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Optimization of Machining Characteristics in Turning operation of LM2 -Al_2O_3 Metal Matrix Composite

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Abstract

The optimization of machining parameters in the turning operation of metal matrix composite (MMC) is a crucial aspect in the manufacturing process. In this research work, Taguchi Method of optimization is used to optimize the cutting parameters, which include cutting speed, feed rate, and depth of cut. The experiments are carried out according to Taguchi L9 algorithm. The optimization is based on minimizing the surface roughness. The results show that the cutting speed has the most significant effect on the responses, followed by feed rate and depth of cut. It is observed a good agreement between the predicted and actual results, indicating the effectiveness of the Taguchi method in optimizing the cutting parameters.

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Keywords

Metal Matrix Composite;

Optimization;

Surface Roughness;

Taguchi Method;

Turning.

Introduction

Metal matrix composites (MMC) are gaining importance in various industrial applications due to their superior mechanical properties compared to conventional metals. However, machining of MMC is a challenging task due to the presence of hard ceramic particles in the matrix, which leads to rapid tool wear, high cutting forces, and poor surface finish. Therefore, optimization of cutting parameters is essential to achieve a better surface finish and higher material removal rate (MRR) while minimizing tool wear and cutting forces.

The Taguchi Method is based on the idea that by optimizing a system for its "robustness" (i.e. its ability to perform well even in the face of variability and other sources of uncertainty), it is possible to achieve better performance and quality. This is in contrast to traditional approaches that focus on optimizing for nominal or average performance, and that may not take into account the effects of variability and other sources of uncertainty. Optimization of parameters affecting the output of an experiment is the major concern of Taguchi method.

In this research paper, the Taguchi method is used to optimize the cutting parameters in the turning operation of LM2 - Al_2O_3 metal matrix composite fabricated by squeeze casting process. The cutting parameters considered are cutting speed, feed rate,

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and depth of cut. The response variable is surface roughness. The experiments were carried out according to Taguchi L9 algorithm, and the results are analyzed using analysis of variance (ANOVA).

Literature Survey

The optimization of cutting parameters for metal matrix composites (MMCs) is crucial to achieve better machining performance, such as higher material removal rate, lower cutting forces, and surface roughness. The Taguchi method and response surface method (RSM) are the widely used methods for optimizing the cutting parameters of MMCs. RSM is a statistical approach that can efficiently model the relationships between the cutting parameters and machining responses, and then optimize the parameters to achieve the desired machining responses.

Several studies have utilized RSM to optimize the cutting parameters of MMCs, including aluminum-based MMCs. The machining operations used were turning, drilling, milling etc. The following review focuses on the articles in which RSM is used for optimization of various cutting parameters.

The study by Muhammad Yusuf *et al*[1] examines the impact of cutting parameters on response factors during turning of aluminium alloy 7050 using the response surface methodology to create and refine mathematical models of surface roughness (Ra) and tool usage. They found with an increase in feed rate and cutting speed, the surface roughness increased. Low cutting speed, feed rate, and depth of cut ranges were where the low surface roughness was discovered.

Using the desirability function, the ideal combination of turning parameters was found. Use of cutting parameters such as cutting speed 40 m/min, feed rate 0.1 mm /rev, and depth of cut 0.5 mm could result in the minimum surface roughness of 0. 363 m. For the purpose of turning, RSM was applied to AISI 410 steel in the work.[2] To examine how machining factors affect surface roughness (Ra), a quadratic model has been created. The feed rate, followed by the tool nose radius and cutting speed, has the greatest impact on the surface roughness. The surface roughness is not significantly impacted by depth of cuts.

In a review study by Ranganath M S *et al*[3] it was found that the surface roughness consistently decreased as cutting speed increased, but surface roughness significantly worsened as feed rate and depth of cut rose. The Response Surface Methodology results offered an organised, effective, and simple strategy for the cutting process optimization. The study looked into applying RSM technique to optimise turning operation parameters for the developed material AlSi10Mg/SCBA/SiC.

The study used RSM technique[3] to examine the optimization of turning operation parameters for the created material AlSi10Mg/SCBA/SiC. The mechanical properties of the base AlSi10Mg alloy are improved by the addition of reinforcement particles SCBA and SiC, increasing the hardness value from 102.7 BHN to 129.8 BHN and the tensile strength value from 138.9 MPa to 161.7 MP.

In another study[5] at low spindle speeds, the formation of BUE significantly affected tool wear, but thermal softening was crucial at higher spindle speeds and feed rates. Low feed rate ranges, low spindle speed, a small percentage of silicon carbide, and shallow cuts all resulted in less tool wear.

According to the study by Elssawi Yahya *et al*,[6] cutting speed has a little effect on surface roughness, whereas feed rate and depth of cut have the greatest effects. The parameters were finally adjusted to achieve the desired level of surface roughness, and the optimization error (residual) was constrained to values between -0.02 and 0.02 m.

Srinivasan, M., P *et al*[7] aimed to optimize the cutting parameters, such as cutting speed, feed rate, and depth of cut, in turning aluminum reinforced with silicon carbide MMCs using the Taguchi method. The authors found that the optimal cutting parameters resulted in a significant reduction in surface roughness and improved the material removal rate. In their experiment, Deepak *et al*[8] optimized the cutting parameters in turning Al 7075 matrix reinforced with titanium diboride particles using the Taguchi design method. The authors found that the optimal cutting parameters improved the surface finish and material removal rate, while reducing tool wear.

Aravindan *et al*[9] in their research, focused on the optimization of the cutting parameters in turning MMCs using the Taguchi method. The authors found that the optimal cutting parameters reduced the surface roughness and improved the material removal rate, while minimizing tool wear.

Kishore *et al*[10] aimed to optimize the machining parameters of Al-Mg-SiC MMCs in the turning process using response surface methodology. The authors found that the optimal machining parameters resulted in a significant reduction in surface roughness and improved the material removal rate.

In another study, Kumar, G., Garg *et al*,[11] the authors optimized the machining parameters in turning Al 6061 matrix reinforced with SiC MMCs using the Taguchi method. The authors found that the optimal machining parameters improved the surface finish and material removal rate while reducing tool wear.

Islam, M. S., Dhar *et al*[12] conducted the experiments and aimed to optimize the cutting parameters of aluminum matrix composites reinforced with silicon carbide particles during turning operation using the Tag.

In the experimentation cariied out by Dwivedi, S. K., & Kumar, S,[13] to optimize the machining parameters of aluminum matrix composites reinforced with Al_2O_3 and ZrB_2 particles using the Taguchi method during the turning operation. The authors found that the optimal machining parameters improved the surface finish and material removal rate, while minimizing tool wear.

The research conducted by Punnathat Bordeenithikasem *et al*[14] is important because it offers a deeper understanding of the mechanisms that control microstructure formation in amorphous metal matrix composites. The results suggest that the laser parameters, such as the laser power and scanning speed, significantly affect the microstructure and phase transformation of the material.

Fenjun Liu *et al*[15] presented a comprehensive analysis of the corrosion and tribological behavior of AZ31 magnesium matrix composites, highlighting the effect of particle reinforcement on these properties. The results suggest that the addition of particles can significantly improve the corrosion resistance and tribological behavior of magnesium composites. In this research work, turning operations on the squeeze casted metal matrix composites were conducted and surface roughness of the specimens were tested. Surface roughness is used as the response and the cutting parameters, cutting speed, feed rate and depth of cut were the input variables. The effect of these variables on the response surface i.e. surface roughness has been studied.

Experimental Setup

Material and Machining

The workpiece material used in the experiments is LM2 - Al_2O_3 metal matrix composite fabricated by squeeze casting process. Metal matrix composite specimens were fabricated using LM2 as the matrix and particulate Al_2O_3 as the reinforcement. Table 1 displays the matrix's chemical constituents as an aluminium alloy (LM2). Al_2O_3 is used as reinforcement, with an average particle size of 40μ. Using varying reinforcement weight percentages (R1=2%, R2=3%, and R3=5%) and squeezing pressures (P1=100kg/cm^2, P2=200kg/cm^2, and P3=300kg/cm^2), a total of thirteen specimens were prepared (see to fig. 1). The die is kept at a constant temperature of 180°C.

Table 1: Chemical analysis of LM2 matrix

Sr.No.	Element	Observed Value
1	% Mn (Mangenese)	0.16
2	% Si (Silicon)	9.64
3	% Cr (Chromiun)	0.030
4	%Ni (Nickel)	0.070
5	%Cu (Copper)	1.34
6	%Sn (Tin)	< 0.010
7	%Pb (Lead)	0.30
8	% Al (Aluminium)	Remainder
9	%Fe (Iron)	0.80
10	%Zn (Zinc)	0.89
11	%Mg (Magnesium)	< 0.030
12	Ti (Titanum)	0.045
13	Total other elements	< 0.50

As a comparison to the squeeze cast metal matrix composite, two specimens were also manufactured as pure alloys but without any reinforcing R0 or squeezing pressure P0.

Fig.1: Specimens made by altering the weight percentage of reinforcement & squeeze pressure

Table 2: CNC machine Specifications

1	Make	LMW- SMARTURN
2	Max Turning Length	262 mm
3	Max Turning Diameter	200 mm
4	Swing over bed	480 mm
5	Max. Chuck Diameter	169 mm
6	Turret No. of Stations	8
7	Tool Shank Size	20 x 20 mm
8	Controller	Fanuc
9	Max Spindle Speed	4500 rpm
10	Spindle Motor Power	Fanuc 5.5 / 7.5 kW
11	Machine Size mm	2275 x 1640 x 1620

	**TaeguTec Turning Insert TNMG 160408 MT Grade TT7310** Type: Turning Insert Grade: TT7310 ISO Designation: TNMG 160408 MT Style: TNMG Insert IC Size Id: 9.52 mm

Fig. 2: Tool Insert Specifications

Machining procedures have been carried out after all specimens have been prepared. On a CNC turning centre, simple turning operations have been performed without using the coolant.

The turning process is completed using CNC (SMARTRUN, Fanuc-5.5/7.5, Spindle Speed 4500 rpm) in dry machining circumstances. The features of the CNC machine are listed in Table 2. The specimens were spun at three different cutting speeds of 1000, 2000, and 3000 rpm, with feed rates of 0.12, 0.15, and 0.18 mm/rev. 0.25 mm, 0.50 mm, and 0.75 mm were chosen as the machining depths of cut. To prevent fluctuation in tool shape and the impact of resharpening on the number of readings during machining, a tungsten carbide-tipped shank is used. The tool insert parameters are shown in Figure 2. For each run, the average surface roughness Ra is recorded. A surface roughness tester, the Mitutoyo SJ-210, is used to measure the surface roughness of each specimen.

Fig. 3: Squeeze cast specimens after turning operations

Figure 3 depicts the squeeze cast specimens following the machining/turning process. It demonstrates the castings' improved surface finish and free of porosity. Fig 4 (a) shows the macrophotograph of specimen P0R0 with highest surface roughness 14.255 μ and Fig. 4 (b) shows the macrophotograph of the specimen P3R1 with lowest surface roughness 1.514 μ.

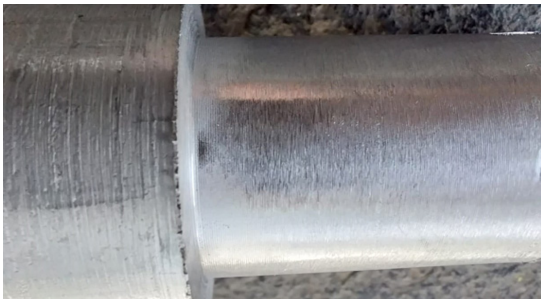


Fig. 4: (a) Macrophotograph of Machined Specimen P0R0-Ra=14.255 μ

Fig. 4: (a) Macrophotograph of Machined Specimen P3R1-Ra=1.514 μ

Experimental Procedure

Design of Experiments

Taguchi's L9 Orthogonal Array (OA) experimental design, which consists of 9 combinations of spindle speed (S), longitudinal feed rate(F), and depth of cut,(D) has been used in the experiments. In the current work, Taguchi's L9 Orthogonal Array design of experiment has been determined to be suitable. It takes into account that three process parameters can vary at three different levels. Table 3 demonstrates the experimental layout and table 4 shows the Selection of Cutting parameters as per DoE.

Table 3 Cutting Parameters and their levels

Levels	Speed (S) rpm	Feed rate (F) mm/rev	Depth of cut (D) mm
1	1000	0.12	0.25
2	2000	0.15	0.50
3	3000	0.18	0.75

27 runs were carried out on every specimen (Table4) as per DOE. There were 13 specimens, hence the total 352 runs were carried out.

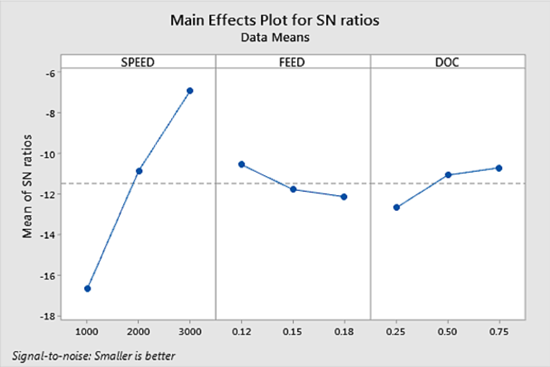
Experimental Procedure

The experiments were carried out on a CNC lathe using a tungsten carbide insert (ISO designation: TNMG 160408 MT). The workpiece is mounted on the lathe, and the cutting parameters are set according to the design of experiment. The cutting parameters are controlled using the CNC program, and the experiments are carried out under dry cutting conditions.

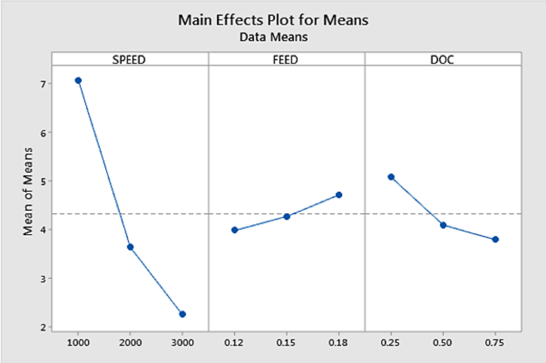
Table 4: Selection of Cutting parameters as per DoE

Sr. No.	Speed	Feed	DOC	Sr.No.	Speed	Feed	DOC	Sr. No.	Speed	Feed	DOC
1	S1	F1	D1	10	S2	F1	D1	19	S3	F1	D1
2	S1	F1	D2	11	S2	F1	D2	20	S3	F1	D2
3	S1	F1	D3	12	S2	F1	D3	21	S3	F1	D3
4	S1	F2	D1	13	S2	F2	D1	22	S3	F2	D1
5	S1	F2	D2	14	S2	F2	D2	23	S3	F2	D2
6	S1	F2	D3	15	S2	F2	D3	24	S3	F2	D3
7	S1	F3	D1	16	S2	F3	D1	25	S3	F3	D1
8	S1	F3	D2	17	S2	F3	D2	26	S3	F3	D2
9	S1	F3	D3	18	S2	F3	D3	27	S3	F3	D3

After each experiment, the surface roughness is measured using a surface roughness tester (Make: Mitutoyo SJ-210). The data obtained from the experiments are analyzed using analysis of variance (ANOVA) to determine the significance of the cutting parameters and their interactions. The Taguchi method (RSM) is used to optimize the cutting parameters based on minimizing the surface roughness.

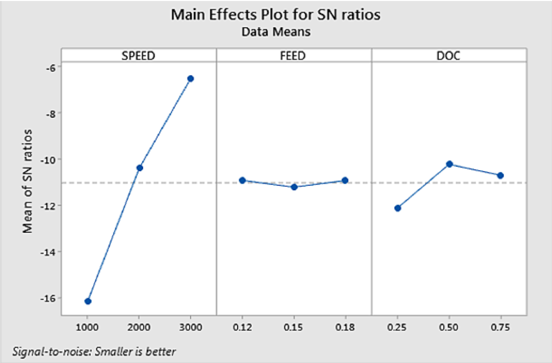


a. Graph of S/N Ratio for Specimen P0R3

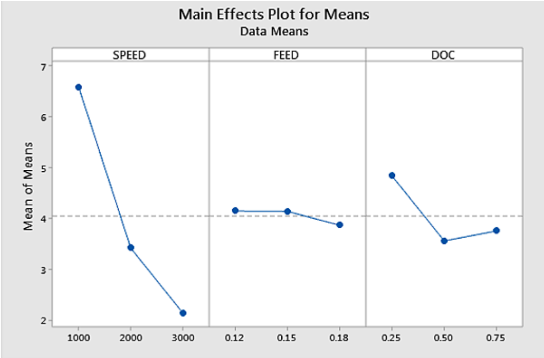


b. Graph of Mean for Specimen P0R3

Fig. 4: Main Effects plots for Surface Roughness for Specimen P0R3

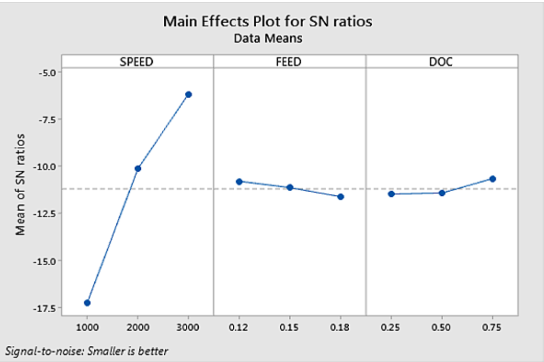


a. Graph of S/N Ratio for Specimen P1R3

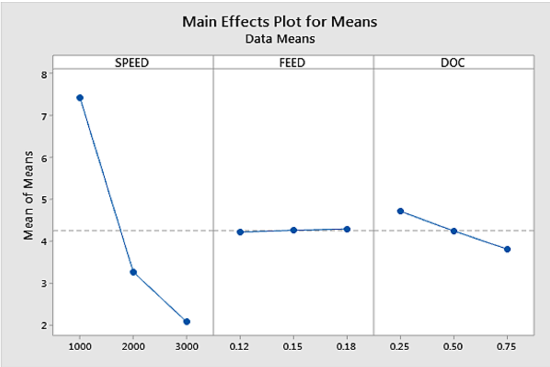


b. Graph of Mean for Specimen P1R3

Fig. 5: Main Effects plots for Surface Roughness for Specimen P1R3



a. Graph of S/N Ratio for Specimen P2R1



b. Graph of Mean for Specimen P2R1

Fig. 6: Main Effects plots for Surface Roughness for Specimen P2R1

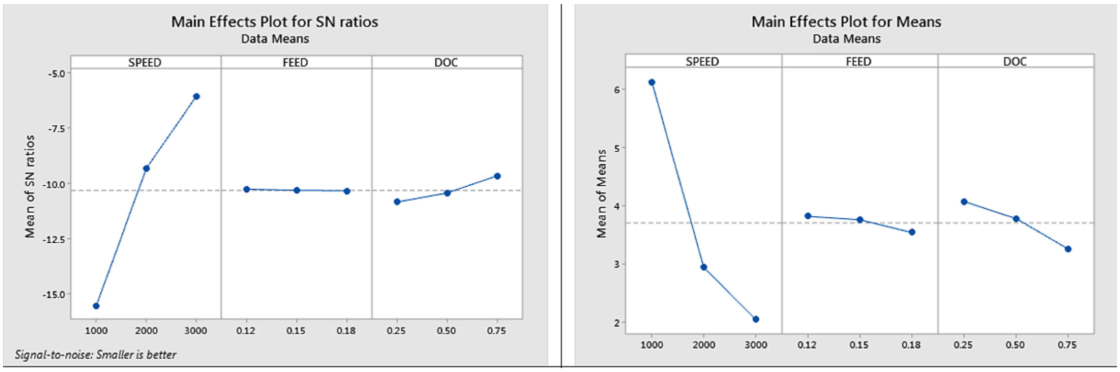


Fig. 7: Main Effects plots for Surface Roughness for Specimen P3R1

Table 5: (a) Response Table for Signal to Noise Ratios for Specimen P0R3s

Smaller is better

Level	SPEED	FEED	DOC
1	-16.704	-10.542	-12.684
2	-10.854	-11.774	-11.068
3	-6.897	-12.138	-10.703
Delta	9.807	1.596	1.981
Rank	1	3	2

Table 5: (b) Response Table for Means

Level	SPEED	FEED	DOC
1	7.076	3.982	5.077
2	3.637	4.269	4.095
3	2.250	4.713	3.791
Delta	4.826	0.731	1.286
Rank	1	3	2

Table 6: (a) Response Table for Signal to Noise Ratios for Specimen P1R3

Smaller is better

Level	SPEED	FEED	DOC
1	-16.181	-10.926	-12.134
2	-10.409	-11.225	-10.236
3	-6.495	-10.935	-10.716
Delta	9.686	0.299	1.898
Rank	1	3	2

Table 6: (b) Response Table for Means for Specimen P1R3

Level	SPEED	FEED	DOC
1	6.592	4.144	4.836
2	3.417	4.137	3.559
3	2.139	3.867	3.753
Delta	4.453	0.277	1.277
Rank	1	3	2

Table 7: (a) Response Table for Signal to Noise Ratios for specimen P2R1

Smaller is better

Level	SPEED	FEED	DOC
1	-17.275	-10.819	-11.494
2	-10.156	-11.151	-11.437
3	-6.178	-11.638	-10.677
Delta	11.097	0.819	0.817
Rank	1	2	3

Table 7: (b) Response Table for Means

Level	SPEED	FEED	DOC
1	7.420	4.215	4.711
2	3.268	4.258	4.242
3	2.076	4.291	3.811
Delta	5.345	0.076	0.900
Rank	1	3	2

Table 8: (a) Response Table for Signal to Noise Ratios for Specimen P3R1

Smaller is better

Level	SPEED	FEED	DOC
1	-15.567	-10.283	-10.859
2	-9.337	-10.335	-10.451
3	-6.069	-10.355	-9.663
Delta	9.498	0.072	1.195
Rank	1	3	2

Table 8: (b) Response Table for Means for Specimen P3R1

Level	SPEED	FEED	DOC
1	6.126	3.816	4.074
2	2.940	3.756	3.778
3	2.043	3.538	3.258
Delta	4.084	0.278	0.816
Rank	1	3	2

Results and Discussion

After all trials and measurements, it is vital to examine the effects of different machining settings when turning LM2-Al_2O_3 Metal Matrix Composites. In order to determine how the spindle speed, feed rate, and depth of cut impacted the machining process, the surface roughness was assessed throughout each experiment.

A number of graphs have been used to convey the major experimental findings.

In all above graphs, it is observed that cutting speed is the most influencing parameter on the response i.e. surface roughness. Maximum cutting speed resulted in minimum surface roughness for all the considered specimens. The second influencing factor observed is depth of cut, the surface roughness increases with increase in depth of cut and the least influencing factor observed is feed rate. Feed rate along with cutting speed give combined effect in decreasing surface roughness. However increase in feed rate, increase in surface roughness.

The findings of the experiment suggest that cutting speed, depth of cut, and feed rate are the most important factors affecting the surface roughness of the specimens. The justification for these findings can be explained as follows:

Cutting speed is the most influencing parameter on the response i.e. surface roughness: The cutting speed is the speed at which the cutting tool moves across the workpiece. A higher cutting speed means that the tool is moving faster, which can result in a smoother surface finish. This is because a higher cutting speed can help to reduce the amount of friction between the cutting tool and the workpiece, which in turn can help to reduce the surface roughness.

Maximum cutting speed resulted in minimum surface roughness for all the considered specimens: This finding supports the idea that a higher cutting speed can result in a smoother surface finish. By increasing the cutting speed to its maximum level, the experimenters were able to achieve the lowest surface roughness values for all of the specimens.

The second influencing factor observed is depth of cut, the surface roughness increases with increase in depth of cut: Depth of cut refers to the amount of material that is removed by each pass of the cutting tool. A deeper cut can result in a rougher surface finish, as the tool is removing more material with each pass. This explains why the surface roughness increased with an increase in depth of cut.

The least influencing factor observed is feed rate: Feed rate refers to the speed at which the workpiece is moved past the cutting tool. While the feed rate can have some effect on the surface roughness, it was found to be the least influential factor in this experiment. This may be because the other factors, such as cutting speed and depth of cut, have a greater impact on the surface roughness.

Feed rate along with cutting speed give combined effect in decreasing surface roughness. However, an increase in feed rate increases surface roughness: This finding suggests that the feed rate and cutting speed can have a combined effect on the surface roughness. When both of these factors are optimized, it is possible to achieve a smoother surface finish. However, an increase in feed rate can also increase surface roughness, which suggests that there is an optimal feed rate that should be used in order to achieve the best results.

Hence, the findings of the experiment suggest that cutting speed is the most important factor affecting the surface roughness, followed by depth of cut and feed rate. By optimizing these factors, it is possible to achieve a smoother surface finish and improve the overall quality of the product.

Conclusions

In the current study, turning of LM2-Al2O3 MMC components was experimentally investigated to determine the best machining parameters to reduce surface roughness. This is a summary of the study's main findings.

1. Cutting speed is observed as the most influencing parameter on the surface roughness. Maximum cutting speed 3000rpm resulted in minimum surface roughness for all the considered specimen.
2. Depth of cut is observed as the second influencing parameter on surface roughness. Increase in depth of cut resulted in increase in surface roughness.
3. Feed rate is found as the least influencing parameter. Increase in feed rate increases the surface roughness for all the specimens considered.
4. For the specimen P0R3, the optimum parameters resulting in least surface roughness are -cutting speed 3000 rpm, feed rate 0.12 mm/rev and depth of cut 0.75 which is maximum in 3 levels considered in the experiment.
5. For specimen P1R3, the optimum parameters resulting in least surface roughness are -cutting speed 3000 rpm, feed rate 0.12 mm/rev and depth of cut 0.5 mm.
6. For specimen P2R1, the optimum parameters resulting in least surface roughness are -cutting speed 3000 rpm, feed rate 0.12 mm/rev and depth of cut 0.75 mm.
7. For specimen P3R1, the optimum parameters resulting in least surface roughness are -cutting speed 3000 rpm, feed rate 0.12 mm/rev and depth of cut 0.75 mm.

The use of Taguchi method to optimize the cutting parameters in the turning operation of LM2-Al_2O_3 MMC resulted in a significant improvement in the surface quality. The optimized cutting parameters can be used in the manufacturing of LM2-Al_2O_3 MMC components, which can lead to reduced production costs and improved component performance. The results of this study can also be used as a basis for further research on the machining of MMCs using advanced cutting tools and machining processes.

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Conflict of Interest

The authors do not have any conflict of interest.

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