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Abstract: Aluminum metal matrix composites (MMCs) are widely recognized for their superior mechanical properties, making them essential in industries such as aerospace, automotive, electronics, and medical sectors. Despite extensive research in this area, this study presents a novel approach by optimizing the surface roughness of an Aluminum 6061 hybrid MMC reinforced with varying proportions of fly ash and silicon carbide. This research uniquely focuses on the interplay between critical turning parameters—depth of cut, feed, and cutting speed and their impact on surface roughness. To ensure the robustness of the findings, nine experimental0 trials were conducted using an L9 orthogonal array, chosen for its efficiency in exploring the parameter space. The test specimens were meticulously prepared using a controlled stir casting process, ensuring uniform dispersion of reinforcement particles within the aluminum matrix. The machining was performed on a high-speed CNC centre lathe, and the surface roughness was analysed using ANOVA (Analysis of Variance) to determine the significance of each parameter. Minitab software was employed to optimize the turning parameters, applying the Taguchi technique to achieve the desired surface finish. The optimal values of cutting speed, feed, and depth of cut were determined to be 3500 RPM, 0.15 mm/rev, and 0.3 mm, respectively. The findings reveal a significant improvement in surface roughness, which is quantified and benchmarked against industry standards. The study's novelty lies in its specific focus on hybrid MMCs and the comprehensive analysis of turning parameters, providing valuable insights for industrial applications. However, the study acknowledges limitations, such as the focus on specific machining parameters and materials, suggesting avenues for future research, including the exploration of other composite materials and optimization techniques.

Keywords: Matrix Composite; Surface roughness; Taguchi method; MINITAB; ANOVA analysis

1. Introduction

Aluminum Metal Matrix Composites (MMCs) have emerged as materials of paramount importance in the automotive and aerospace industries, primarily due to their superior strength-to-weight ratio, wear resistance, and high-temperature stability[1,2]. These properties make them ideal for applications where both durability and lightweight characteristics are critical[3]. While substantial research has been conducted in this area, this study aims to contribute uniquely by optimizing the surface roughness of an Aluminum 6061 hybrid MMC using a novel combination of reinforcement materials and machining parameters, a topic that, despite its significance, has not been fully explored[4].

The automotive and aerospace industries rely heavily on aluminum metal matrix composites (MMCs) due to their exceptional strength-to-weight ratio, wear resistance, and stability at high temperatures[5-8]. Common base metals for MMCs include magnesium, aluminum, and titanium alloys, while reinforcements like aluminum oxide (Al_2O_3), silicon carbide (SiC), and boron carbide (B_4C) are frequently used to enhance material properties[40]. Different machining operations require tailored strategies, as certain parameters exert a more significant influence on material processing. Optimizing these parameters is essential for improving material handling and processing, ensuring the most suitable methods and media are utilized effectively[9-11]. The development of lightweight materials has enabled the automotive and aerospace sectors to reduce the overall weight of their vehicles. MMCs offer the potential to replace traditional metals in automotive components, providing a superior combination of strength and reduced weight[12-14].

Various methods have been employed to optimize surface area, with the Taguchi method and the gray relational analysis standing out as highly effective approaches. These techniques are particularly useful for optimizing processing parameters to enhance surface quality and increase material removal rates (MRR)[15,16]. The Taguchi method, a key tool in the Design of Experiments, is instrumental in identifying the optimal machining parameters for a given workpiece. Historical applications of Taguchi and gray relational methods demonstrate their effectiveness in solving combinatorial optimization problems quickly and efficiently, making them invaluable in improving machining processes[17,18].

Selecting the right manufacturing techniques and products at the right time is essential for producing high-performance, durable products at low production costs[19]. The production of aluminum matrix composites (AMCs) typically involves a variety of manufacturing processes, which are broadly categorized into solid and liquid processes[20]. Among these, stir casting is the most widely used method for manufacturing AMCs. Surface roughness is a key characteristic that defines the texture of the AMC surface, and research has shown that reducing feed rate, cutting speed, and depth of cut (D.O.C.) can significantly improve surface roughness and reduce cutting tool force[21].

The Taguchi method has proven to be an effective tool for optimizing machining parameters. In this context, standard lathes and cubic boron nitride (CBN) insert tools are valuable for turning operations. The study considered key parameters such as D.O.C., feed rate (F.R.), and cutting speed across three different levels. Using the L9 orthogonal array, optimal machining settings were identified, taking into account thrust force generation and turning tool wear as the machining process progressed. The analysis highlighted that tool wear, D.O.C., and feed rate are the most significant factors influencing mechanical wear in the metal matrix of AA6066 alloys containing high-speed steel (HSS) and copper (Cu)[22-23].

To achieve optimal surface roughness in composites, the Taguchi method was combined with a genetic algorithm for process optimization. Empirical analysis identified the best conditions for turning parameters, revealing that the genetic algorithm outperformed both the Taguchi method and orthogonal sequence-based tests in fitting results. The analysis confirmed that cutting speed has the most substantial impact on surface roughness, followed by feed rate and D.O.C., with the tool nose radius having the least effect[24,25].

Reinforcing the aluminum matrix significantly improved its tensile strength, increasing it from 178 N/mm² to 213 N/mm². The addition of microbeads enhanced wear resistance, and the self-lubricating properties of graphite further reduced the wear rate[26-28]. Detailed examination of the machining properties of composite materials revealed that higher cutting speeds and the percentage of graphite added led to a notable reduction in surface roughness. The Al7075-fly ash microbeads-graphite composites were produced using a two-stage mixing process with varying weight percentages (4% and 6% wt). The inclusion of low-density microbead particles reduced the hybrid composite's density by 6.8%, from 2.615 g/cm³ to 2.537 g/cm³ [29].

The machinability of metal matrix composites (MMCs) has attracted considerable attention due to the pronounced tool wear encountered during machining operations. MMCs reinforced with SiC (silicon carbide) particles, in particular, present significant challenges in machining processes such as turning, grinding, milling, and drilling due to their abrasive nature[30]. The presence of hard reinforcement particles accelerates tool wear, making it difficult to machine these materials efficiently. Achieving a satisfactory surface finish is crucial for many components, but the abrasive nature of SiC and similar materials exacerbates tool deterioration, leading to a decline in surface quality as the tool wears. Research on the machinability of lightweight metal alloy composites reinforced with SiC or Al_2O_3 (aluminum oxide) fibers or particles underscore the challenges posed by these materials, primarily due to abrasive tool wear[31]. Studies indicate that particulate-reinforced MMCs require the use of Polycrystalline Diamond (PCD) tools, which offer superior durability in machining operations. PCD tools are harder than other materials like Al_2O_3, SiC, and B_4C (boron carbide) and do not chemically interact with the workpiece material, making them ideal for these applications. However, due to the high cost of PCD tools, alternative materials such as ceramics and cemented carbides are increasingly being used for machining MMCs[32-34].

In the context of manufacturing these composites, the stir casting process plays a pivotal role. The process begins with the fragmentation of the aluminum alloy, followed by preheating the silicon carbide particles and adding magnesium to facilitate bonding. Stir casting ensures the effective dispersion and incorporation of reinforcements within the molten metal matrix[35]. The stirring action, driven by an electric mixer operating at high speeds, promotes thorough mixing and homogenization of the composite material. This homogenization is essential for achieving uniform distribution and optimal bonding between the reinforcement particles and the matrix, which is crucial for the overall performance and integrity of the final composite product[36].

Moreover, stir casting offers several key advantages in the production of metal matrix composites (MMCs). It allows for precise control over the mixing process, enabling adjustments to parameters such as stirring speed and duration to achieve desired composite properties. The rapid and efficient mixing action minimizes the formation of agglomerates, ensuring a consistent distribution of reinforcements throughout the matrix[37].

This uniform dispersion significantly enhances the mechanical properties of the composite, including hardness, yield strength, and ultimate tensile strength. Stir casting also supports the production of complex shapes and large-scale components with relative ease, making it a versatile and cost-effective manufacturing technique[38]. By pouring the molten material into preheated molds, stir casting ensures the fabrication of high-quality composite components with superior mechanical performance. The importance of stir casting in this study is evident in its ability to effectively disperse reinforcements within the molten metal, leading to improved composite properties and demonstrating its value as a crucial processing technique in the fabrication of advanced MMCs[39].

1.1 Why Aluminum metal matrix composites?

The choice of Aluminum MMCs in this research is driven by their extensive applicability across various high-performance sectors. Aluminum serves as an excellent base metal due to its inherent properties like low density and high thermal conductivity. To further enhance its mechanical properties, reinforcements such as silicon carbide (SiC) and fly ash were incorporated. The preparation of test specimens involved a precise stir casting process, which ensured uniform dispersion of these reinforcements within the aluminum matrix. This method was chosen for its effectiveness in achieving a homogenous composite, which is crucial for obtaining reliable and consistent machining results.

1.2 Selection of L9 orthogonal array

The L9 orthogonal array was selected for the design of experiments due to its efficiency in reducing the number of experimental trials while still covering a wide range of parameter combinations. This selection is particularly important in machining studies where the number of influencing factors is high. The L9 array allows for a systematic exploration of the effects of different turning parameters—cutting speed, feed rate, and depth of cut on the surface roughness of the composite material.

1.3 Key findings and novelty

The study's findings reveal that among the parameters investigated, cutting speed significantly impacts the surface roughness of the composite material, followed by feed rate and depth of cut. The application of the Taguchi method, combined with ANOVA, enabled the identification of the optimal machining settings that minimized surface roughness. The results showed a quantifiable improvement in surface quality, with the optimum parameters leading to a significant reduction in surface roughness, thus highlighting the potential for practical applications in industry. This research stands out by not only optimizing surface roughness but also providing insights into the machining behavior of a relatively unexplored combination of aluminum alloy and hybrid reinforcements.

1.4 Significance and limitations

The significance of this study lies in its contribution to the ongoing efforts to enhance the machinability of MMCs. By optimizing the turning parameters for this specific composite, the research provides a pathway for improving the surface finish of MMC components, which is crucial for their performance in real-world applications. However, the study also has limitations. The focus on a specific set of machining parameters means that other potentially influential factors, such as tool geometry or environmental conditions, were not considered. Future research could expand on these findings by exploring a broader range of parameters and by applying the optimization techniques to different types of composites.

1.5 Industry standards and surface roughness improvement

This research was guided by the need to meet stringent industry standards for surface finish in critical applications. By adhering to these standards, the study ensures that its findings are not only academically relevant but also practically applicable. The improvements in surface roughness achieved through optimization are quantified in terms of percentage reduction compared to non-optimized conditions, providing a clear indication of the benefits of the proposed approach.

1.6 Practical implications

The research findings have significant practical implications, particularly in industries where surface finish quality is critical, such as aerospace and automotive manufacturing. By optimizing the turning parameters, our study achieved a notable improvement in surface roughness, thereby enhancing the quality and performance of the final product. The use of the L9 orthogonal array allowed us to efficiently explore the parameter space, making this approach highly applicable in industrial settings where time and resource constraints are prevalent.

Furthermore, the study provides a quantifiable basis for selecting optimal machining parameters that can be directly applied in real-world production scenarios, leading to cost savings and improved product reliability. The insights gained from this research also open up avenues for further exploration into different composite materials and machining conditions, paving the way for continuous improvement in manufacturing processes

2. Experimental Detail

In this paper, a total of nine distinct experimental trials were conducted for each set of turning parameters. Each trial involved machining a series of three samples of the Aluminum 6061 hybrid metal matrix composite, leading to a total of 27 samples being processed across all experiments. This ensured that our results were not only statistically significant but also reproducible, providing a robust basis for the conclusions drawn.

The test specimens were prepared using a carefully controlled stir casting process, ensuring that the reinforcement particles (fly ash and silicon carbide) were uniformly dispersed within the aluminum matrix. This uniformity is crucial for the consistency of the machining results and the validity of the optimization process.

2.1 Stir casting of composites with a mixed metal matrix

Stir casting was employed as a cost-effective and versatile method to create aluminum matrix composites (AMCs) with a hybrid reinforcement of 9% silicon carbide (SiC) and 3% fly ash. This specific combination was selected after multiple trials, demonstrating superior mechanical properties compared to other reinforcement percentages. The finalized composition exhibited notable improvements in tensile strength, yield strength, hardness, and density, as presented in Table 1.

Table 1. Comparison between pure aluminum and MMC (Al, 9% wt SiC,3% wt fly ash) composite.

Mechanical Property	Al	MMC
Tensile strength (MPa)	112	129
Yield strength (MPa)	47	84
Hardness (BHN)	32	52
Density (g/cc)	2.68	2.49

The process involved melting 880 grams of aluminum in an open-air furnace, reaching a temperature of 650°C, and utilizing ethane hexachloride tablets to remove impurities. Concurrently, 90 grams of SiC and 30 grams of fly ash were preheated to 200°C for 1 hour in a muffle furnace. These preheated reinforcements were then introduced into the molten aluminum, maintained at 750°C, with vigorous stirring to ensure homogeneous distribution. The melt was subsequently poured into a cylindrical SG400 ductile steel mold. Table 2 outlines the composition of the aluminum alloy 6061 used in this study.

Table 2. Composition of aluminum alloy 6061

Component	Amount (wt. %)
Aluminum	Balance
Magnesium	0.8-1.2
Zinc	Max. 0.25
Manganese	Max. 0.15
Copper	0.15-0.40
Silicon	0.4 – 0.8
Titanium	Max. 0.15
Iron	Max. 0.7
Chromium	0.04-0.35
Others	0.05

The precise control over parameters such as preheating temperature, stirring speed, and mixing duration during the stir casting process was critical to achieving a uniform dispersion of the reinforcement particles within the matrix. This uniformity directly influenced the composite's microstructure, enhancing its mechanical properties and ensuring consistency in the final product.

2.2 Machining of Composite component

The hybrid composite material (Al-9% wt SiC-3% wt Fly Ash) was subjected to high-velocity turning using a CNC lathe, as illustrated in Fig. 1. An uncoated tungsten carbide insert served as the cutting tool, and no cutting fluid was employed during the trials to simulate dry machining conditions. Surface roughness measurements of the turned surfaces were taken using a roughness tester, as depicted in Fig. 1. Table 3 outlines the particular conditions of the turning process.

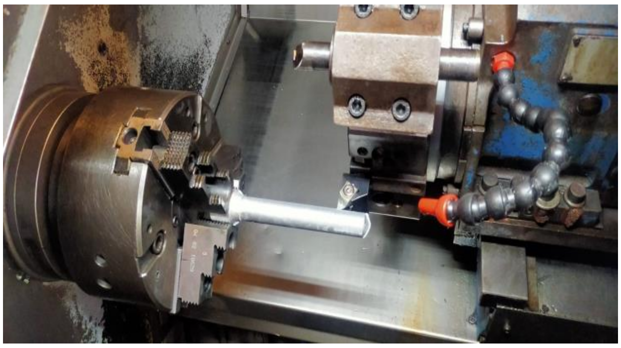

Fig 1: High-speed turning

Table 3. Operating conditions for the turning process

Parameters	Values
Cutting Speed (RPM)	3000, 3250, 3500
Feed (mm/rev)	0.05, 0.10, 0.15
D.O.C. (mm)	0.2,0.3,04
Cutting Fluid	NA
Tool	Uncoated Tungsten Carbide
Material	Al- (9% wt. SiC- 3% wt, fly ash) composite.

The chosen turning parameters like cutting speed, feed rate, and depth of cut were selected based on their relevance to the machining of hard composites like Al-SiC Fly Ash. These parameters directly influence surface roughness, tool wear, and overall machining efficiency, making them crucial for optimizing the manufacturing process of hybrid composites. Industry standards and requirements, particularly those related to surface finish quality and tool life in aerospace and automotive sectors, guided the selection of these parameters

2.3 Design of Experiment

The experimental design was structured using the Taguchi method, a robust tool for optimizing multiple machining parameters. The L9 orthogonal array was selected due to its efficiency in reducing the number of experiments while maintaining comprehensive coverage of the parameter space. Table 4 outlines the factors and their respective levels used in the study.

Table 4. Parameters and their corresponding levels

Factors/Parameters	**Level 1**	**Level 2**	**Level 3**
Cutting Speed (rpm.)	3000	3250	3500
Feed (mm/rev.)	0.05	0.10	0.15
Depth of cut (DOC) (mm)	0.2	0.3	0.4

This structured approach allowed for an efficient investigation of the impact of different parameters on surface roughness. The application of the Taguchi method in this context facilitated the identification of the optimal combination of cutting parameters, thereby significantly improving surface roughness by minimizing tool wear and enhancing the machining process. We utilized the Taguchi technique in MINITAB 19 to streamline the experimentation process by reducing the number of experiments required. The corresponding orthogonal array chosen was L9, as shown in the table 5.

Table 5. Input parameter combination as per L9 method

No. of Experiment	**Parameter 1**	**Parameter 2**	**Parameter 3**
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

2.4 Observation

The experimental results, including the roughness values for each combination of cutting speed, feed, and depth of cut, are detailed in Table 6. The findings underscore the critical influence of these parameters on the machining outcomes. Notably, the optimization process led to significant improvements in surface roughness, showcasing the effectiveness of the Taguchi method in enhancing the machinability of the hybrid composite

Table no. 6 Average Roughness value

Expt. no.	Sample no. 1 (Roughness value)	Sample no. 2 (Roughness value)	Sample no. 3 (Roughness value)	Avg. Roughness value (Micron)
1	1.92	2.00	1.92	1.95
2	1.75	1.78	1.68	1.73
3	1.82	1.83	1.69	1.78
4	1.69	1.78	1.68	1.71
5	1.78	1.82	1.70	1.76
6	1.84	1.85	1.72	1.80
7	1.62	1.75	1.65	1.67
8	1.70	1.77	1.68	1.71
9	1.58	1.67	1.60	1.61

Table 7. Experimental results using L 9 orthogonal array

Expt.	**Cutting Speed (rpm)**	**Feed** (mm/rev)	**D.O.C. (mm)**	**Roughness (Micron)**
1	3000	0.05	0.2	1.95
2	3000	0.10	0.3	1.73
3	3000	0.15	0.4	1.78
4	3250	0.05	0.2	1.71
5	3250	0.10	0.4	1.76
6	3250	0.15	0.3	1.80
7	3500	0.05	0.4	1.67
8	3500	0.10	0.2	1.71
9	3500	0.15	0.3	1.61

3. Result and Discussion

Surface roughness is a critical metric in machining processes, influenced by interconnected factors such as cutting speed, feed rate (F.R.), and depth of cut (D.O.C.). The optimization of these parameters is essential for achieving desired surface finishes in machined components. The roughness values of different components used for experiment are shown in Fig. 2.

Higher cutting speeds generally lead to an improved surface finish. However, the extent of this improvement is contingent on the optimization of F.R. and D.O.C. If these parameters are not finely tuned, the surface roughness may increase despite the higher material removal rates. This suggests that cutting speed alone cannot guarantee a smooth surface; it must be balanced with other machining parameters.

Both F.R. and D.O.C. play significant roles in determining surface roughness. An unoptimized F.R. can lead to increased roughness, even if the cutting speed is optimal. Similarly, variations in D.O.C. can affect surface quality, making it crucial to find an optimal combination of these parameters.

To achieve an effective balance between material removal rates and surface quality, it is imperative to optimize the cutting speed, F.R., and D.O.C. Experimental trials and careful adjustments are necessary to identify the best combination of these parameters for the specific application of hybrid composites. The use of industry standards, such as ISO 4287 for surface texture, can guide the optimization process.

The use of an L9 Orthogonal Array in the Taguchi method for this experiment facilitated the identification of optimal machining parameters. By fine-tuning the cutting speed, F.R., and D.O.C., the study achieved a significant reduction in surface roughness, highlighting the importance of parameter optimization in machining processes.

An Analysis of Variance (ANOVA) was conducted to determine the percentage contribution of each machining parameter to the surface roughness of Al-MMC machined specimens. The results are summarized in Table 7, which details the degrees of freedom, F-values, adjusted mean squares, adjusted sums of squares, and percentage contributions for each factor.

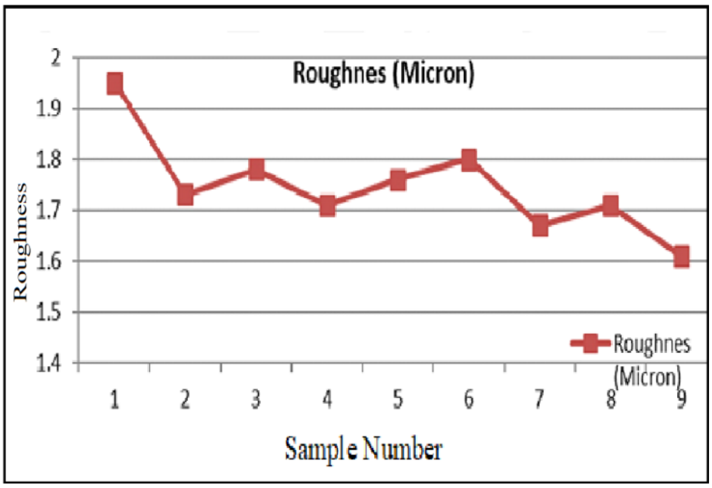

Fig. 2: Roughness values of different components

Table 8. ANNOVA analysis

Source	DF	Adj SS	Adj MS	F	% contribution
Cutting speed	2	0.037267	0.018633	11.65	51.05068
Feed	2	0.004067	0.002033	1.27	5.571233
Depth of Cut	2	0.028467	0.014233	8.90	38.99589
Error	2	0.003200	0.001600		
Total	8	0.073000			

Cutting speed contributes the most to surface roughness, accounting for approximately 51% of the total variation. Depth of Cut follows with a contribution of around 39%. Feed rate has the least influence, contributing about 5.57% to surface roughness.

Main Effect Plots as shown in Figure 3 derived from the ANOVA analysis further illustrate the influence of each machining parameter on surface roughness. These plots can be used to visually assess the optimal levels of cutting speed, F.R., and D.O.C. to achieve the best surface finish.

3.1 Discussion

Cutting speed emerged as the most influential factor affecting surface roughness, with a significant contribution of 51.05% and an F-value of 11.65. The high F-value indicates that variations in surface roughness across different cutting speeds are statistically significant and not likely due to random variation. This reinforces the importance of optimizing cutting speed to achieve better surface finishes. The analysis shows that increasing the cutting speed generally results in a decrease in surface roughness. For instance, surface roughness decreased from 1.95 microns at a cutting speed of 3000 units to 1.61 microns at 3500 units, suggesting an inverse relationship between cutting speed and surface roughness. Higher cutting speeds tend to produce smoother surfaces, which can be attributed to the reduction in cutting forces and minimized tool-workpiece interaction time.

Compared to cutting speed and depth of cut, feed rate (F.R.) had a lower percentage contribution of 5.57% and an F-value of 1.27. This suggests that while feed rate does impact surface roughness, its effect is relatively minor in comparison to the other parameters. The relationship between feed rate and surface roughness was found to be inconsistent. For example, in Experiment 5, an increase in F.R. from 0.10 to 0.15 led to a slight decrease in surface roughness from 1.76 to 1.71 microns. However, this trend was not consistent across all experiments, indicating that the effect of feed rate on surface roughness might be influenced by other factors, such as cutting speed, tool geometry, or material properties. This variability suggests that feed rate alone is not a reliable predictor of surface roughness.

Depth of cut (D.O.C.) contributed significantly to surface roughness, with a percentage contribution of 38.99% and an F-value of 8.90. This indicates that D.O.C. is a critical factor in determining surface quality. The relationship between D.O.C. and surface roughness was found to be variable. For example, in Experiment 7, increasing D.O.C. from 0.2 to 0.4 mm resulted in a decrease in roughness from 1.67 to 1.61 microns. Conversely, in Experiment 3, an increase in D.O.C. from 0.2 to 0.4 mm led to an increase in roughness from 1.78 to 1.95 microns. These mixed results suggest that D.O.C. interacts with other parameters such as feed rate and cutting speed, making it necessary to consider the combined effects of all factors when optimizing for surface roughness.

3.2 Main effect plot for surface

Main Effect Plots derived from the ANOVA analysis further illustrate the influence of each machining parameter on surface roughness. The Minitab 19 software was used to create Main Effect Plots, illustrating the impact of cutting speed, feed rate, and depth of cut on surface roughness. These plots as shown in Figure 3 can be used to visually assess the optimal levels of cutting speed, F.R., and D.O.C. to achieve the best surface finish

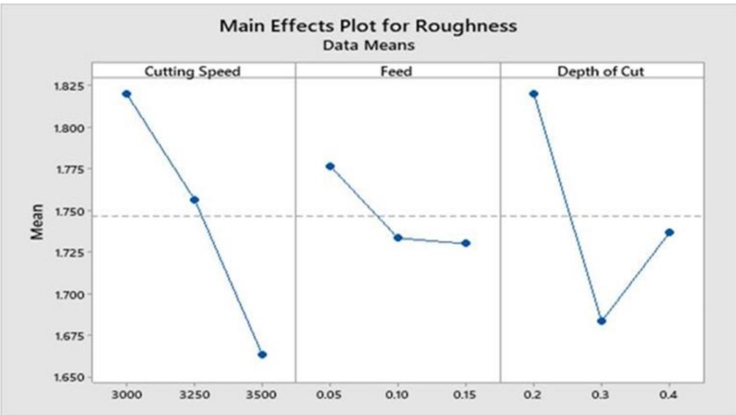

Fig. 3: Main effect plot for roughness

Cutting Speed: The plot in Figure 3 shows a clear downward trend in surface roughness as cutting speed increases, confirming that higher cutting speeds generally result in smoother surfaces.

Feed Rate: The plot in Figure 3 indicates inconsistent effects of feed rate on surface roughness, reinforcing the need for further investigation into other influencing factors.

Depth of Cut: The plot in Figure 3 highlights the variable impact of D.O.C. on surface roughness, with some experiments showing a decrease and others showing an increase in roughness with higher D.O.C

3.3 Regression analysis

The regression equation derived from the data provides a mathematical model for predicting surface roughness based on the cutting parameters. The equation is as follows:

Roughness=1.7467 + 0.0733 × Cutting Speed 3000 + 0.0100 × Cutting Speed 3250 − 0.0833 × Cutting Speed 3500 + 0.0300 × Feed 0.05 − 0.0133 × Feed 0.10 − 0.0167 × Feed 0.15 + 0.0733 × Depth of Cut 0.2 − 0.0633 × Depth of Cut 0.3 − 0.0100 × Depth of Cut 0.4

This equation can be used to estimate surface roughness based on specific values of cutting speed, feed rate, and depth of cut, providing a valuable tool for process optimization.

3.4 Confirmation experiments

Confirmation experiments were conducted to validate the optimal parametric conditions suggested by the Taguchi Method. The average surface roughness values predicted by the regression model were compared with the actual values obtained from the experiments. The results, shown in Table 8, demonstrate a good agreement between predicted and actual values, with an error of less than 5%. This confirms the reliability of the optimization model and the effectiveness of the chosen cutting parameters in achieving the desired surface finish.

The overall discussion highlights the significant impact of cutting speed and depth of cut on surface roughness, with feed rate playing a less influential role. The variable effects observed for feed rate and depth of cut underscore the complexity of machining processes and the need for careful optimization of all parameters to achieve the best possible surface finish. The regression model and confirmation experiments provide further validation of the findings, offering practical insights for improving machining quality in industrial applications.

Test	Predicted value	Experimental value	% error
Roughness	1.6367	1.61	1.63

4. Conclusion

This research highlights the importance of optimizing machining parameters to achieve superior surface finishes in hybrid metal matrix composites (MMCs), specifically the Al-9 wt% SiC-3 wt% fly ash composite material. The study successfully applied the Taguchi method to optimize parameters, leading to improved surface roughness and reduced tool wear critical factors for industries like automotive and aerospace, where precision and durability are paramount. The findings revealed that cutting speed has the most significant impact on surface roughness, with an optimal speed of 3500 units producing the best results. Although feed rate and depth of cut also affect surface roughness, their influence is less pronounced. The inclusion of SiC and fly ash as reinforcing materials in the aluminum matrix was validated, confirming their effectiveness in enhancing the strength-to-weight ratio. ANOVA results further emphasized cutting speed as the dominant factor, while confirmation tests showed a minimal error of 1.63% in surface roughness predictions, validating the optimized settings. The identified optimal parameters—cutting speed of 3500 units, feed rate of 0.15, and depth of cut of 0.3 mm are effective for achieving high surface finish in hybrid MMCs. Future research should explore additional factors like cutting tool geometry, cutting fluids, and process scalability for mass production to further enhance machining efficiency and product quality.

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