Eng. Sci., 2022, **18,** 271–277

Engineered Science

DOI: https://dx.doi.org/10.30919/es8d680

Multi-Response Optimization of Milling Process Parameters for Aluminum-Titanium Diboride Metal Matrix Composite Machining Using Taguchi - Data Envelopment Analysis Ranking Approach

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Abstract

Ceramic reinforced aluminum matrix composites are increasingly gaining importance because of their specific, particulate reinforced physical features. Machining such materials is a time-consuming process due to their superior physical properties. Moreover, only a few recorded research documents discuss the optimization of machining parameters in the milling of aluminum-titanium diboride (Al/TiB$_2$) composites. Thus, the current study sought to evaluate the effect of process parameters on the face milling machining process while machining Al/TiB$_2$ metal matrix composite. Reinforcement weight percentage, cutting speed, feed rate, and depth of cut used in milling were used as input parameters in the Taguchi-DEA ranking methodology to evaluate performance metrics, including material removal rate and material's arithmetic average roughness. According to the results of the experimental investigation, cutting speed and reinforcement weight percentage have a greater influence on determining performance metrics in the milling process due to their role in determining impact strength. Among the selected process factors, the ideal combination of reinforcing weight percent (9%), cutting speed (1500 rpm), feed rate (300 mm/min), and depth of cut (0.15) were discovered and evaluated using a confirmation test with 3.14 and 2.34 percent variation in material removal rate (MRR) and surface roughness (Ra) values, respectively.

Keywords: Metal matrix composite; Aluminum; Milling; Roughness; Material removal rate; Taguchi.
Received: 17 January 2022; Revised: 12 March 2022; Accepted: 12 March 2022.
Article type: Research article.

1. Introduction

Metal matrix composites (MMCs) have been one of the most significant material breakthroughs in the last 20 years.[1] They are made up of a continuous matrix of metal or alloy with reinforcement that might be a particle, short fiber, whisker, or continuous fiber.[2] Aluminum alloys in their natural form are primarily used in structural applications in the automobile and aerospace industries due to their exceptional forming and joining characteristics, low density, excellent strength, and corrosion resistance.[3] Hard ceramic particle-reinforced aluminum matrix composites (AMCs) are a distinct class of innovative materials with superior strength, corrosion resistance, and wear resistance compared to traditional materials.[4] These MMCs can be a great substitute for expensive traditional alloys used in advanced structural and functional applications.[3] The ceramic reinforcement in the aluminum alloy improves the mechanical and physical qualities of the base material, but it also makes machining more complex.[5] The presence of highly abrasive ceramic reinforcements damages the workpiece and produces rapid wear in the cutting tool. Although various processes are available today to create almost net-shaped components, the need for machining is not eliminated due to complicated design, dimensional constraints, and tight tolerance

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requirements.[6] When it comes to machining operations, the three most frequent traditional machining processes utilized in the industry are turning, milling, and drilling.[7] Compared to milling and drilling, the turning process has been widely used for machining MMCs because of the inexpensive machine tools, simple tooling, and machining operation. However, research on machining MMCs with milling is not as extensive as turning.[6]

Furthermore, the initial research concentrated on the effect of milling conditions on tool wears rather than investigating the effect on work material quality.[8–11] Even in recent years, only a small amount of research has been published on the effect of milling machining parameters and material composition on the machining quality of AMC, notably with Al 7075 alloy as the basis material,[12–19] with only three dealing with the traditional milling process of aluminum-titanium diboride (Al/TiB_2) composite.

Given the widespread use of Al7075 composites and the scarcity of recorded literature on their machinability, this study attempts to give a case study of optimizing machining settings for the Al/TiB_2 composite. To be more specific, the effect of machining parameters such as speed, feed, depth of cut, and reinforcement weight percentage on the machinability of Al7075-TiB_2 composites is examined in this work. This study focuses on multi-response optimization to achieve an ideal output of low surface roughness and high MRR for a face milling operation utilizing the Taguchi strategy paired with the data envelopment analysis (DEA) ranking method.

2. Experimental section

2.1 Material preparation

The TiB_2 particles reinforced Al7075 composite measuring 150 × 150 × 10 mm was used as a workpiece specimen in this investigation and was manufactured using the stir casting process because of its value as a structural composite.[20] Al 7075 is placed in a crucible in the stir casting method and heated to 800°C in an electrical furnace. The micron-sized powder particles were first heated to 1000°C to generate the oxidized layer while removing the moisture content. TiB_2 particles with an average diameter of 4 μm were used as reinforcement particles. Then, according to the desired weight percentage (3, 6, and 9), preheated TiB_2 particles (about 450°C) were gradually introduced to molten Al7075 at a rate of 15 g/min during a time span of 2–6 minutes. Stirring was performed in the crucible during this preparation phase to ensure the homogenous distribution of the composite mixture. Stirring was done for around 40 minutes with a hand-held drilling

machine with a graphite stirrer attached to it at a stirring speed of 250 rpm. The liquid was then poured into the mold cavity and allowed to cool at ambient temperature. Table 1 displays the mechanical characteristics of produced composites.

Table 1. Mechanical properties of Al7075 and Al/TiB_2 MMC composites.

S. No.	TiB_2 wt.%	Mechanical properties		
		Average tensile strength (MPa)	Average impact strength (J/mm^2)	Brinell hardness number (BHN)
1	0	175.64	0.326	39.2
2	3	168.72	0.284	43.1
3	6	165.64	0.251	45.8
4	9	159.34	0.243	47.7

2.2 Experimental setup and design

Specimens were face milled using a CNC vertical machining center (ACE Micron) capable of working at a speed of 8000 rpm. The L16 orthogonal array (OA) design was chosen based on the Taguchi design of experiments[21] because the current study works with four input levels using four independent process parameters. Apart from reinforcement weight percentage, because of their importance in the face milling process, cutting speed, feed rate, and depth of cut have been used as input parameters.[22] The process variables and all four levels of each chosen variable are listed in Table 2, based on the pilot study conducted prior to the main experiment. The width of the cut was maintained at 0.3 mm throughout the process. The material removal rate (MRR) and surface roughness in terms of arithmetic average roughness (Ra) were used as response parameters.

Multi-response optimization was used in the process because the current analysis used more than one performance parameter. The material removal rate can be calculated by comparing the weights of the specimens before and after the machining process. It is expressed in mm^3 per minute. Taylor Hobson Surtronic 3+ surface roughness tester with a standard cut-off length of 0.8 mm was used to calculate the average surface roughness. The surface roughness was calculated using the centerline average method and expressed in millimeters.

Table 2. Experimental parameters used for milling experiment and their levels.

Levels	Parameters			
	Cutting speed, N (rpm)	Feed rate, f (mm/min)	Depth of cut, d (mm)	Reinforcement, w (%)
1	500	200	0.10	0 (naked alloy)
2	750	250	0.15	3%
3	1000	300	0.20	6%
4	1500	350	0.25	9%

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Table 3. Experimental results for milling of Al/TiB$_2$ metal matrix composite with parameters.

Exp. No.	Factors				Responses	
	w (%)	N (rpm)	F (mm/min)	d (mm)	MRR (mm^3/min)	Ra (μm)
1	0	500	200	0.1	7.02	1.839
2	0	750	250	0.15	13.16	1.659
3	0	1000	300	0.2	21.06	1.512
4	0	1500	350	0.25	30.71	1.232
5	3	500	250	0.2	17.55	1.957
6	3	750	200	0.25	19.66	1.773
7	3	1000	350	0.1	24.45	1.627
8	3	1500	300	0.15	35.80	1.356
9	6	500	300	0.25	26.33	2.138
10	6	750	350	0.2	28.57	1.833
11	6	1000	200	0.15	29.53	1.710
12	6	1500	250	0.1	32.78	1.417
13	9	500	350	0.15	28.43	2.187
14	9	750	300	0.1	30.53	1.930
15	9	1000	250	0.25	31.94	1.878
16	9	1500	200	0.2	34.04	1.414

2.3 Multi-response optimizing using the DEA ranking approach

Data envelopment analysis (DEA), a quantitative tool introduced by Farrell, is a commonly used non-parametric frontier analysis method for estimating the efficiency of a homogenous collection of decision-making units (DMUs) based on multiple inputs and outputs[23] DEA can be used as a decision analysis technique in a variety of situations because it does not strive to find universal relationships among all the units in the sample. Rather, DEA permits each unit in the dataset to have its production function and then compares the efficiency of that single unit to the efficiency of the other units in the dataset to determine its efficiency.[24] DEA Ranking Methodology (DEAR) involves the following steps: Using Equations (1) and (2), computing the weights (w) for MRR and Ra for all 16 experiments.[24]

$$W_{MRR} = \frac{MRR_i}{\sum_{i=1}^{16} MRR} \tag{1}$$

$$W_{R_a} = \frac{\frac{1}{R_a}}{\sum_{i=1}^{16} \frac{1}{R_a}} \tag{2}$$

By multiplying the observed data by its weight, and converting the response data to weighted data using Equations (3) and (4).[24]

$$A = MRR \times W_{MRR} \tag{3}$$

$$B = R_a \times W_{R_a} \tag{4}$$

Divide larger-the-better data by smaller-the-better to calculate the multi-response performance index (MRPI). In the present work, MRR data represents larger-the-better in this study, whereas Ra data represents smaller-the-better. Equation (5) represents the mathematical form of calculating the MRPI.[24]

$$MRPI_i = \frac{A_i}{B_i} \tag{5}$$

3. Results and discussion

3.1 Results of the experiment

Table 3 summarizes the findings of all trials done as per Taguchi OA L16. The weights assigned to the individual performance measures for various combinations of process parameters, determined using the DEA ranking methodology, are shown in Table 4. The Taguchi-DEA ranking method using MINITAB 21 is shown in Table 5. The values were calculated by summing the MRPI values for each process parameter's corresponding level.

Table 4. Multi-response performance indicator values for the experimental data for milling of Al/TiB$_2$ metal matrix composite.

Exp. No.	Weights of responses		MRPI
	MRR (mm^3/min)	Ra (μm)	
1	0.017058	0.056839	1.145
2	0.031983	0.063016	4.027
3	0.051173	0.069143	10.309
4	0.074628	0.084837	21.924
5	0.042644	0.053421	7.159
6	0.047776	0.058965	8.985
7	0.059403	0.064244	13.891
8	0.086977	0.077086	29.780
9	0.063966	0.048907	16.107
10	0.069421	0.057035	18.972
11	0.071754	0.061126	20.268
12	0.079639	0.073779	24.967
13	0.069075	0.047794	18.783
14	0.074184	0.054179	21.664
15	0.077604	0.055668	23.707
16	0.082713	0.073961	26.932

The maximum level value for each process parameter shows the ideal level for determining the response characteristics. The maximum MRPI value for each process parameter is ideal for the process variables.

As a result, Taguchi's larger-is-better criterion is employed to determine the optimal parametric condition for the MRPI. According to Table 5, the ideal combination of input process parameters for the milling process under the experimental conditions is reinforcing weight percent (9%), cutting speed (1500 rpm), feed rate (300 mm/min), and depth of cut (0.15 mm). A larger delta value implies that process parameters have a greater influence on the multi-response performance indicator. Thus, cutting speed followed by reinforcing weight percent significantly affects performance metrics due to their role in determining MRR and work material surface roughness throughout the milling process. The feed rate and depth of cut are ranked lower. As a result, it can be concluded that selecting the ideal speed and reinforcement weight percentage during the milling process can improve the milling process's performance metrics when machining Al/TiB_2 composites.

Table 5. Mean and delta values of multi-response performance index for each parameter used in milling of Al/TiB_2 metal matrix composite obtained using Taguchi-DEA method.

Factors	Levels				Delta
	1	2	3	4	
Reinforcement wt.% (w)	9.351	14.954	20.078	22.771	13.42
Cutting speed N (RPM)	10.799	13.412	17.044	25.901	15.102
Feed rate f (mm/min)	14.333	14.965	19.465	18.392	5.132
Depth of cut d (mm)	15.417	18.214	15.843	17.681	2.798

3.1.1 Analysis of surface roughness

Arithmetic average roughness (Ra) quantifies the surface roughness response variable in the current work. Ra is analyzed using Taguchi's smaller-is-better function since a higher finish is expected in the final product. Reduced reinforcing in the material, along with a high cutting speed (1500 rpm), a low feed rate (200 mm/min), and a low depth of cut (0.2 mm), results in good surface quality, as illustrated in Fig. 1.

The most significant component identified for Ra is cutting speed. At lower cutting speeds, it was discovered that poor surface finishes are obtained due to the development of pressure on the tool rake surface, which contributes to the formation of build-up edges and excessive chip fracture. Whereas, as the cutting speed increases, the material roughness reduces due to the high temperature of the cutting zone and the formation of discontinuous chips with a decreased chip fracture rate. The finding agrees with one of the prior works concerning MMC machining.[25] Similarly, increasing the weight percentage of reinforcing material (TiB_2) results in an increase in roughness. The obtained result is consistent with prior work,[26] which indicates a reduction in the surface finish of the MMC with an increase in the weight percent of TiB_2. The poor surface quality produced at higher TiB_2 is due to the pull-out of abrasive particles during machining. The broken abrasives slide along with the workpiece during the machining operation and cause a poor finish. Additionally, the slide mechanism enhances the porosity of the composite structure, lowering the surface finish even further.

3.1.2 Analysis of MRR

The material removal rate (MRR) is expected to be higher while machining a component. Thus, the larger-the-better function of Taguchi's approach is preferred for analyzing MRR

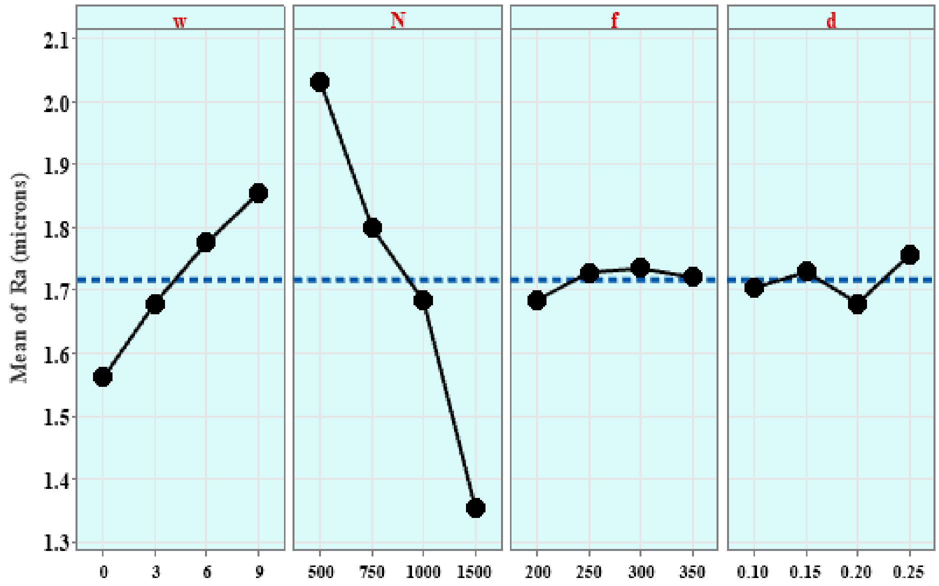

Fig. 1 Mean effect plot for surface roughness (Ra) of Al/TiB_2 metal matrix composite considering reinforcement, w (%), cutting speed, N (rpm), feed rate, f (mm/min), and depth of cut, d (mm).

responses. The cutting speed is determined to have the maximum impact on the MRR. MRR is expected to be greater at higher speeds due to the cumulative effect of increased cutting temperature, rapid cutting action, and secondary cutting action of the rapidly created abrasive particles from the material. Additionally, the MRR is seen to be altered by the material's reinforcing weight percentage. As previously stated, the increased presence of TiB_2 results in increased abrasive particle pull-out during machining,[25] which adds to the MRR as a secondary cutting action. Thus, it can be said that increased reinforcing in the material, along with a high cutting speed (1500 rpm), a nominal feed rate (between 300–350 mm/min), and a higher depth of cut (0.25 mm), results in good surface quality, as illustrated in Fig. 2.

3.1.3 Analysis of MRPI

Feed rate and depth of cut are not determined to be highly influencing factors in the present work for the selected materials and the selected machining conditions. On the other hand, cutting speed and TiB_2 wt.% affect both the response mentioned above variables more. Therefore, the effects of feed and depth of cut are neglected for further analysis. Considering the cutting speed and reinforcing material weight percentage, the high speed is advisable in both cases, but the material composition concerning the reinforcement weight percentage has a contrary effect. The increase in the TiB_2 improves the MRR but leads to a poor finish, and the effect is vice-versa with the decrease in the reinforcement material. Thus, the multi-response performance index is calculated and analyzed to achieve an optimum solution for the problem and to achieve optimum cutting conditions.

The analysis of MRPI, as illustrated in Fig. 3, indicates that the best possible combination is a high-speed and high-weight fraction of reinforcement. The temperature difference in low and high cutting speeds can be diagnosed further with the help of a thermocouple integrated into the machining setup. The microstructural analysis concerning scanning electron microscopy (SEM), transmission electron microscopy (TEM), and energy-dispersive X-ray spectroscopy (EDX) can also be used to get a deeper insight. Nevertheless, thermal and microstructural studies do not fall in the scope of the present work, which mainly focuses on statistically analyzing the effects of various independent variables on the MRR and Ra, and can be thought of as a possible extension of this work by future researchers.

3.2 Validation using confirmation experiment

A confirmation experiment is used to validate the methodology's optimal process parameter combination. Therefore, a confirmation experiment was conducted using the optimal amounts of significant components in the current study. The average response values from the confirmation experiments were determined as 29.57 mm^3/min (MRR) and 1.975 μm (Ra). MRR and Ra have error percentages of 3.14 and 2.34 percent, respectively. As a result, the best combination of process parameters has been evaluated in this investigation as adequate.

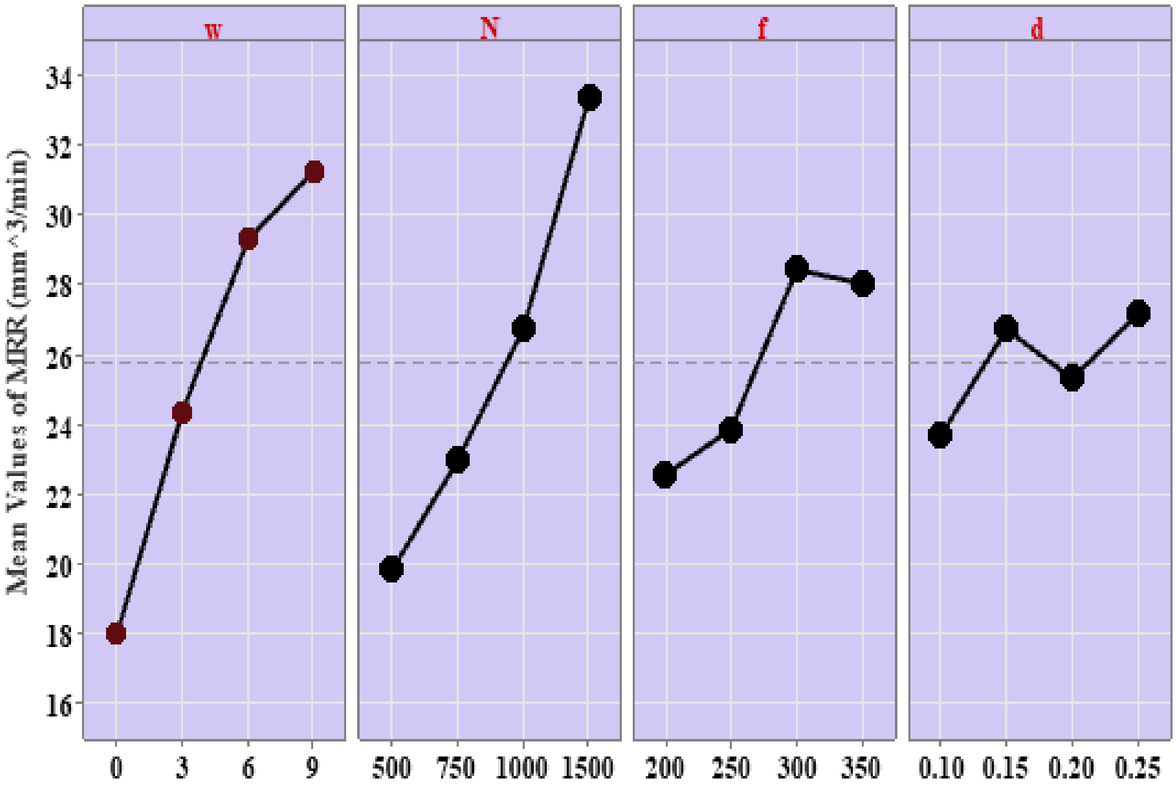

Fig. 2 Mean effect plot for material removal rate (MRR) of Al/TiB_2 metal matrix composite considering reinforcement, w (%), cutting speed, N (rpm), feed rate, f (mm/min), and depth of cut, d (mm).

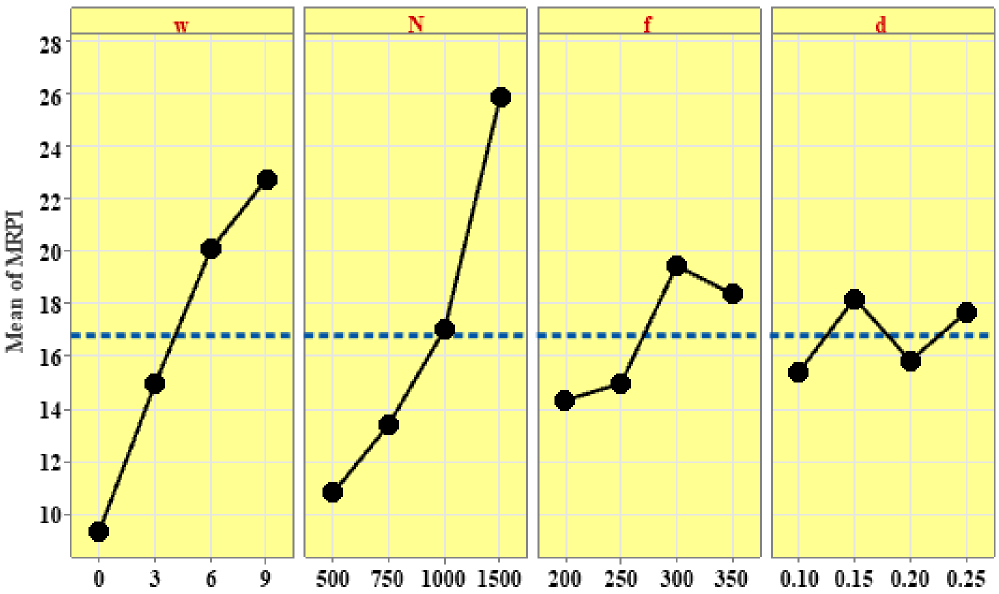

Fig. 3 Mean effect plot for multi-response performance index (MRPI) of Al/TiB$_2$ metal matrix composite considering reinforcement, w (%), cutting speed, N (rpm), feed rate, f (mm/min) and depth of cut, d (mm).

4. Conclusion

Taguchi-DEA ranking multiple response optimization techniques were used in this study to determine the optimal process parameters for milling Al/TiB$_2$ composites. Among the selected process variables, the optimal process parameter combination is 9% reinforcing weight, 1500 rpm cutting speed, 300 mm/min feed rate, and 0.15 mm depth of cut. According to the confirmation test, the optimal condition had a variance in MRR and Ra values of only 3.14 and 2.34 percent, respectively. Cutting speed is found to have a significant effect on the material removal rate and surface roughness, followed by the percentage of reinforcement. Multi-response optimization using the DEA ranking approach was advantageous for determining the optimal value of machining, as the reinforcement weight percentage had a contradictory effect on MRR and Ra in the current investigation.

Conflict of Interest

The authors declare no conflict of interest.

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