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TiB_2 Particle Influence for Processing Parameter Improvement of TiB_2/Al7175 Metal Matrix Composites

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Abstract

Compounds made of titanium diboride (TiB_2) particles and aluminum substrate (TiB_2/Al7175 metal matrix composites (MMCs)) produced in-situ have certain remarkable features that enable these highly potential materials to be excellent performance aviation blades. Machinability remains an issue attributable to the effect of TiB_2 particulate, limiting the applicability of TiB_2/Al7175 MMCs. For suit manufacturing demands, the effect of TiB_2 particulate upon its processing parameters for TiB_2/Al7175 MMCs was successfully examined. This investigation also looked into the best processing parameters for these types of MMCs. There are various factors to consider. The surface's roughness and the amount of material removed (Material removal rate, MRR) were determined for the end process variables of the procedure after determining their optimum cutting velocity, feed rate, and depth of cut. The findings demonstrate a significant departure from TiB_2 nanoparticles strengthened MMCs and give another valuable roadmap for further optimizing the machining of this material.

Keywords

Material removal rate, Surface roughness, Machining, Titanium diboride, Orthogonal array

Introduction

Particle-reinforced composites made from metal matrices (PRMMCs) are crucial in aviation and other industries due to their superior features, like improved strength-to-weight ratios, elastic modulus, and wear resistance. These materials offer enhanced performance [1, 2]. PRMMCs are manufactured using *ex-situ* and *in-situ* processes. Stir-casting generates the reinforcement, later combined with the substrate through a similar technique. However, this method results in less bonding at the interface, affecting reinforcement particle distribution in stir-casting composites [3, 4]. Al7075/Al_2O_3&SiC composites with varying weight percentages (2, 4, 6, and 8%) were efficiently produced using a cost-effective stir casting method, exhibiting higher hardness compared to non-reinforced Al7075 [5]. An economically viable stir casting technique was effectively employed to create a metal matrix compound using Al7075, grey cast iron, and ash dust. These materials showed higher rigidity compared to non-reinforced Al7075 with ash dust and grey cast iron compounds [6]. In contrast, the *in-situ* nanocomposite involves spontaneous synthesis of reinforcement within the substrate, enhancing surface adsorption and resulting in increased rigidity. Immediate synthesis fosters better incorporation and additional benefits for overall composite effectiveness [7]. The current research on *in-situ* PRMMCs emphasizes material preparation

[8] and mechanical property analysis [9, 10]. Understanding fabrication techniques and performance characteristics is vital for diverse applications in engineering. However, machining these high-performance materials faces challenges due to the high abrasiveness of embedded reinforcement particles, causing accelerated tool wear and compromised surface finish [11]. *Ex-situ* MMCs with SiC particle reinforcement are widely used in industry due to their ease of preparation. Research mainly concentrates on machinability aspects, including tool wear [12, 13], surface integrity [14, 15], and chip formation, to comprehend their performance during machining [16, 17]. The research on the machining of *in-situ* MMCs has been limited. A novel aluminum MMC with *in-situ* ceramic reinforcement was developed and evaluated for machinability, comparing it to composites containing Al_2O_3 and Al_2O_3-SiC [18]. Investigation focused on grinding characteristics of TiC_p/Ti-6Al-4V MMCs, known as PTMCs. PTMCs showed higher material removal difficulty than Ti-6Al-4V. Improved surface quality was achieved with low depth of cut and high workpiece speed. Comparing electroplated and brazed CBN wheels, the latter exhibited greater potential for high-speed grinding of PTMCs [19, 20]. The study examined the machinability of *in-situ* Al6061-TiB_2 MMCs. Cutting parameters' impact on tool wear, cutting force, and surface roughness were analyzed. The investigation also established a correlation between TiB_2 reinforcement ratio and tool wear, surface roughness, and cutting forces [21]. Study analyzed machinability properties of Al-Cu/TiB_2 *in-situ* MMCs. Parameters' impact on turning performance measures, built-up edge, and chip formation were examined [22]. An experimental study analyzed TiB_2/Al MMCs' machinability. PCD tools showed the lowest wear compared to PCBN and coated-carbide tools, with a focus on tool wear, surface quality, and chip formation [23]. Explored surface integrity and tool wear mechanisms in TiB_2/Al MMCs. Primary wear mechanisms were abrasion, adhesion, chipping, and peeling. Uncoated carbide tools had tool life ranging from 3 to 20 min, with milling speed being the dominant factor. In practical engineering applications, selecting cutting conditions for MMCs is considered a crucial task in machining operations [24, 25]. Assessed machining parameter impact on surface finish during turning of LM23 Al/SiC composites. Response surface methodology identified optimal conditions to maximize MRR and minimize surface roughness [26]. Optimized machining conditions using the desirability function approach to minimize surface roughness [27]. Investigating turning of Al/SiC_p composites with an uncoated tungsten carbide insert in a dry environment, cutting speed, feed rate, and depth of cut impact flank wear and surface roughness. The Taguchi approach determined the optimal process parameter combination for minimizing flank wear and surface roughness [28].

Researchers focused on optimizing cutting parameters using soft computing techniques. The investigation studied surface roughness of Al-SiC(20p) with a PCD insert under different conditions. Analysis of variance (ANOVA) and artificial neural network were used to analyze the experimental data [29]. Investigation analyzed turning of Al/SiC MMCs with a PCD insert. The study established relationships between cutting parameters, specific power, and surface finish. Optimal machining parameters were determined using Grey relational analysis, particularly suitable for *in-situ* PRMMCs [30]. Analyzed process parameters (cutting speed, feed rate, and depth of cut) on turning *in-situ* Al6061-TiC metal matrix composites, examining cutting force, surface roughness, and flank wear [31]. Investigation assessed the effect of cutting speed, feed rate, and depth of cut on cutting force and surface roughness in Al6061-TiC using Taguchi L-27 orthogonal array and ANOVA techniques to determine each parameter's contribution [32].

Extensive research has focused on optimizing cutting parameters for *ex-situ* MMCs with SiC reinforcement, but *in-situ* MMCs with distinct microstructures show different mechanical properties. Limited exploration exists for *in-situ* MMCs' machinability and parameter optimization. Efficient machining is vital for industrial applications. This study aims to investigate the influence of reinforced particles on machining forces, residual stress, and surface roughness in TiB_2 PRMMCs. Various cutting parameters are explored, and a multi-objective optimization model is proposed based on experimental results, considering MRR and surface roughness. The paper is structured as follows: Section 2 covers machining trials, Section 3 presents and discusses experimental results, Section 4 formulates and optimizes the multi-objective model using a genetic algorithm (GA), and Section 5 offers conclusions and future work suggestions.

Experimentation

Material and specimen

During investigation, two types of materials were utilized: Al7175, both unreinforced along with reinforced consists of 6 vol.% TiB_2 particles, between 50 and 200 nm at dimension, developed through a technique incorporating combined solutions. Table 1 provides its matrices alloy's molecular constitution (in weight percent). Table 2 displays its natural yet engineered properties with 6 percent in-place TiB_2/Al7175 MMCs, while figure 1 illustrates their microstructure. circular

Table 1: Chemical composite of 7175 alloy.

Element	Content
Chromium	0.18 - 0.28
Copper	1.2 - 2.0
Ferrite	0.2
Magnesium	2.1 - 2.9
Manganese	0.1
Silicon	0.15
Zinc	5.1 - 6.1
Titanium	0.1
Aluminum	Balance

Table 2: TiB_2/Al7175 multi-material composites' morphological while physiological properties.

Property	Content
Yield strength (MPa)	435
Density (kg.m^3)	2800
Elastic modulus (GPa)	72
BHN (HB)	135
Elongation (%)	13
Poisson's ratio	0.33

specimens with Al7175/TiB_2 MMCs were fabricated through a turning process. The dimensions of the specimens are Ø30 x 80 mm, see figure 2.

In-lab procedures

In this study, these experimental procedures exist conducting using a 2Y2K speed lathe revolving center under dry conditions, employing a bar turning process. To address its scratchy impact with additive constituent part, with cemented carbide implement take part chosen for the investigation. The specific turning conditions, including cutting parameters, are provided in detail in table 3. Furthermore, figure 3 illustrates the configuration of the cutting setup, offering a visual representation of the experimental arrangement. 2Y2K speed lathe turning center served as the platform for the experiments, facilitating precise control and measurement during the bar turning process. The dry environment was adopted to isolate those possessions with cutting consideration on its machining presentations of its materials. By utilizing a cemented carbide tool, known for its durability and resistance to abrasion, the research aimed to effectively manage its roughness caused by its TiB_2 nanoparticles within its substance. Table 3 presents the specific turning conditions employed, including considerations that are speed tool feed, and cutting depth. The selected variables play with vital task here determining its machinability also surface excellence with its turned components. For a visual representation, figure 3 showcases the arrangement of the cutting setup, providing insight into the spatial configuration and orientation of the tools, workpiece, and related components during the turning process.

Measurement

Surface roughness was evaluated using a talysurf (SJ210) tester shortened to a certain size and evaluation length with 20 mm. Two repeated measurements took place at every point, also the standard significance seemed recorded and indicated for analysis. The MRR refers to the rate at which material is removed or cut during a machining process. It is typically measured in volume or weight of material removed per unit of time, such as cubic millimeters per second or grams per minute. The MRR is a crucial indicator of the effectiveness and productivity of machining processes. Superior MRR often results in faster machining times, but it is important to balance this with other factors such as tool life and surface quality.

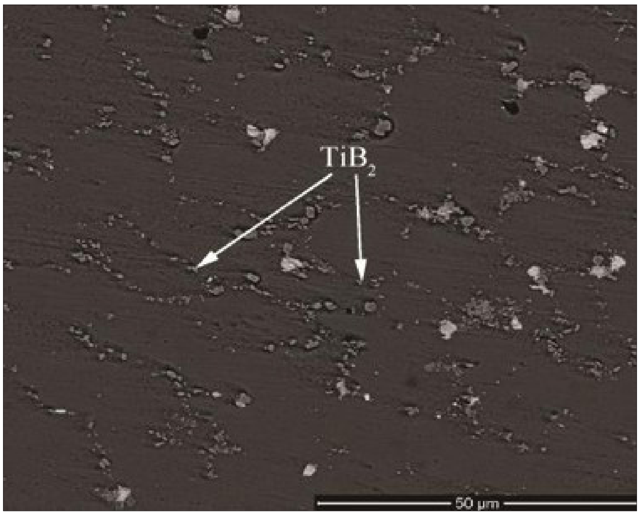

Figure 1: Al7175/TiB_2 microstructure.

Figure 2: Al7175/TiB_2 specimens.

Table 3: Machining variables and their levels.

Feature	1-level	2-level	3-level
Cutting speed	480	750	1145
Feed	0.4	0.8	1.2
Cutting depth	0.2	0.4	0.6

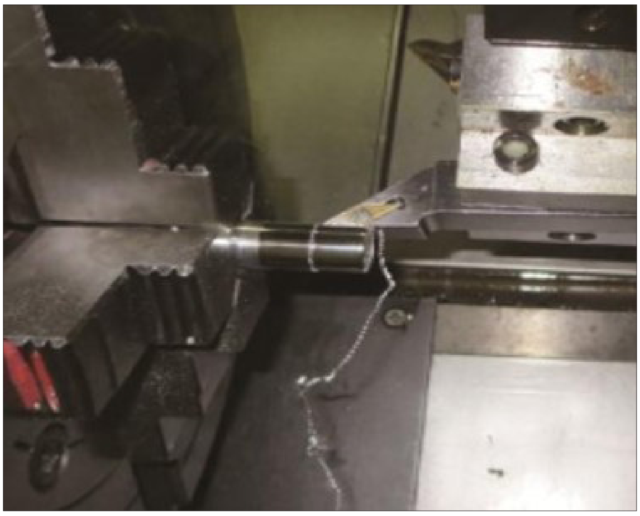

Figure 3: Machining set-up.

Results and Discussion

The texture of the substrate

The analysis of cutting speed's impact on surface roughness (Figure 4) reveals that TiB_2/Al7175 MMCs exhibit lower roughness compared to un-strengthened Al7075 at all cutting speeds. This is attributed to reduced ductility here Al7075/TiB_2 MMCs appropriate in the direction of its presence of reinforcement particles, leading to easier fracture during turning. Moreover, increasing cutting speed improves exterior irregularity, possibly due to reduced material flow at higher speeds. Figure 5 shows the influence of feed rate on surface roughness. As feed rate increases, surface roughness also increases. At lower feed rates, MMCs have lower roughness than the non-reinforced alloy, but this trend reverses at higher feed rates. The machined surface images of the non-reinforced alloy and *in-situ* TiB_2-reinforced MMCs (Figure 6 and figure 7, respectively) under identical cutting conditions demonstrate distinct differences. The non-reinforced alloy surface exhibits irregular feed marks, possibly due to material softening during cutting. In contrast, MMCs show distinct feed marks, becoming more pronounced with increasing cutting speed. Experimental results differ significantly from conclusions drawn in previous studies on *ex-situ* SiC PRMMCs. The variation can be attributed to the disparity in reinforcement particle size. The nanometer to sub-micrometer sized TiB_2 particles have minimal influence on the machined surface, differing from the effects of larger reinforcement particles. Therefore, considering the size of reinforcement particles is crucial when examining the effects of *in-situ* TiB_2 particles on MMCs' machined surface.

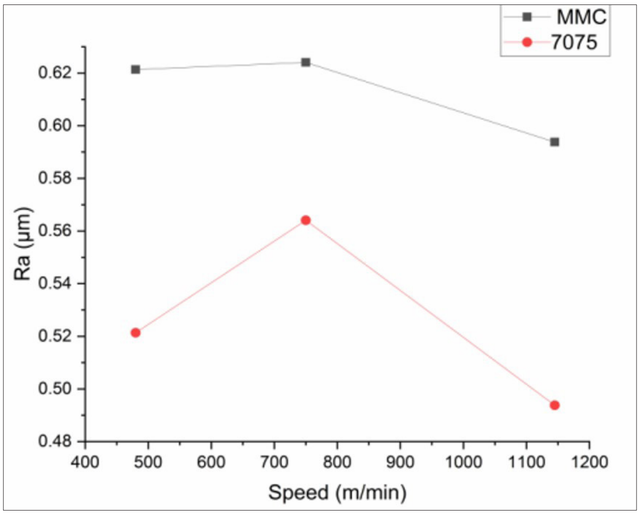

Figure 4: Effect machining speed on surface roughness.

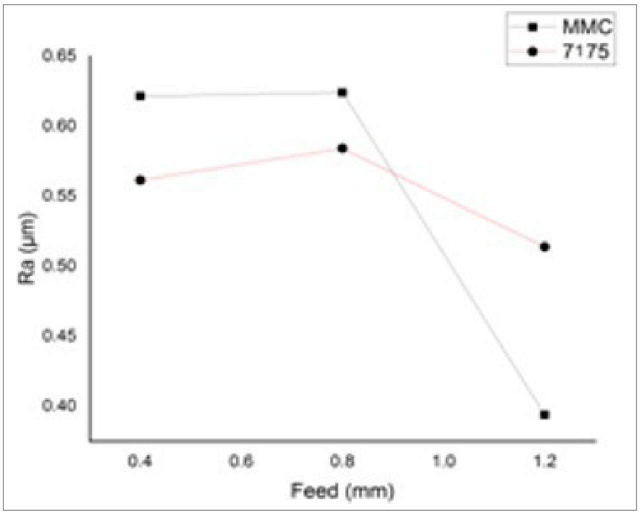

Figure 5: Result for feed rate on surface roughness.

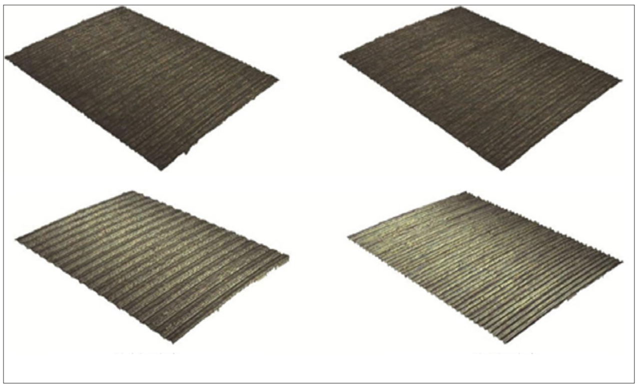

Figure 6: Different rates of MMC surface machining.

Machining variables optimization including surface roughness and MRR

Exterior irregularities play a vital role here assessing its excellence with specimen surface. It serves as a crucial parameter due to its ability to create potential sites for crack formation or corrosion when irregularities are present [33]. This section focuses on conducting tentative assessment to examine its correlation between machining parameters along with exterior irregularity. To quantitatively analyze this relationship, the tactile characteristics of surfaces were modelled using response surface methodology. It was a significant technique used to establish this causal connection between manipulated inputs and average outputs, showing that as a hypersurface across two or three dimensions. Machining settings are subsequently optimized taking into account surface roughness along with MRR are limitations.

Roughness of the surface fabrication of models

Here, we'll go over, the experiments seemed designed using Box-Behnken designs due to their ability to provide accurately estimating variables for both the first and second order with a smaller integer with design position match up to inner compound intends. Each factor in its Box-Behnken intends was set to have three levels. Its machine velocity varied from 480 rpm to 1145 rpm, its rate of feed ranged from 0.4 mm/min to 1.2 mm/min, and cutting depth was used to 0.2 mm to 0.6 mm. Table 4 presents this investigation variables with their consequent reactions. As mentioned here in prior studies [34, 35], it has been determined that a second-order quadratic representation was proficient with achieving its preferred level of precision in approximating its true functional correlation among surface roughness also its machining variables. This relationship is able to mathematically be represented by equation 1.

$$y = \beta + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i} \sum_{j} \beta_{ii} x_i x_j + \varepsilon \qquad (1)$$

In equation 1, surface roughness represents that exterior irregularity with the specimen, the expressions β correspond to its deterioration coefficient, x_i denotes that standard with

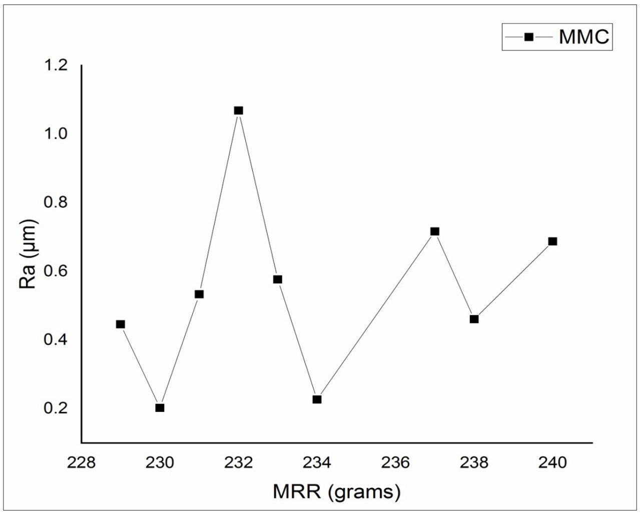

Figure 7: Pareto optimal solutions.

Table 4: Value of parameters suggested after optimization.

S. No.	Speed	Feed	Depth of cut	Rake angle	MRR	Ra
1	480	0.4	0.2	2	240	0.6875
2	480	0.8	0.4	4	238	0.4603
3	480	1.2	0.6	6	237	0.7162
4	750	0.4	0.4	6	234	0.2268
5	750	0.8	0.6	2	233	0.5765
6	750	1.2	0.2	4	232	1.0689
7	1145	0.4	0.6	4	231	0.5336
8	1145	0.8	0.2	6	230	0.2024
9	1145	1.2	0.6	2	229	0.4454

its i^{th} machining variables, also ε represents its investigational miscalculation associated with its examinations. ANOVA was used to investigate how the input factors affected the surface roughness, and the results were compared to those of previous research. Three models, including linear, 2FI, also quadratic, be evaluated for their effectiveness. Table 5 provides a summary of the regular difference, R^2-coefficient of determination, determination of adjusted coefficients, predicted coefficient of determination (Pred. R^2), also press. According to the results in table 5, it is evident that the quadratic model is the most suitable and hence recommended as its reaction exterior occupation. Utilizing this information presented here table 4, this association among its surface roughness and cutting variables have been established by response surface methodologies was encoded entity, yielding the following second-order response surface model.

$$\textit{Surface roughness} = 2.33 - 0.00441V + 0.0911f + 1.257a_p - 0.00037Vf + 0.0026Va_p + 0.00062fa_p + 0.000048V^2 + 0.00016f^2 - 1.11a_p^2 \quad (2)$$

Original data from the regression model construction were used for verification purposes to determine the model's accuracy. Additionally, a further position for validation information consisting of 3 exterior irregularities significance was employed to evaluate its accuracy with its response surface representation. This validation statistics, presented in table 6, with carefully elected beginning various points within the cutting parameters' range to ensure a comprehensive evaluation of the model's accuracy. From table 6, the margin of error is clearly less than 10%. Hence, the results of the regression analysis indicate that has been successfully validated.

Table 5: Summary of process variables.

Sources	Std. dev	R^2	Adj. R^2	Pred. R^2	Press
Linear	0.150961	0.9382	0.9254	0.9289	1.58674
2FI	0.126385	0.9504	0.9406	0.9452	1.17654
Quadratic	0.087173	0.9824	0.9857	0.9841	0.44706

Optimization problem formulation

The surface roughness can vary depending on the type and location of the parts, which implies that additional criteria should be considered when achieving a specific surface roughness value. Using a more realistic strategy, the rate of material extract at a crucial factor with cutting operations. Therefore, both surface roughness and MRR were minimized by this investigation. its rate of materials removed measured with mm^3/min, mentioned directly considered using equation 3.

$$MRR = V \times f \times \alpha_p \times 1000 \quad (3)$$

By considering the constraint of surface roughness, it is possible to achieve high values of MRR by adjusting the cutting conditions using a suitable mathematical minimization approach. Subsequently, the following is a typical mathematical formulation of the multi-objective optimization paradigm.

$$\text{Find: } V, f, \alpha_p \quad (4a)$$

$$\text{Maximize} = MRR\left(V, f, \alpha_p\right) \quad (4b)$$

Subjected to constraints: Ra ≤ definitely significant (4c)

Ranges are machine speed: 480 rpm to 1150 rpm, Feed rate: 0.4 to 1.2 m/min, cutting depth: 0.2 mm to 0.6mm.

Equation 4 MRR representation, while described with equation 3, was denoted as MRR. Its surface roughness representation (Ra). The optimization problem definition aims to find an improved solution, and this is further enforced by these restrictions' designations at equation 4c. This series with the machining variables for minimize took place determined support with its recommendations provided in the cutting handbook.

Outcomes of the optimization with conversation

Two competing goals were used in this investigation,

Table 6: Summary of cutting parameter.

Run	Cutting parameter V (m/min)	Cutting parameter f (mm/min)	α_p (mm)	Measurement results	Ra (μm) RS model	Error (%)
1	480	48	0.5	1.191	1.27210	6.809%
2	750	54	0.7	1.804	1.96562	8.959%
3	1150	60	1.1	0.477	0.45118	5.413%

MRR, and surface roughness, were considered. Increasing the feed rate enhances MRR but leads to higher surface roughness, necessitating a compromise. The commonly used method of summing weighted factors was employed to solve this multi-objective problem, with normalized weights and a Pareto-based approach. The Pareto-based GA was utilized for optimization, providing a range of solutions for user selection. The GA involved essential operations like initialization, assessment, intersect, transformation, and collection. MATLAB was used to optimize the model, obtaining Pareto optimal solutions for all objectives (Figure 7). It revealed a trade-off between MRR and surface roughness, resulting in conflicting optimal values. The points in figure 7 represented unique Pareto optimal solutions. The one point exhibited the smallest surface roughness but relatively low MRR, while another point demonstrated higher roughness and relatively high MRR. A compromise solution optimizing both objectives can be found near the base points in figure 7. To validate the optimal results, a comparative experiment was conducted using the optimal cutting parameters from the study and a set of conventional parameters achieving the same MRR. The surface roughness of TiB_2/Al7175 specimens cut with these parameters was measured and compared. Results (Table 7) showed that the optimal cutting parameters produced superior surface roughness compared to conventional parameters for the same MRR. This aligned with prior research, indicating that increased cutting speed improves surface roughness by reducing material side flow, while higher feed rates tend to increase roughness. In conclusion, this study effectively addressed the trade-off relationship between MRR and surface roughness by employing a Pareto-based approach with a GA for optimization. The obtained results demonstrated the possibility of achieving a compromise solution that optimizes both objectives. Experimental validation further confirmed the superiority of the optimal cutting parameters for surface roughness, offering valuable insights for machining in situ TiB_2/Al7175 MMCs.

Future Research Directions and Implications

To explore this machinability with 6% TiB_2/Al MMCs, a comparative analysis with Al7175 alloy was conducted in the direction of investigate its impact with TiB_2 particles make use of stir casting MMCs its machinability. TiB_2 particle impacts on surface roughness were investigated. Surface roughness was the focus of a recently developed response surface model. Additionally, the Pareto-based inherited algorithm was utilized for minimizing these multiple objectives, considering both MRR and surface roughness. Its key findings and finale derived from the research be able to be summarized mentioned as:

- As its cutting speed increased, both materials exhibited a significant reduction in surface roughness, reaching a plateau beyond a certain point. When the feed rate was low, the surface roughness with Al7175/TiB_2 compound, was lesser than that of Al7175. However, as that feed rate increased, this surface roughness with Al7175/TiB_2 compound exhibited with superior evidence with increase compared to that of the Al7175 alloy. Additionally, it was found that the Al7175/TiB_2 compounds had different feed marks, while they appeared irregular on the Al7175 alloy. These findings deviate from the results reported in other research papers, indicating a disparity in the observed phenomena.
- The surface roughness response surface methodology made in this investigation demonstrates strong validation through the use of independent checking data. In addressing the multi-objective optimization problem involving both MRR, and surface roughness, the Pareto-based GA proves to exist good robust device on behalf of variables minimized. A collection with Pareto clarification was obtained, offering a range of optimal outcomes for surface roughness and MRR.

Table 7: The data from the comparison study.

Machining type	Machining parameter			Ra (µm)	MRR (mm^3/min)
	Ap	V	F		
Conventional	0.8	480	0.4	0.85	140800
Optimal	0.8	750	0.8	0.593	141360

Nevertheless, significant research efforts are still required for expand with broad thoughtful with its machinability for this novel material. There is a need for further investigation into various aspects, that are material removal mechanism, chip formation. These areas will be the focus of upcoming studies to enhance our knowledge of the machining characteristics of this new material.

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None.

Conflict of Interest

None.

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