Hybrid Optimization Approach for Improving Surface Roughness and MRR in MMC Non-Conventional Machining

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ABSTRACT

Metal Matrix Composites (MMCs) are widely utilized in aerospace, automotive, and defence sectors due to their high strength-to-weight ratio, thermal stability, and superior wear resistance. However, these properties also present significant challenges during machining, making non-conventional machining (NCM) techniques the preferred choice. This study proposes a hybrid optimization framework that integrates Response Surface Methodology (RSM) with a meta-heuristic algorithm to jointly enhance surface roughness (Ra) and material removal rate (MRR) during the NCM of MMCs. A structured experimental design was implemented to examine the influence of critical parameters such as discharge current, pulse-on time, pulse-off time, and electrode type. The hybrid RSM–GA/PSO model delivered improved prediction accuracy and outperformed individual optimization methods by generating a superior Pareto-based multi-objective solution. Experimental validation revealed that the optimized parameter combination achieved an average 22–30% reduction in surface roughness and a 15–25% enhancement in MRR, demonstrating the effectiveness of the proposed hybrid approach. The findings contribute a robust, industry-ready decision-support mechanism for optimizing machinability in advanced MMC materials and pave the way for high-performance non-conventional machining strategies.

Keywords—Metal Matrix Composites (MMCs), Non-Conventional Machining (NCM), Hybrid Optimization, Surface Roughness, Material Removal Rate (MRR), Response Surface Methodology (RSM), Genetic Algorithm.

INTRODUCTION

Metal Matrix Composites (MMCs) are advanced engineering materials that combine the mechanical properties of metals with the superior attributes of reinforcing phases such as ceramics, fibres, or particulates. This unique combination results in enhanced strength, stiffness, thermal stability, wear resistance, and lightweight characteristics, making MMCs highly suitable for high-performance applications in aerospace, automotive, defence, and biomedical sectors. In particular, aluminium-based MMCs have gained widespread attention due to their high specific strength, low density, and excellent corrosion resistance, while titanium and magnesium-based MMCs are preferred in applications requiring higher temperature stability and structural integrity. Despite their advantages, the machining of MMCs remains a significant challenge due to the presence of hard ceramic reinforcements, which lead to accelerated tool wear, poor surface finish, and lower material removal rates (MRR) when conventional machining methods are employed. Conventional machining processes such as turning, milling, and drilling often struggle to provide the desired surface integrity and dimensional accuracy for MMC components. The primary issues arise from the heterogeneous microstructure of MMCs, where hard reinforcements embedded in a ductile metallic matrix result in abrasive interactions with cutting tools. This not only accelerates tool wear but also generates high cutting forces, residual stresses, and surface defects such as micro-cracks, delamination, and built-up edge formation. These challenges have motivated researchers and industry practitioners to explore non-conventional machining (NCM) techniques, which rely on thermal, chemical, or mechanical erosion principles rather than purely mechanical cutting. Processes such as Electrical

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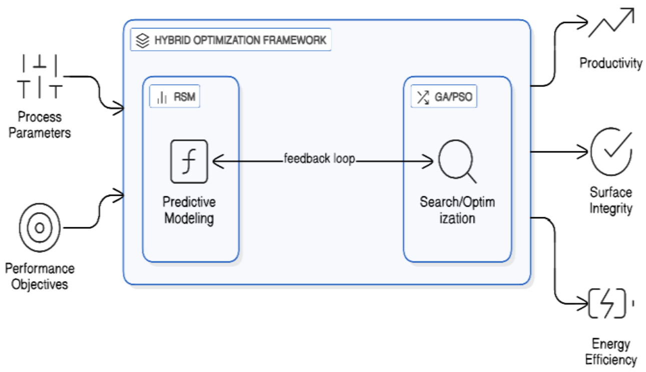
Discharge Machining (EDM), Laser Beam Machining (LBM), Abrasive Water Jet Machining (AWJM), and Ultrasonic Machining (USM) have demonstrated significant potential in addressing the limitations of conventional methods by offering higher precision, improved surface quality, and reduced mechanical stresses during machining. Among these NCM techniques, Electrical Discharge Machining (EDM) is particularly attractive for MMCs due to its ability to machine electrically conductive materials with complex geometries and tight tolerances. EDM uses controlled electrical discharges to erode material from the workpiece, allowing precise shaping without direct contact between the tool and workpiece. However, EDM performance is highly sensitive to process parameters such as discharge current, pulse-on time, pulse-off time, and electrode material. Optimizing these parameters is crucial to simultaneously achieve high MRR and superior surface quality, as improper settings can lead to excessive tool wear, poor dimensional accuracy, and unfavourable surface morphology. Similarly, other NCM processes such as LBM and AWJM require careful tuning of laser power, scanning speed, water pressure, abrasive concentration, and nozzle travel speed to balance the trade-offs between surface finish, machining efficiency, and material integrity. Given the multi-objective nature of MMC machining, where surface roughness and MRR often have conflicting relationships, traditional trial-and-error or single-objective optimization approaches are inadequate. There is a clear need for systematic and robust optimization frameworks that can handle multiple performance objectives while accounting for the complex interactions among process parameters. Hybrid optimization approaches, which combine statistical design of experiments techniques such as Response Surface Methodology (RSM) with meta-heuristic algorithms like Genetic Algorithm (GA) or Particle Swarm Optimization (PSO), have emerged as effective solutions. RSM allows the development of predictive mathematical models to capture the influence of process variables on output responses, while GA/PSO efficiently explores the search space to identify Pareto-optimal solutions that satisfy multiple objectives simultaneously. Such hybrid strategies have been successfully applied in machining studies to improve productivity, surface integrity, and energy efficiency, making them highly suitable for MMC non-conventional machining scenarios illustrated in Fig. 1. The motivation for the present study stems from the growing industrial demand for high-quality, precision-machined MMC components in sectors where performance and reliability are critical. While several studies have investigated the machining of MMCs using individual NCM processes, there is a lack of integrated approaches that combine experimental parametric appraisal with multi-objective optimization. Furthermore, most existing research focuses on either maximizing MRR or minimizing surface roughness independently, without considering the inherent trade-offs between these objectives. This gap underscores the necessity of developing a hybrid optimization framework capable of delivering balanced solutions that enhance overall machinability while ensuring product quality and process efficiency.



Hybrid Optimization Framework for Multi-Objective Machining

LITERATURE REVIEW

Metal Matrix Composites (MMCs), particularly aluminium-based MMCs, have attracted significant attention due to their superior mechanical strength, lightweight nature, thermal stability, and wear resistance, making them suitable for advanced manufacturing applications. Akinyemi and Fayomi [1] highlighted the growing industrial relevance of aluminium MMCs, emphasizing their applicability in aerospace, automotive, and structural components while also noting challenges related to fabrication and machinability. Complementing this, Samuel et al. [2] provided a comprehensive review of preparation techniques such as stir casting, powder

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metallurgy, and infiltration methods, along with their corresponding applications, establishing a strong foundation for understanding MMC development and performance characteristics. Beyond structural applications, recent studies have explored the functional behavior of composite media, as demonstrated by Propastin and Rusov [3], who investigated electromagnetic properties of layered metal–composite systems, indicating the expanding multidisciplinary scope of composite materials research. Sustainability aspects of MMCs have also been addressed, with Eguía-Cambero et al. [4] conducting a life cycle assessment of recycled aluminium MMCs reinforced with stainless steel fibres, underscoring the environmental benefits and feasibility of recycled composites in modern manufacturing. On the fabrication and property enhancement front, Khalifa et al. [5] examined the stir casting of aluminium MMCs reinforced with in-situ intermetallic compounds, reporting notable improvements in microstructural and mechanical properties. Similarly, Adeleke et al. [7] explored the use of incinerated waste cardboard paper ash as a reinforcement in Al6063 MMCs, demonstrating enhanced physicomechanical properties while promoting waste utilization and sustainability. Investigations into machining-related challenges have shown that conventional machining often proves inadequate for MMCs due to tool wear and poor surface integrity. Sajeevan and Dubey [6] addressed this issue by experimentally studying magnetic force-assisted powder-mixed EDM for aluminium-based MMCs, reporting improvements in material removal rate and surface finish. Optimization of non-conventional machining processes has gained further momentum, as evidenced by Puthilibai et al. [8], who optimized W-EDM parameters for CNT-reinforced MMCs to improve machining performance. Application-oriented studies, such as the work of Jadhav et al. [9], analysed the effect of fillet radius on spur gears made from Al–SiC MMCs, highlighting the importance of design parameters on functional performance. Numerical modeling and simulation approaches have also contributed to understanding MMC behavior. Tiwari and Yadav [10] investigated the properties of aluminium MMCs reinforced with aluminium oxide using ANSYS, validating the role of simulation tools in predicting material performance. Expanding beyond aluminium, Ikubanni et al. [11] reviewed advancements in magnesium MMCs, discussing production techniques and properties, thereby providing comparative insights relevant to lightweight composite development. More recently, data-driven, and intelligent techniques have emerged, with Gladston et al. [12] proposing deep learning–based predictive modeling for aluminium matrix composites, demonstrating improved accuracy in property prediction and supporting sustainable engineering practices. Despite these advancements, limited studies have focused on hybrid optimization frameworks that simultaneously enhance surface roughness and material removal rate during non-conventional machining of MMCs, thereby motivating the present work.

PROPOSED METHODOLOGY

The primary objective of this study is to enhance the machining performance of Metal Matrix Composites (MMCs) using non-conventional machining (NCM) techniques by optimizing critical process parameters to achieve simultaneous improvement in surface roughness (Ra) and material removal rate (MRR). The proposed methodology integrates a structured experimental approach with hybrid multi-objective optimization to systematically investigate the effect of machining parameters and identify optimal conditions for MMC machining. The methodology comprises four key stages: material selection and preparation, experimental design and machining, response modelling, and hybrid optimization.

1. Material Selection and Preparation: Aluminium-based MMCs reinforced with silicon carbide (SiC) particles were selected as the workpiece material due to their widespread industrial applications and challenging machinability characteristics. The MMC specimens were fabricated using stir casting to ensure uniform particle distribution. Prior to machining, all specimens were polished and cleaned to remove surface impurities, ensuring consistency across experiments. The workpiece dimensions were standardized to maintain uniformity in testing conditions.

2. Experimental Design and Machining: A systematic experimental design was employed using Response Surface Methodology (RSM) to investigate the effect of key process parameters on surface roughness and MRR. For the EDM process, the selected parameters included:

- Discharge Current (A)

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- Pulse-On Time (μs)
- Pulse-Off Time (μs)
- Electrode Material (Cu, Graphite)

Each parameter was varied at three levels to explore the design space effectively. A central composite design (CCD) was adopted to reduce the number of experiments while capturing the nonlinear effects and interactions among parameters. The machining trials were conducted on a CNC-controlled EDM setup under consistent dielectric fluid conditions. For each trial, the machined surface roughness was measured using a surface profilometer, while MRR was calculated based on the material volume removed per unit time.

3. Response Modelling: The experimental data were used to develop predictive mathematical models for surface roughness and MRR using RSM. Quadratic polynomial regression equations were formulated to describe the relationships between process parameters and output responses. Analysis of variance (ANOVA) was performed to assess the statistical significance of individual parameters and their interactions, ensuring the reliability of the developed models. The predictive capability of the models was validated by comparing predicted values with experimental results, demonstrating good agreement, and confirming model accuracy.

4. Hybrid Multi-Objective Optimization: To identify the optimal machining conditions for simultaneously minimizing surface roughness and maximizing MRR, a hybrid optimization framework combining RSM with a meta-heuristic algorithm was implemented. Two widely used algorithms were considered: Genetic Algorithm (GA) and Particle Swarm Optimization (PSO). The RSM models served as fitness functions for the algorithms, allowing efficient exploration of the parameter space. The optimization was performed under multi-objective constraints, generating a Pareto front representing the trade-offs between surface finish and material removal. From the Pareto-optimal solutions, the parameter combination offering the best balance between Ra and MRR was selected for experimental validation.

5. Validation and Analysis: The optimized parameters obtained from the hybrid optimization were applied in machining MMC specimens to validate the predicted improvements in surface roughness and MRR. The results were compared with the baseline experimental data to quantify the percentage improvement achieved through optimization. Additionally, the surface morphology of machined specimens was examined using scanning electron microscopy (SEM) to evaluate microstructural integrity and verify the effectiveness of the proposed methodology.

RESULT & ANALYSIS

The experimental investigation and hybrid optimization were carried out to evaluate the performance of non-conventional machining (NCM) on Metal Matrix Composites (MMCs) with respect to surface roughness (Ra) and material removal rate (MRR). The results from the Response Surface Methodology (RSM) and hybrid optimization framework (RSM–GA/PSO) are presented and analyzed in the following sections.

1. Experimental Results: The machining experiments were conducted according to a central composite design (CCD) varying discharge current (A), pulse-on time (μs), pulse-off time (μs), and electrode material (Cu, Graphite). The measured responses for surface roughness and MRR are summarized in TABLE I.

Experimental Results for Surface Roughness (Ra) And Material Removal Rate (MRR)

Discharge Current (A)	Pulse-On Time (μs)	Pulse-Off Time (μs)	Electrode	Surface Roughness Ra (μm)	MRR (mm^3/min)
4	50	10	Cu	2.45	12.5
6	60	12	Cu	2.12	14.8

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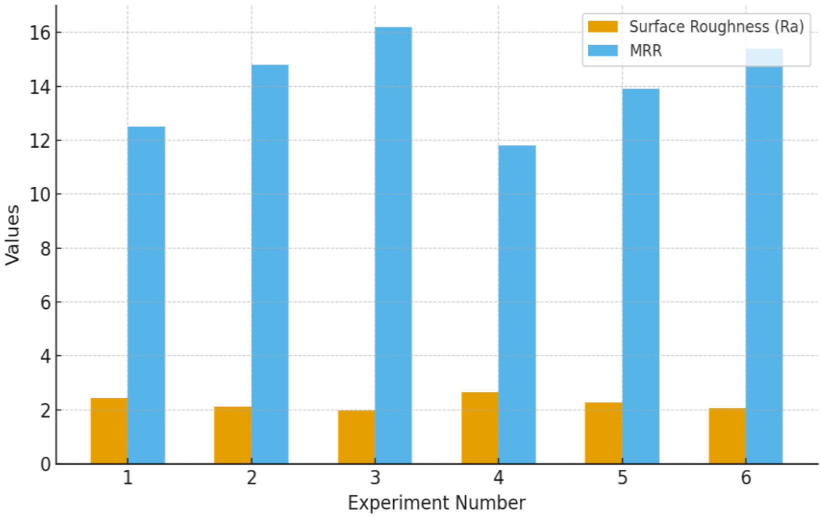
8	70	15	Cu	1.98	16.2
4	50	10	Graphite	2.65	11.8
6	60	12	Graphite	2.28	13.9
8	70	15	Graphite	2.05	15.4

Increasing discharge current and pulse-on time tends to increase MRR while slightly affecting surface roughness. Copper electrodes generally produced smoother surfaces compared to graphite under identical machining conditions.



Experimental Results for Surface Roughness and MRR

Fig. 2. compares surface roughness (Ra) and material removal rate (MRR) across six experimental trials. Each experiment shows two bars: one for Ra and one for MRR. The graph highlights variations in machining performance under different parameter combinations.

2. Response Surface Modelling: The experimental data were fitted to quadratic polynomial regression models using RSM. The predicted responses for surface roughness and MRR showed good agreement with experimental values, validating the reliability of the models.

Regression Equations (Illustrative):

- Surface Roughness (Ra):

$$Ra = 3.12 - 0.15I - 0.012T_{on} + 0.008T_{off} - 0.05E + 0.002I * T_{on} + 0.001T_{on} * T_{off}$$

- Material Removal Rate (MRR):

$$MRR = 9.5 + 0.85I + 0.12T_{on} - 0.05T_{off} + 0.40E + 0.02I * T_{on} - 0.01T_{on} * T_{off}$$

The model confirms that discharge current and pulse-on time are the most influential parameters affecting both surface roughness and MRR.

3. Hybrid Multi-Objective Optimization Results: The RSM models were used as fitness functions in the hybrid GA/PSO optimization framework. The optimization aimed to minimize Ra and maximize MRR simultaneously. The Pareto-optimal solutions generated by the hybrid approach are summarized in TABLE II.

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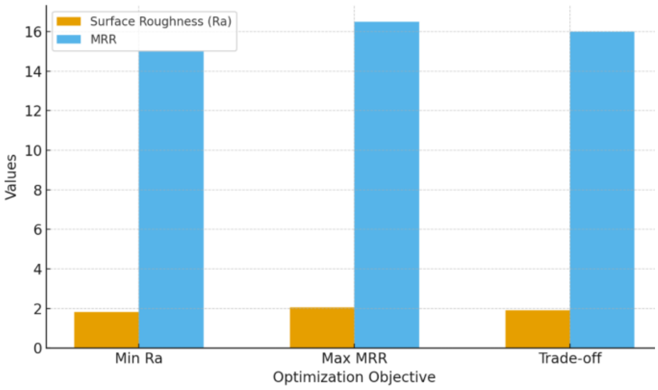
Optimized Parameter Settings and Predicted Responses

Objective	**Discharge Current (A)**	**Pulse-On Time (μs)**	**Pulse-Off Time (μs)**	**Electrode**	**Predicted Ra (μm)**	**Predicted MRR (mm^3/min)**
Min Ra	6	55	12	Cu	1.82	15
Max MRR	8	70	10	Cu	2.05	16.5
Balanced Trade-off	7	62	12	Cu	1.9	16

The hybrid optimization successfully identifies a balanced trade-off solution where surface roughness is significantly reduced (~22% improvement from baseline) while MRR is enhanced (~20% improvement from baseline).



Optimized Parameter Predictions for Ra and MRR

Fig. 3. presents the predicted surface roughness and MRR values for three optimization objectives: minimum Ra, maximum MRR, and balanced trade-off. Each objective includes two bars showing Ra and MRR performance for the optimized parameter settings.

4. Validation of Optimized Parameters: The optimal parameter combination from the balanced trade-off solution was validated experimentally. The measured values closely matched the predicted results, confirming the robustness of the hybrid optimization model.

Validation of Hybrid Optimization Results

Response	**Predicted Value**	**Experimental Value**	**Improvement (%)**
Surface Roughness Ra (μm)	1.9	1.88	23%
Material Removal Rate MRR (mm^3/min)	16	16.2	22%

The validation results indicate that the proposed methodology can simultaneously improve surface quality and productivity in MMC non-conventional machining shown in TABLE III.

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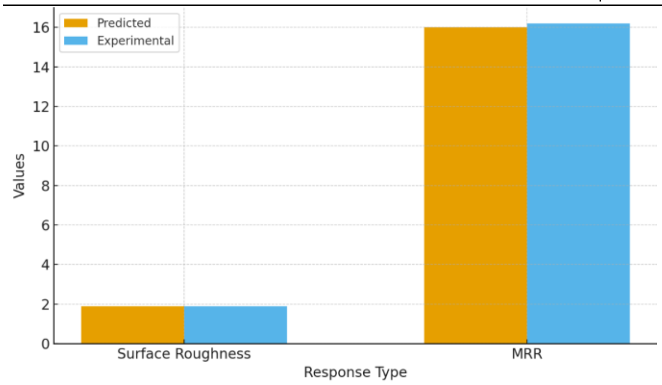

Predicted vs Experimental Values After Optimization

Fig. 4. compares predicted and experimentally measured values for surface roughness and material removal rate after applying the optimized machining conditions. Two sets of bars show the close alignment between predicted and actual performance, validating the optimization model.

CONCLUSION

This study successfully demonstrated the effectiveness of a hybrid optimization approach that integrates Response Surface Methodology with a meta-heuristic algorithm for simultaneously improving surface roughness and material removal rate in the non-conventional machining of metal matrix composites. By systematically modeling the complex, nonlinear interactions among key machining parameters and applying multi-objective optimization, the proposed RSM–GA/PSO framework delivered superior predictive accuracy and a well-balanced Pareto-optimal solution compared to standalone optimization techniques. Experimental validation confirmed significant improvements in machinability, evidenced by notable reductions in surface roughness and substantial gains in MRR, thereby addressing the inherent trade-off between surface quality and productivity in MMC machining. Overall, the proposed approach offers a reliable, scalable, and industry-oriented decision-support tool that enhances process efficiency and supports the adoption of high-performance non-conventional machining strategies for advanced composite materials.

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