International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048
Volume 10, Issue 5, pp 360-365, May-2026
https://doi.org/10.47001/IRJIET/2026.105047

Optimization of Machining Parameters of MMC Using Taguchi's Method

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Abstract **- Metal Matrix Composites (MMCs), especially aluminum based composites reinforced with particles like SiC, B4C, AlO, TiB, CNTs and graphene, are widely used in aerospace, automobile and defense industries because of their high strength to-weight ratio, good wear resistance and better thermal properties. However, machining of MMCs is quite difficult due to the presence of hard reinforcement particles. These particles cause rapid tool wear, poor surface finish, high cutting forces and sometimes unstable machining behaviour. Therefore, selecting proper machining parameters becomes very important in order to improve performance and reduce production cost. Among various optimization techniques available, the method developed by Genichi Taguchi is one of the most commonly used methods because it reduces the number of experiments and gives reliable results using signal-to-noise ratio analysis. In this review paper, nearly 50 recent research articles published in reputed indexed journals (SCI, Scopus, Springer, Elsevier and Web of Science) from 2024 to 2026 are studied and analysed. The papers mainly focus on optimization of machining parameters in turning, milling, drilling, wire EDM, spark EDM and abrasive water jet machining of MMCs using Taguchi method and its hybrid combinations.**

Keywords: Metal Matrix Composites (MMCs), Taguchi Method, Machining Parameter Optimization, Surface Roughness (Ra), Material Removal Rate (MRR), CNC Turning.

I. INTRODUCTION

In recent years, Metal Matrix Composites (MMCs) have gained significant attention in advanced engineering applications. These materials are mainly developed to overcome the limitations of conventional metals such as low wear resistance, poor strength at elevated temperatures and limited stiffness. Among different types of MMCs, aluminum based composites are the most widely used due to their light weight, good corrosion resistance and relatively easy fabrication. Reinforcements such as silicon carbide (SiC), boron carbide (B4C), aluminum oxide (AlO), titanium diboride (TiB), carbon nanotubes (CNTs) and graphene are commonly added to improve mechanical and tribological properties.

II. LITERATURE REVIEW

A. Material and Fabrication Optimization Studies

The study [1] investigated optimization of low-velocity impact behavior of FML structures using statistical techniques. It demonstrated that optimized stacking sequence significantly improves impact resistance. The influence of nano-TiB reinforcement in Al7075 was analyzed in [9], where reinforcement percentage improved hardness and strength but increased machining difficulty. Similarly, [32] studied SiC-modified Al7075 alloy and reported improved mechanical properties with optimized reinforcement distribution. The work [33] evaluated mechanical and microstructural behavior of Al reinforced with SiC and showed uniform dispersion enhances wear resistance. Hybrid reinforcement effects were studied in [39] on AA7075/B4C/ZrO composites, highlighting improved hardness and microstructural stability. The research [40] investigated AW2024/E-glass/TiC hybrid composites and reported enhanced strength due to proper reinforcement bonding. Fabrication parameter optimization using stir casting was performed in [29] for A6082-SNSA/MWCNT hybrid composites. Mechanical milling time influence on AA2024/B4C/GNP hybrid nanocomposites was examined in [36], concluding optimum milling time prevents agglomeration. Friction stir processing optimization for AA5083/SiC was performed in [35] using Taguchi and regression modelling. These studies show that reinforcement percentage and fabrication conditions significantly influence machinability and mechanical properties.

B. CNC Turning Optimization Studies

The study [2] applied integrated multi-objective optimization for high-precision CNC turning of 7075 aluminum alloy. Feed rate was found most influential for surface roughness. Multi-objective optimization of CNC turning of AL6061 was performed in [12], confirming feed rate dominance. Machining of Al-ZrB nanocomposites was analyzed in [13], showing reinforcement increases cutting force. In [19], optimization of machining AA4015/B4C MMC

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concluded depth of cut and feed rate strongly affect surface quality. The machining behaviour of AW-7020 aluminum alloy shafts was investigated in [16], where feed rate contributed most to surface roughness variation. The study [21] applied grey-fuzzy optimization for ECAP processed aluminum and improved multi-response performance. Sustainable lubrication was examined in [23], where Jatropha seed oil reduced surface roughness during turning. Air-assisted cooling effects during turning of AISI 1018 steel were studied in [38], improving tool life and reducing temperature. Overall, turning studies consistently indicate feed rate as the dominant machining parameter.

C. Optimization of Material Removal Rate (MRR) and Surface Roughness (Ra)

Material Removal Rate (MRR) and Surface Roughness (Ra) are the two most critical output responses in machining of Metal Matrix Composites. Almost all machining optimization studies focus on maximizing MRR while minimizing surface roughness. The selected research papers demonstrate extensive application of Taguchi's method and hybrid techniques for achieving this balance. In CNC turning studies such as [2], multi-objective optimization was performed for high-precision machining of 7075 aluminium alloy. Using Taguchi-based design, feed rate was identified as the most influential parameter affecting surface roughness, whereas cutting speed significantly influenced MRR. Similarly, in [12], multi-objective optimization of AL6061 turning revealed that feed rate contributes maximum variation in surface roughness, while depth of cut plays an important role in MRR enhancement. The study [16] on AW-7020 aluminum alloy shafts also confirmed through ANOVA that feed rate has the highest contribution towards Ra variation. Lower feed rate improved surface finish but reduced MRR.

Overall trends observed across the reviewed papers:

- Feed rate is the dominant factor influencing surface roughness in turning and drilling.
- Depth of cut and cutting speed mainly influence MRR.
- In EDM/WEDM, pulse-on time and current dominate both MRR and Ra.
- There exists a trade-off between maximizing MRR and minimizing surface roughness.
- Hybrid Taguchi-based methods provide better multi-objective optimization.

Thus, optimization of machining parameters using Taguchi's method remains an effective approach for balancing productivity (MRR) and quality (Ra) in MMC machining.

D. Machining Tools Used for MMC Machining

Selection of appropriate cutting tool material plays a very important role in machining of Metal Matrix Composites (MMCs). Due to the presence of hard ceramic reinforcements such as SiC, B4C and TiB, severe abrasive wear occurs on cutting tools. Therefore, most of the reviewed studies have carefully selected tool materials to improve machining performance. In CNC turning optimization studies such as [2], [12] and [16], coated carbide inserts were commonly used due to their good balance between hardness and toughness. These tools provided acceptable surface finish, but tool wear increased significantly at higher feed rates. In the machining of AA4015/B4C composite [19], carbide inserts were used, and it was observed that reinforcement particles caused flank wear and micro-chipping of tool edges. For drilling operations, High Speed Steel (HSS) tools were used in [20] for machining Al-SiC-Graphite composite. However, rapid tool wear was reported due to abrasive reinforcement particles. In WEDM studies such as [8] and [17], brass wire electrodes were used as cutting tools. In EDM investigations such as [25], [27], [34] and [37], copper and graphite electrodes were commonly used. Additionally, sustainable machining approaches such as bio-lubricant-assisted turning in [23] and air-assisted cooling in [38] helped in reducing tool wear and improving tool life.

E. Materials and Method

Most of the reviewed studies used aluminium-based metal matrix composites reinforced with ceramic and nano-particles. The base materials commonly included Al7075, Al6061, Al2024, AA4015 and LM series alloys. Hybrid and nano-reinforced MMCs were widely studied in [9], [13], [28], [39], and [41], where reinforcements such as SiC, B4C, ZrO and SiN were incorporated to improve mechanical and tribological properties. The study [29] optimized stir casting parameters for hybrid composites, while [36] investigated mechanical milling time effects on AA2024/B4C/GNP nanocomposites. For machining optimization, Taguchi's orthogonal array design was primarily used in [2], [12], [14], [19], [25], and [26]. Multi-objective optimization approaches such as NSGA-II [3], Grey-Fuzzy [21], and TOPSIS [5] were also applied. In EDM-based studies like [27] and [34], thermal modelling and powder-mixed techniques were incorporated to improve machining responses.

F. Cutting Parameters Considered

In Turning (confirmed in [2], [12], [16], [19], [21]):

- Cutting Speed (rpm)
- Feed Rate (mm/rev)
- Depth of Cut (mm)

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G. Metal Matrix Composites (MMCs)

The majority of research focused on aluminium-based MMCs due to their lightweight and high strength properties. Common reinforcements include:

- Silicon Carbide (SiC) – [21], [33], [34]
- Boron Carbide (B4C) – [19], [39]
- Nano-SiN – [28], [41]
- ZrO – [39]
- Graphene and carbon fiber – [4], [15], [30]
- TiB – [9]

Hybrid composites showed improved hardness and wear resistance but increased machining difficulty. Studies like [11], [18], [28], and [41] focused on tribological properties of MMCs and demonstrated that increasing reinforcement improves wear resistance but may increase tool wear during machining.

H. Vertical Machining Center (VMC)

Vertical Machining Centers (VMC) were extensively used in turning and milling-based optimization studies. In CNC turning investigations such as [2] and [12], precision machining centers were used to maintain controlled cutting conditions. The machining of Al-ZrB nanocomposites in [13] and AA4015/B4C composites in [19] was conducted using controlled CNC setups to evaluate surface roughness and MRR. In drilling studies such as [14] and [26], VMC-based drilling setups ensured accurate spindle speed and feed control.

VMC machines provide:

- High rigidity
- Controlled spindle speed
- Stable feed rate
- Repeatability for Taguchi experiments

These features are essential for statistical optimization using orthogonal arrays.

III. DISCUSSIONS

The reviewed studies collectively demonstrate that Taguchi's method remains one of the most effective techniques for optimization of machining parameters in Metal Matrix Composites (MMCs). However, variations exist depending on machining process, reinforcement type, and optimization objectives.

A. Influence of Cutting Parameters on Surface Roughness

Surface roughness (Ra) is one of the most studied response parameters across almost all machining operations. In turning studies such as [2], [12], and [16], feed rate was consistently identified as the most significant parameter influencing surface roughness. ANOVA results in these studies showed that feed rate contributed more than cutting speed and depth of cut. Similarly, drilling investigations [14] and [26] also confirmed that higher feed rate increases thrust force and surface irregularities, resulting in poor surface finish. In WEDM processes, the situation differs slightly. Studies [8] and [17] reported that pulse-on time and discharge current are the dominant factors affecting surface roughness. Higher spark energy produces larger craters, increasing Ra. ANN-based prediction study [31] and deep learning-based work [30] improved prediction accuracy of surface roughness compared to traditional regression methods.

B. Influence of Cutting Parameters on Material Removal Rate (MRR)

MRR is critical for productivity. Turning optimization studies [2] and [12] showed that depth of cut and cutting speed significantly influence MRR. Increasing depth of cut increases MRR but may reduce surface quality. In drilling studies [14], higher feed rate increased MRR but also increased thrust force. In EDM investigations [25], [27], and [37], pulse-on time and discharge current strongly affected MRR. Higher current increased material removal but also increased surface damage. Powder-mixed EDM optimization in [34] improved MRR while maintaining acceptable surface finish. AWJM study [22] confirmed that water pressure significantly affects MRR. Thus, a clear trade-off exists between maximizing MRR and minimizing surface roughness.

C. Effect of Reinforcement on Machining Performance

Reinforcement particles significantly influence machinability. Studies such as [9], [13], [19], [28], [39], and [41] demonstrated that increasing reinforcement percentage improves hardness and wear resistance but increases tool wear during machining. Hybrid composites involving graphene and carbon fiber [4], [15], [30] showed improved mechanical properties but complex machining behavior. The tribological studies [11] and [18] confirmed that reinforcement enhances wear resistance but affects machining forces. Thus, optimization becomes essential when machining reinforced MMCs.

D. Tool Wear and Machining Stability

Tool wear is strongly influenced by reinforcement particles. In turning studies [19] and [13], carbide tools

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experienced flank wear due to abrasive SiC and B4C particles. Drilling study [20] reported rapid wear of HSS tools. EDM studies [25] and [37] showed that electrical parameters influence electrode wear rate. Sustainable lubrication and cooling methods in [23] and [38] improved tool life and surface finish.

IV. CONCLUSION

From the detailed review of the selected research papers, it can be clearly understood that optimization of machining parameters plays a very important role in improving the performance of Metal Matrix Composites during machining. MMCs, especially aluminium-based composites reinforced with SiC, B4C, TiB, graphene and nano-ceramic particles, provide excellent mechanical and tribological properties, but their machining remains challenging due to the presence of hard abrasive reinforcements.

Most of the reviewed studies have successfully applied Taguchi's method to optimize machining parameters such as cutting speed, feed rate, depth of cut, pulse-on time and discharge current. In conventional machining processes like turning and drilling, feed rate was consistently found to be the most influential parameter affecting surface roughness. At the same time, depth of cut and cutting speed were observed to have a greater impact on material removal rate. In non-traditional processes such as EDM and WEDM, electrical parameters, particularly pulse-on time and discharge current, were found to dominate both MRR and surface quality.

Another important observation from the literature is the trade-off between productivity and quality. Increasing MRR often leads to deterioration in surface finish, and therefore multi-objective optimization becomes necessary. While the traditional Taguchi method provides reliable and economical optimization, many recent studies have integrated hybrid techniques such as Grey Relational Analysis, NSGA-II, TOPSIS, ANN and deep learning to improve prediction accuracy and handle multiple responses simultaneously. It is also evident that increasing reinforcement percentage enhances hardness and wear resistance of MMCs, but at the same time it increases tool wear and machining difficulty. This makes proper parameter selection even more critical. Sustainable approaches such as bio-lubricants and advanced cooling techniques are also emerging as supportive methods to improve machining performance.

Overall, the reviewed research confirms that Taguchi's method remains a strong and practical tool for optimizing machining parameters of MMCs. However, the future direction seems to be moving toward intelligent, AI-assisted and multi-objective optimization techniques that can provide better control, accuracy and industrial applicability. Proper integration of statistical optimization with modern predictive modelling will further improve machining efficiency and surface integrity of advanced MMC materials.

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Volume 10, Issue 5, pp 360-365, May-2026
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ISSN (online): 2581-3048
Volume 10, Issue 5, pp 360-365, May-2026
https://doi.org/10.47001/IRJIET/2026.105047

Citation of this Article:

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