

Influence Of Machining Parameters On Drilling Characteristics Of Al6061/Sic Mmcs: A Taguchi-Based Approach

Akash Pandey¹, Sheetal Soni^{2*}, Urvish Patel³, Bhavik Chaudhari⁴

¹Assistant Professor, Department of Mechanical Engineering, Faculty of Technology & Engineering, The Maharaja Sayajirao University of Baroda, Vadodara, Gujarat, India

^{2*}Assistant Professor, Department of Mechanical Engineering, Faculty of Technology & Engineering, The Maharaja Sayajirao University of Baroda, Vadodara, Gujarat, India
(Corresponding author)

³Assistant Professor, Department of Mechanical Engineering, Faculty of Technology & Engineering, The Maharaja Sayajirao University of Baroda, Vadodara, Gujarat, India

⁴Research Scholar, Department of Mechanical Engineering, Faculty of Technology & Engineering, The Maharaja Sayajirao University of Baroda, Vadodara, Gujarat, India

ABSTRACT

This research investigates the influence of machining parameters on the drilling characteristics of Al6061/SiC metal matrix composites (MMCs), which are increasingly employed in the aerospace and automotive sectors due to their exceptional mechanical and tribological properties. However, the presence of hard SiC particles complicates the drilling process, resulting in heightened thrust forces, tool wear, and surface imperfections. The study utilizes a Taguchi L9 orthogonal array to systematically assess the effects of four process parameters—spindle speed (800, 1200, 1600 rpm), feed rate (0.1, 0.2, 0.3 mm/rev), tool diameter (6, 8, 10 mm), and reinforcement percentage (5%, 10%, 15%)—on thrust force, material removal rate (MRR), and surface roughness. The experimental findings indicate that the feed rate is the most significant factor influencing all responses. An increase in feed rate from 0.1 to 0.3 mm/rev results in a thrust force increase of approximately 70%, from 200 N to over 340 N, and a rise in surface roughness (Ra) by about 0.012 μm , while MRR enhances by roughly 50%. In contrast, higher spindle speeds (from 800 to 1600 rpm) lead to a 35% reduction in thrust force and a decrease in surface roughness by 0.005 μm , attributed to thermal softening effects. Larger tool diameters (from 6 mm to 10 mm) significantly boost MRR but also increase cutting forces. ANOVA analysis reveals that the feed rate contributes to over 60% of the variation in thrust force and MRR, while the reinforcement percentage primarily influences surface roughness and thrust forces. The regression models correlate well with the experimental data, offering reliable predictions for process optimization. These findings underscore the necessity of balancing productivity and surface quality through optimized parameter settings, which is essential for enhancing MMC manufacturing efficiency.

Keywords: Aluminium Metal Matrix Composites (AMMCs), Taguchi Method, Drilling of AMMMC, Thrust force.

1. Introduction

Metal Matrix Composites (MMCs) represent a category of advanced engineering materials that integrate the ductility of metals with the exceptional strength, hardness, and wear resistance provided by ceramic reinforcements. Aluminium-based MMCs (AMMCs) are especially appealing due to their favorable strength-to-weight ratio, enhanced thermal stability, and superior tribological performance, rendering them ideal for applications in aerospace, automotive, and defense sectors [1,2]. The addition of reinforcements such as silicon carbide (SiC), alumina (Al_2O_3), and boron carbide (B_4C) markedly enhances both mechanical and physical properties, although it simultaneously presents significant challenges in machining.

Metal Matrix Composites (MMCs) are commonly acknowledged as challenging materials to machine, primarily because of the hard, abrasive reinforcement particles that are

integrated within a comparatively softer metallic matrix. The presence of these reinforcements results in accelerated tool wear, increased cutting forces, and compromised surface integrity during machining processes [3, 4]. Among the various machining techniques, drilling stands out as a critical operation for assembly; however, it poses significant challenges when applied to MMCs, including excessive thrust force, tool degradation, delamination, and subpar hole quality [5, 6].

2. Literature Review

Early studies on MMC drilling highlighted the severe tool wear associated with conventional cutting tools. Ramulu et al. [7] demonstrated that polycrystalline diamond (PCD) tools provide superior performance compared to carbide and high-speed steel tools due to their excellent hardness and wear resistance. Similarly, investigations into tool coatings and geometries have shown that diamond-coated and carbide tools significantly improve tool life and surface finish during machining of aluminium alloys and composites [8].

The influence of machining parameters such as spindle speed, feed rate, and drill geometry on drilling performance has been extensively studied. Taguchi-based optimization techniques have been widely applied to determine optimal machining conditions. Rajmohan et al. [9] investigated drilling of hybrid MMCs and identified feed rate as the most influential parameter affecting thrust force and surface roughness. Similar findings were reported by Ravinder Kumar et al. [10] and Bammidi et al. [11], confirming that feed rate dominates drilling performance, while spindle speed plays a secondary role.

Hybrid MMCs reinforced with multiple particles have gained increasing attention due to their tailored properties. Narale et al. [12] and Senthil Babu et al. [13] reported that increasing reinforcement content leads to higher cutting forces and reduced surface quality, thereby complicating machining processes. In addition, Waleed et al. [14] explored friction drilling of MMCs and identified key process parameters affecting thrust force and torque, highlighting the importance of parameter optimization.

Advanced modeling approaches have also been employed to understand drilling behavior. Doomra et al. [15] developed finite element models to predict thrust force during MMC drilling, emphasizing the importance of process parameter selection. Langella et al. [16] analyzed the contribution of drill geometry and revealed that the chisel edge can contribute significantly to thrust force, particularly at higher feed rates.

Recent studies have focused on microstructural and morphological analysis to better understand tool-workpiece interactions. Parasuraman et al. [17] and Palanikumar et al. [18] utilized scanning electron microscopy (SEM) and other advanced techniques to study chip formation, tool wear, and surface integrity, providing deeper insights into machining mechanisms of MMCs. These studies highlight the need for optimized machining conditions to minimize defects and improve performance.

In addition to conventional drilling, researchers have explored alternative approaches such as abrasive-assisted drilling and improved cooling strategies. Singh et al. [19] demonstrated that abrasive-assisted drilling enhances surface finish and material removal rate, while other studies have emphasized the role of lubrication and cooling in reducing thermal effects and tool wear.

Overall, the drilling of MMCs is governed by a complex interaction between material properties, tool characteristics, and process parameters. Although significant advancements have been made, there remains a need for systematic experimental investigations to establish robust relationships between machining inputs and

performance outputs such as thrust force, material removal rate (MRR), and surface roughness.

The present study focuses on the experimental investigation of drilling characteristics of Al6061-based MMCs using a Vertical Machining Centre (VMC). The Taguchi method and Analysis of Variance (ANOVA) are employed to evaluate the effects of spindle speed, feed rate, tool diameter, and reinforcement percentage on drilling performance. This work aims to provide optimized machining conditions and contribute to improved machinability of MMCs for industrial applications.

3. Materials and Methodology

A systematic experimental approach using the Taguchi L9 orthogonal array was employed to evaluate the effects of machining parameters on Al6061/SiC MMC drilling performance, measuring thrust force, MRR, and surface roughness under controlled conditions on a CNC VMC.

3.1 Workpiece Material and Composite Preparation

The workpiece material used in this study is Aluminium 6061 alloy reinforced with silicon carbide (SiC) particles. Aluminium 6061 is widely used due to its excellent machinability, strength, and corrosion resistance. The addition of SiC particles enhances hardness and wear resistance but simultaneously reduces machinability. The chemical composition of Al 6061 material is shown in Table 1.

Table 1. Chemical Composition of 6061 aluminium alloys

Material	Al	Copper	Magnesium	Manganese	Silicon	Chromium
Alloys 6061	97,7%	0,25%	1%	0,15%	0,60%	0,20%

The MMC specimens were fabricated using the stir casting process. In this process, the aluminium alloy was melted in a furnace and preheated SiC particles were introduced into the molten metal under continuous stirring to ensure uniform distribution. The molten composite was then poured into molds and allowed to solidify. The cast samples were then machined into rectangular work pieces suitable for drilling experiments.

3.2 Selection of Process Parameters and Levels

Based on an extensive literature review and preliminary experimentation, four key drilling process parameters were identified as critical factors influencing the machining performance of Al6061/SiC metal matrix composites. These parameters include spindle speed, feed rate, tool diameter, and reinforcement percentage. The selection of these variables was guided by their direct impact on cutting mechanics, material removal behaviour, and surface integrity during drilling operations.

To systematically evaluate their effects, each parameter was investigated at three distinct levels, ensuring a comprehensive representation of the operating range and enabling the capture of both linear and interaction effects on performance characteristics. The chosen levels were finalized to maintain practical relevance and machining stability during experimentation. The detailed parameter levels and their corresponding values are presented in Table 2, which forms the basis for the subsequent experimental design and analysis.

Table 2 Process Parameters and Levels

Parameter	Level 1	Level 2	Level 3
Spindle Speed (rpm)	800	1200	1600
Feed Rate (mm/rev)	0.1	0.2	0.3
Tool Diameter (mm)	6	8	10

Reinforcement (%)	5	10	15
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These process parameters were selected because they significantly influence thrust force, material removal rate, and surface roughness during drilling operations.

3.3 Design of Experiments Using Taguchi Method

The experimental design was developed using the Taguchi L9 orthogonal array. This design allows the study of four parameters at three levels with only nine experimental runs, thereby reducing experimental cost and time while maintaining accuracy.

The orthogonal array ensures balanced representation of all parameter combinations and enables the evaluation of individual parameter effects independently. The experimental layout was generated as shown in Table 3 and trials were conducted accordingly.

Table 3 Taguchi L9 Orthogonal Array

Experiment No.	Spindle Speed (rpm)	Feed Rate (mm/rev)	Tool Diameter (mm)	Reinforcement (%)
1	800	0.1	6	0
2	800	0.2	8	3
3	800	0.3	10	6
4	1200	0.1	8	6
5	1200	0.2	10	0
6	1200	0.3	6	3
7	1600	0.1	10	3
8	1600	0.2	6	6
9	1600	0.3	8	0

The design matrix was generated ensuring balanced representation of all parameter combinations.

3.4 Experiential Methodology

The drilling experiments were conducted on a CNC Vertical Machining Centre (VMC), which offers high precision, rigidity, and repeatability. Figure 1 (a) shows the cast MMC piece. Figure 1(b) shows the work pieces cut from the MMC piece for carrying out the drilling operation. Figure 1 (c) shows the work pieces after drilling.





(a)

(b)

(c)

***Fig. 1 Work Material (a) Developed MMC (b) Work Pieces before drilling
(c) Work Pieces after drilling***

The work piece was clamped firmly on the machine table to avoid vibration and ensure accuracy. Carbide drill bits of specified diameters were used for machining.



Fig. 2 Carbide Drill Bits

Figure 2 shows the carbide drill bits of three different diameters used for the experimental work. Drilling operations were carried out under dry conditions to evaluate the intrinsic machinability of the MMC material.

A systematic experimental procedure was adopted to ensure accuracy, repeatability, and consistency throughout the drilling trials. Initially, the Al6061/SiC metal matrix composite workpieces were prepared to the required dimensions as per the experimental specifications. The prepared specimens were then securely mounted and properly aligned on the table of the CNC Vertical Machining Centre (VMC) to minimize positional errors and vibrations during machining.

Once the setup was completed, the drilling operations were carried out for each experimental run under controlled conditions. After the completion of each trial, the output response parameters, including thrust force, material removal rate (MRR), and surface roughness, were measured using suitable instruments. This structured procedure ensured reliable data acquisition for further statistical analysis and optimization



Fig. 3 Fitting the Workpiece and Drill Bit On VMC

Figure 3 shows the mounting of the work piece and drilling tool on the VMC. The drilling performance was evaluated using three primary response parameters, thrust force, material removal rate (MRR) and surface roughness (Ra). Thrust force generated during drilling was measured using a dynamometer shown in Figure 4.



Fig. 4 Dynamometer

It is one of the most critical parameters influencing tool wear, dimensional accuracy, and potential damage to the composite. MRR was calculated using the weight difference method. Surface roughness was measured using a surface roughness tester Mitutoyo SJ-201.

4. Results and Discussion

The drilling experiments were conducted based on the Taguchi L9 orthogonal array to evaluate the influence of spindle speed, feed rate, tool diameter, and reinforcement percentage on drilling performance of Al6061/SiC metal matrix composites. The response parameters considered include thrust force, material removal rate (MRR), and surface roughness (Ra).

The experimental results were analyzed using and Analysis of Variance (ANOVA) to determine the significance of process parameters and identify optimal machining conditions.

4.1 Effect of Process Parameters on Thrust Force

Thrust force is a critical parameter in drilling operations, as it directly influences tool wear, hole quality, and dimensional accuracy. The variation of thrust force with respect to process parameters is illustrated through main effect plots.

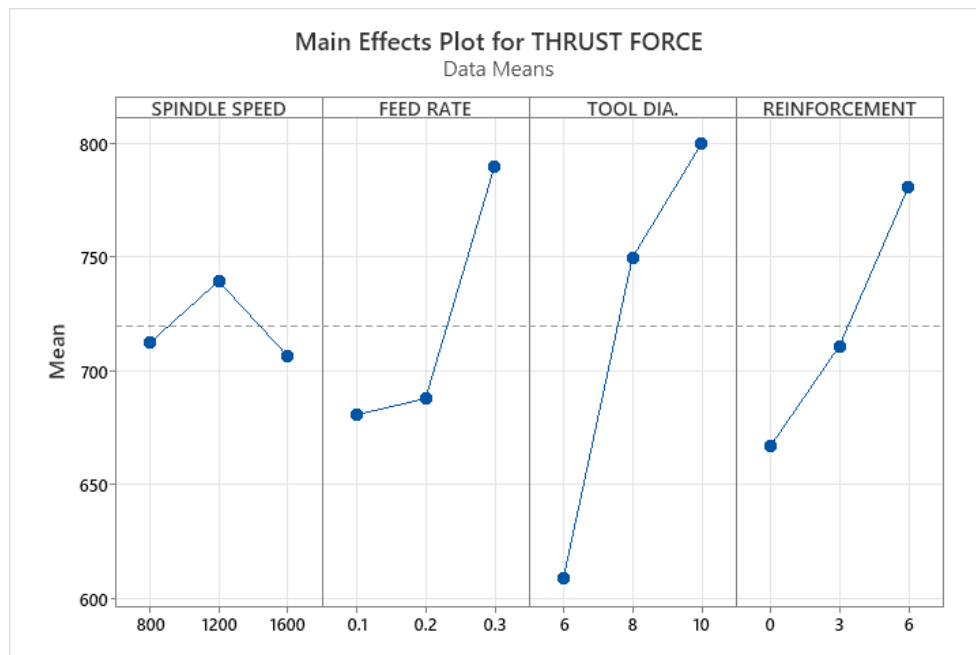


Fig. 5 Effect of Drilling process parameters on Thrust Force

The impact of process parameters, particularly spindle speed, feed rate, tool diameter, and reinforcement percentage, on thrust force during the drilling of Al6061/SiC MMCs is represented in Fig.5. It is apparent that the feed rate has the most significant effect, with thrust force considerably increasing as the feed rate rises. This observation is backed by the understanding that higher feed rates involve greater material removal per revolution, which leads to increased cutting resistance and, consequently, higher thrust forces [2]. The graph shows a steady increase in thrust force from the lowest to the highest feed rate levels, with a steep slope emphasizing the predominant effect. In contrast, spindle speed displays an inverse relationship with thrust force; as spindle speed increases from 800 to 1600 rpm, the thrust force decreases, a phenomenon attributed to the thermal softening effect that reduces cutting resistance, thereby facilitating easier drill bit penetration [9]. This is visually confirmed by the downward trend in the corresponding plot. Additionally, tool diameter influences thrust force; larger diameters (10 mm) yield higher thrust forces compared to smaller diameters (6 mm), mainly due to an increased contact area and enhanced cutting engagement with the workpiece [10]. Finally, reinforcement percentage exhibits a positive relationship with thrust force; a higher SiC content (15%) results in an increase in thrust force due to the abrasive nature of SiC particles, which resist cutting and elevate tool loading [1]. These findings validate that feed rate is the most significant parameter influencing thrust force, followed by reinforcement content and tool diameter, while spindle speed has a lesser impact. Understanding these interactions is vital for optimizing machining parameters to effectively balance productivity and tool longevity.

4.2 Effect of Process Parameters on Material Removal Rate (MRR)

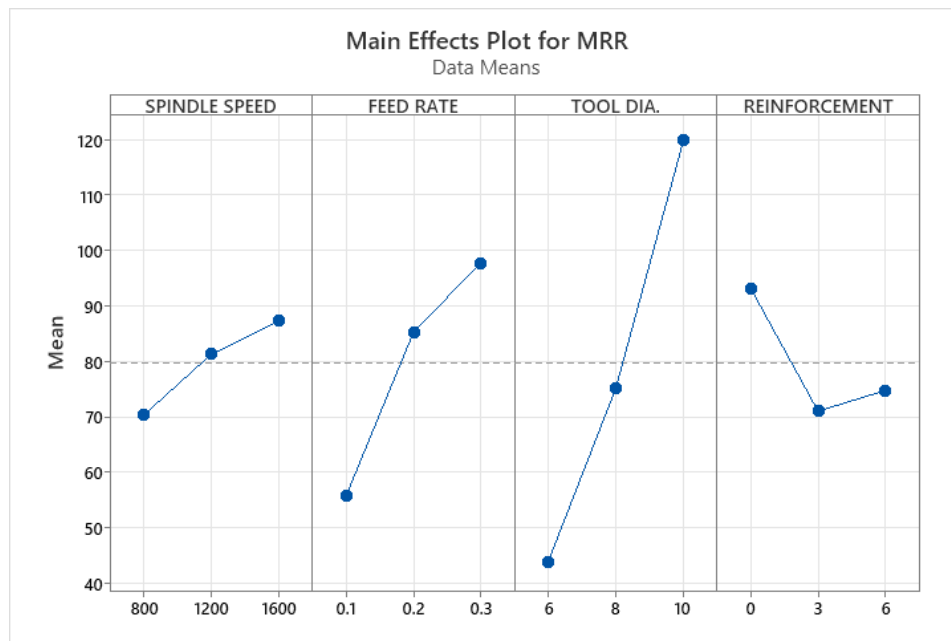


Fig. 6 Effect of Drilling process parameters on MRR

The impact of various process parameters on the Material Removal Rate (MRR) during the drilling of Al6061/SiC Metal Matrix Composites (MMCs) is depicted in the main effect plot, Fig. 6. The results distinctly show that the feed rate has the most substantial effect on MRR, with elevated feed rates leading to greater material removal. This is due to the fact that larger feed rates enable a higher volume of material to be cut per revolution, which inherently boosts productivity [2]. The trend illustrated in the plot demonstrates a steady upward movement as the feed rate increases from 0.1 mm/rev to 0.3 mm/rev, emphasizing its significant influence. In addition, spindle speed has a moderate effect on MRR; as the spindle speed rises from 800 to 1600 rpm, a minor increase in MRR is observed. Higher spindle speeds enhance cutting efficiency by diminishing cutting forces and increasing the rate at which material is machined away [11], which accounts for the trend depicted in the graph.

The tool diameter also plays a significant role in affecting MRR; larger diameters (10 mm) remove more material per pass compared to smaller diameters (6 mm), due to increased cutting engagement and a larger active cutting surface area [10]. This trend is clearly illustrated in the graph, which depicts a consistent rise in MRR as tool sizes increase. Conversely, the percentage of reinforcement has a negligible impact on MRR; an elevated SiC content (15%) marginally decreases MRR, probably due to the enhanced abrasive characteristics of SiC particles that resist cutting and contribute to increased tool wear, thereby impeding material removal [1]. The graph's slight fluctuations with varying reinforcement content corroborate this minor effect. In summary, the analysis verifies that the feed rate is the predominant factor affecting MRR, with tool diameter acting as a notable secondary factor, while spindle speed and reinforcement content exert comparatively lesser influences. These findings are crucial for refining drilling parameters to achieve a balance between high productivity and tool durability [2].

4.3 Effect of Process Parameters on Surface Roughness

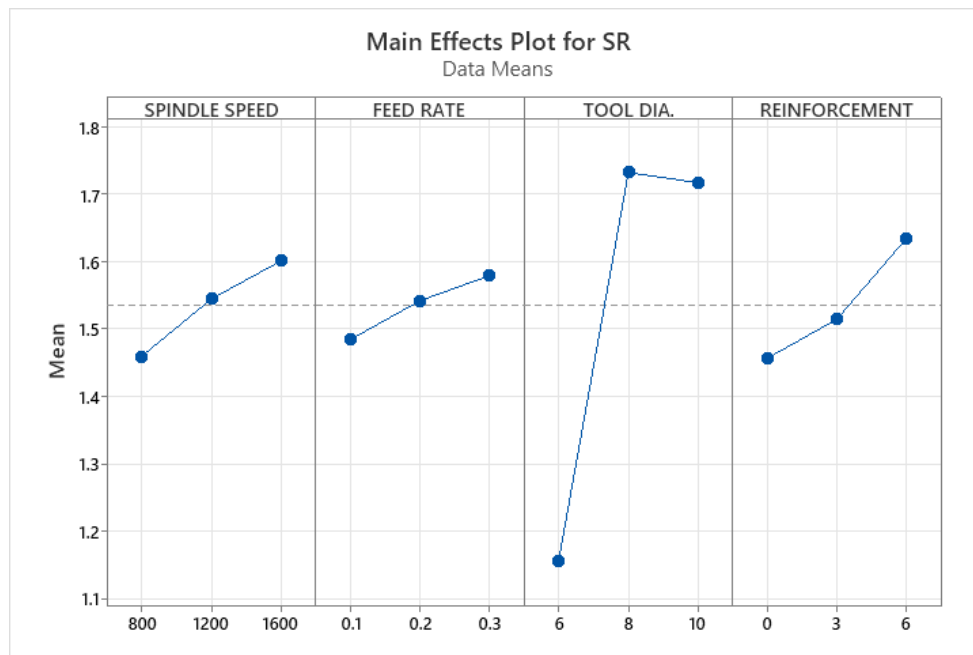


Fig. 7 Effect of Drilling process parameters on Surface Roughness

The impact of process parameters on surface roughness (Ra) is critical for defining the functional performance and finishing quality of drilled holes in Al6061/SiC MMCs. As shown in Figure 7, the main effect plot demonstrates that the feed rate has the most pronounced effect on surface roughness. An increase from 0.1 mm/rev to 0.3 mm/rev leads to a significant increase in Ra values. This is attributed to the fact that higher feed rates result in more noticeable feed marks and irregular chip formation, which contribute to a rougher surface finish [3]. The enhanced cutting resistance and greater material engagement at elevated feed rates result in heightened surface irregularities and micro-cracks, thereby compromising the quality of the machined surface.

Conversely, the spindle speed positively influences surface roughness. An increase in spindle speed from 800 rpm to 1600 rpm results in lower Ra values, suggesting an improvement in surface quality. Elevated spindle speeds encourage smoother cutting processes and lessen the occurrence of built-up edges, which contributes to a decrease in surface waviness and micro-roughness. [10] The thermal softening of the aluminum matrix at increased speeds reduces cutting forces and minimizes surface flaws, thus supporting the attainment of finer surface finishes.

The graph further illustrates that larger tool diameters, for instance, 10 mm, generally yield superior surface finishes in comparison to smaller diameters such as 6 mm. This phenomenon can be attributed to the fact that larger tools provide enhanced rigidity and stability throughout the machining process, which in turn minimizes vibrations and oscillations that may result in surface imperfections. The increased stiffness associated with larger tools effectively reduces micro-vibrations, resulting in smoother surface finishes.

In contrast, an increase in the percentage of reinforcement (from 5% to 15% SiC) negatively impacts surface roughness, evidenced by elevated Ra values at higher levels of reinforcement. The abrasive and heterogeneous characteristics of SiC particles hinder cutting action, leading to micro-cracking, particle pull-out, and increased surface micro-roughness [1]. Furthermore, these particles can create micro-defects that undermine surface integrity and contribute to greater roughness.

In conclusion, the findings indicate that utilizing lower feed rates along with higher spindle speeds is beneficial for achieving enhanced surface finishes in the drilling of metal matrix composites (MMCs). The interaction of well-optimized cutting parameters minimizes surface imperfections, improves product quality, and increases the lifespan of tools. Moreover, the analysis suggests that careful calibration of these parameters can lead to notable enhancements in the overall drilling efficiency. Thus, the study emphasizes the significance of these factors in the effective machining of MMCs. [3].

4.4 Analysis of Variance (ANOVA)

ANOVA was performed to determine the statistical significance of each process parameter on the response variables.

Table 4 ANOVA for Thrust force

Source	DF	Adj SS	Adj MS	F-Value	P-Value
FEED RATE	1	717973	717973	21.26	0.019
TOOL DIA.	1	14013	14013	0.41	0.565
REINFORCEMENT	1	11218	11218	0.33	0.605
SPINDLE SPEED	2	50360	25180	0.75	0.546
Error	3	101310	33770		
Total	8	894875			

The ANOVA shows feed rate is the most significant factor affecting thrust force, with higher feed rates increasing the force due to more material removal. Spindle speed reduces thrust force by softening the material at higher speeds. Tool diameter and reinforcement percentage have lesser effects and are less statistically significant. The regression model (1) confirms feed rate as the main influence on thrust force during drilling.

$$\text{Force(N)} = 181 - 0.0073 \text{ spindle speed} + 544 \text{ feed rate} + 47.7 \text{ tool dia.} + 18.94 \text{ reinforcement} \quad (1)$$

Table 5 ANOVA for MRR

Source	DF	Adj SS	Adj MS	F-Value	P-Value
FEED RATE	1	2630.7	2630.7	13.92	0.034
TOOL DIA.	1	8650.2	8650.2	45.79	0.007
REINFORCEMENT	1	504.7	504.7	2.67	0.201
SPINDLE SPEED	2	445.5	222.8	1.18	0.419
Error	3	566.8	188.9		
Total	8	12798.0			

Table 5 displays ANOVA for MRR. Tool diameter has the strongest effect on MRR, with larger diameters increasing material removal. Feed rate also significantly impacts MRR, with higher rates improving productivity. Spindle speed and reinforcement percentage have minimal influence, indicated by higher p-values. The regression equation (2) highlights tool diameter and feed rate as key parameters for optimizing MRR.

$$\text{MRR (mm}^3\text{/min)} = -1.7 + 0.0212 \text{ spindle speed} + 353.9 \text{ feed rate} - 4.59 \text{ tool dia.} + 7.84 \text{ reinforcement} \quad (2)$$

Table 6 ANOVA for SR

Source	DF	Adj SS	Adj MS	F-Value	P-Value
FEED RATE	1	0.00570	0.00570	0.00	0.949
TOOL DIA.	1	0.10375	0.10375	0.09	0.786
REINFORCEMENT	1	0.59661	0.59661	0.50	0.529
SPINDLE SPEED	2	0.56873	0.28436	0.24	0.800
Error	3	3.54542	1.18181		
Total	8	4.82021			

The Table 6 displays ANOVA for surface roughness. None of the parameters—feed rate, tool diameter, spindle speed, or reinforcement percentage—significantly affect surface roughness, as their p-values are high. Reinforcement percentage has the least effect. The regression model (3) suggests Ra remains relatively unaffected within the tested ranges, indicating other factors may influence surface finish.

$$\text{Surface Roughness (Ra)} = 0.019 + 0.000177 \text{ spindle speed} + 0.472 \text{ feed rate} + 0.1402 \text{ tool dia.} + 0.0295 \text{ reinforcement} \quad (3)$$

5. Conclusions

This research offers an in-depth insight into the machining characteristics of Al6061/SiC metal matrix composites, emphasizing the considerable influence of critical process parameters on drilling efficiency. The conducted experimental studies and statistical evaluations reveal that the feed rate is the most significant factor affecting all response variables, particularly leading to an increase in thrust force and surface roughness, while also improving the material removal rate (MRR). This highlights the necessity of optimizing the feed rate to attain a suitable equilibrium between productivity and surface quality.

The spindle speed plays a crucial role in improving surface finish and reducing cutting forces, primarily due to the thermal softening effects that facilitate smoother cutting processes. Conversely, the diameter of the tool has a beneficial impact on material removal rate (MRR) but simultaneously increases cutting forces due to the larger contact area, necessitating a careful evaluation of trade-offs according to specific application requirements. An increase in the percentage of reinforcement significantly enhances thrust force while adversely affecting surface quality, a situation that can be explained by the abrasive and hard nature of SiC particles, which contribute to accelerated tool wear and surface damage.

The research illustrates the effectiveness of the Taguchi design and ANOVA in successfully determining optimal machining parameters, thereby decreasing experimental workload while ensuring reliable predictions. The regression models formulated show a strong correlation with experimental findings and act as essential instruments for process optimization.

Importantly, the findings emphasize the inherent trade-offs between manufacturing efficiency and surface integrity. Higher material removal rates can be achieved at the expense of increased surface roughness and tool wear, while prioritizing surface quality may limit productivity. These insights are crucial for developing tailored machining strategies in industrial contexts, especially in high-performance sectors like aerospace and automotive engineering where component quality and operational efficiency are paramount.

In summary, this study not only enhances the basic comprehension of MMC drilling behavior but also provides actionable recommendations for optimizing processes. The application of these findings can greatly improve tool longevity, surface finish, and overall

productivity, thereby facilitating the broader industrial use of aluminium-based composites that contain difficult reinforcement materials in rigorous applications.

References (Chicago Style)

1. Surappa, M. K. 2003. "Aluminium Matrix Composites: Challenges and Opportunities." *Sadhana* 28 (1-2): 319-334.
2. Miracle, D. B. 2005. "Metal Matrix Composites – From Science to Technological Significance." *Composites Science and Technology* 65: 2526-2540.
3. Teti, R. 2002. "Machining of Composite Materials." *CIRP Annals* 51 (2): 611-634.
4. Davim, J. P. 2013. *Machining of Composite Materials*. London: Springer.
5. Hocheng, H., and C. C. Tsao. 2005. "The Path Towards Delamination-Free Drilling of Composite Materials." *Journal of Materials Processing Technology* 167: 251-264.
6. Jain, V. K. 2002. "Advanced Machining Processes." New Delhi: Allied Publishers.
7. Ramulu, M., D. K. Pedersen, and J. L. Briggs. 2002. "Drilling of Aluminium/Al₂O₃ Metal Matrix Composites." *Journal of Materials Processing Technology* 124: 244-254.
8. Thamban, I., et al. 2014. "Machining of Al6061-T6 Using Diamond Coated Tools." *Procedia Engineering* 97: 1550-1559.
9. Rajmohan, T., K. Palanikumar, and S. Ranganathan. 2011. "Optimization of Machining Parameters in Drilling Hybrid MMCs." *Journal of Composite Materials* 45: 1179-1190.
10. Kumar, R., et al. 2015. "Optimization of Drilling Parameters for Al/B₄C Composites Using Taguchi Method." *Materials Today: Proceedings* 2: 2640-2647.
11. Bammidi, R., et al. 2020. "Optimization of Drilling Parameters Using Taguchi Technique." *Materials Today: Proceedings* 27: 2391-2396.
12. Narale, M. N., et al. 2018. "Drilling of Hybrid Metal Matrix Composites Using Grey Relational Analysis." *Materials Today: Proceedings* 5: 18545-18552.
13. Senthil Babu, S., et al. 2019. "Drilling Performance of Al/SiC/Mica Hybrid MMCs." *Journal of Manufacturing Processes* 37: 583-593.
14. Waleed, W. A., et al. 2018. "Friction Drilling of Metal Matrix Composites." *Journal of Manufacturing Processes* 32: 265-274.
15. Doomra, V. K., et al. 2014. "Finite Element Modeling of Drilling of MMCs." *Procedia Materials Science* 6: 1800-1807.
16. Langella, A., et al. 2004. "Analytical Study of Drilling Forces in Composite Materials." *Composites Part A* 35: 1021-1029.
17. Parasuraman, S., et al. 2021. "Machinability Study of AA7075/TiB₂ MMCs." *Materials Today: Proceedings* 46: 7843-7848.
18. Palanikumar, K., et al. 2021. "Machining Behavior of Hybrid Aluminium MMCs." *Journal of Materials Research and Technology* 12: 1410-1422.
19. Singh, P., et al. 2016. "Abrasive-Assisted Drilling of Metals." *Procedia Engineering* 149: 454-461.
20. Davim, J. P., ed. 2008. *Machining: Fundamentals and Recent Advances*. London: Springer.