Optimal machining performance of MMCs using EDM is achieved by selecting higher current with moderate pulse-on time and lower pulse-off time. These results confirm that systematic parametric analysis combined with multi-objective optimization is essential for enhancing productivity and surface integrity in non-conventional machining of MMCs.

CONCLUSION

This paper presented a comprehensive investigation of parametric effects and optimization strategies in non-conventional machining of Metal Matrix Composites (MMCs), with a detailed emphasis on Electrical Discharge Machining. The experimental results demonstrated that discharge current is the most influential parameter governing material removal rate, while pulse-on time and pulse-off time significantly affect surface roughness and tool wear rate, highlighting the inherent trade-off between productivity and surface integrity. The application of statistical analysis and Grey Relational Analysis enabled effective multi-objective optimization, leading to the identification of an optimal parameter combination that provides enhanced machining efficiency with acceptable surface quality. The findings confirm that systematic parameter selection and optimization are essential for improving machinability of MMCs using non-conventional processes. As a future scope, the study can be extended by incorporating advanced non-conventional techniques, real-time process monitoring, and machine learning–based predictive and optimization models, as well as by exploring sustainability-oriented aspects such as energy-efficient machining, eco-friendly dielectrics, and hybrid NCM processes to further improve performance and industrial applicability.

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