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Optimisation of Process Parameters in Drilling of Hybrid Al-TiB2-B4C Metal Matrix Composite using Grey- Taguchi Technique

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Metal matrix composites (MMCs) are composed of hard ceramic particles, which pose considerable challenges in machining due to their abrasive qualities. To promote their potential for extensive utilization, it is necessary to create a suitable technology for efficient machining. This research aims to explore the optimal parameters for drilling MMCs, utilizing the Taguchi Technique for analysis. The study involved the selection of six different combinations of hybrid Al7075/B4C/TiB2 composites for a comprehensive assessment of their machinability in drilling. The hybrid Al7075/B4C/TiB2 composites were developed using stir casting technique. The L18 Taguchi orthogonal array was adopted for the design of experiments (DOE). The selected parameters for the drilling operation encompass the composition of the hybrid composite (weight percentage of reinforcements), the drilling speed and the diameter of the drill tool. The response paramenter for the study were thrust force and surface roughness. The parameters were analysed using Taguchi signal to noise ratio. The weight percentage of reinforcement material is most significant factor for both the responses. The multi objective optimisation has been carried out using grey relational analysis.
Keywords: Hybrid metal matrix composite, Drilling, Taguchi analysis, Grey relational analysis, Thrust force, Surface roughness.

1. Introduction

Metal-matrix composites (MMCs) represent a cutting-edge class of materials engineered to improve performance across a range of industrial applications. These composites are characterized by a metallic matrix that is enhanced with ceramic materials, yielding a distinctive set of properties that can exceed those found in conventional metals and alloys. A key advantage of MMCs is their reduced weight, which plays a significant role in enhancing fuel efficiency and lowering emissions in the automotive and aerospace industries. Additionally, MMCs are known for their superior wear resistance, which prolongs the lifespan of components and reduces the frequency of maintenance or replacement. A vital component of metal matrix composites (MMCs) is the integration of ceramic reinforcements, which generally consist of materials like aluminum oxide (Al_2O_3), silicon carbide (SiC), and boron carbide (B_4C) [1]. The increasing appreciation for metal matrix composites (MMCs) stems from their unique properties, which integrate the toughness and ductility of the metal matrix with the high hardness and strength offered by ceramic reinforcements. A number of machining characteristics associated with MMCs are not yet fully comprehended, leading to divergent results in scholarly research. Nonetheless, a broad consensus indicates that these materials are difficult to machine [2] [3]. Consequently, research has been directed towards gaining a deeper understanding of these materials and improving their machinability.

The aerospace, automobile and marine sector relies heavily on twist drilling as a critical machining process, necessitating the creation of millions of holes for the assembly of structures, particularly in the fabrication of riveted and bolted connections [4]. J. Paulo Davim [5] has examined the impact of cutting speed, feed rate, and cutting time on the drilling performance in metal-matrix composites utilizing a Taguchi-based experimental design. The primary aim of this investigation was to establish correlations between input paarameters with tool wear, specific cutting pressure, and the roughness of holes. Multiple linear regression analysis was employed to derive these correlations. S, Senthi Babu et al. [6] presented a mathematical model formulated through response surface methodology aimed at optimizing drilling parameters to enhance hole quality in Al/SiC and Al/SiC/Gr composites. The experiments are performed on a CNC machine, manipulating spindle speeds, feed rates, and drill diameters to assess their impact on thrust force, torque, and the circularity of the holes produced. Utilizing ANOVA and regression analysis, the study identifies key influencing factors, and the resulting model offers precise predictions that improve the drilling process within defined parameter limits. Hari Singh et al. [7] utilized a grey-based Taguchi method to optimize drilling parameters on Al 6063/SiC MMC, converting multi-response outputs (surface roughness, burr height, and hole diameter error) into a single-response problem using grey relational analysis. Drilling experiments conducted with an L27 orthogonal array consider variables like cutting speed, feed rate, step angle, and cutting environment. The findings indicate that combining Taguchi's design of experiments with grey relational analysis effectively reduces surface roughness, burr height, and hole diameter error, improving the drilled hole's quality. J. Udaya Prakash et al. [8] investigated the optimization of drilling parameters for LM6/B4C/Fly ash composites, which incorporate 3, 6, and 9 wt.% reinforcements and are produced through stir casting techniques. Utilizing Taguchi's design of experiments, the study identifies key input factors such as feed rate, spindle speed, drill material, and reinforcement percentage, with the objective of reducing surface roughness and burr height. The optimal conditions for achieving minimal surface roughness were determined to be a feed rate of 50 mm/min, spindle speed of 3000 rpm, the use of a TiN-coated drill bit, and a reinforcement of 6 wt.%. Conversely, the ideal parameters for minimizing burr height were established at the same feed rate and spindle speed, with a TiN-coated drill bit and a reinforcement percentage of 9 wt.%. S. J. Juliyana [9] performed optimization of drilling parameters for $LM5/ZrO_2$ composites, utilizing the Taguchi Technique. The LM5 aluminum alloy was fabricated with 3, 6, and 9 wt.% Zirconia through stir casting. The research focused on analyzing the effects of feed rate, spindle speed, drill material, and reinforcement on thrust force, using an L27 orthogonal array and Signal-to-Noise ratio. The results indicate that spindle speed and feed rate are the most influential parameters, with ANOVA identifying the key variables that impact response characteristics.

2. Materials and method

2.1 Materials

The present study investigates Al 7075-T6, an aluminum-zinc alloy known for its remarkable strength, good fatigue resistance, and moderate machinability. This alloy is widely used in structural and aerospace applications due to its enhanced machinability characteristics [10] [11]. The research incorporates boron carbide (B_4C) and titanium diboride (TiB_2) as reinforcement materials. Table 1 shows the elemental composition of base Al 7075 material.

Table 1. Chemical composition of Al7075- T6

Composition	Zn	Si	Cu	Ti	Fe	Mg	Mn	Cr	Al
%	5.318	0.110	1.498	0.013	0.123	2.333	0.079	0.214	89.86

Stir casting process is used to manufacture the hybrid MMC. The process involves the use of an induction furnace to melt the aluminum 7075 matrix, with temperature stability maintained throughout the stirring operation. Prior to mixing, the reinforcement particles are preheated to 500°C for 40 minutes to eliminate moisture and avoid clumping. The aluminium material was then placed in a graphite crucible and heated to 800°C to achieve complete melting. A mechanical stirrer, powered by a variable-speed motor, is subsequently introduced into the molten aluminum and stirred for 10 minutes at a speed defined by the experimental conditions. To enhance the wettability of the mixture, 1% magnesium is added along with the reinforcement particles. The weight percentages of the reinforcement material (B_4C) incorporated into the mixture were 3%, 6%, and 9%. Similarly, the percentages of TiB_2 added to the composition were also 3%, 6%, and 9%.

2.2 Experimental Details

The drilling experiments were performed utilizing a computer numerical control (CNC) Vertical Machining Centre (model: Jyoti PX10). A range of carbide twist drills with 8, 10 and 12 mm diameters were used to drill workpieces composed of different materials. The thrust force during the drilling of hybrid metal matrix composites (MMCs) was measured using a Kirsler piezoelectric dynamometer The thrust force from the dynamometer is amplified and fed for electronic storage through a data–acquisition system. Additionally, surface roughness was assessed with a Mitutoyo SJ 201 surface roughness tester.

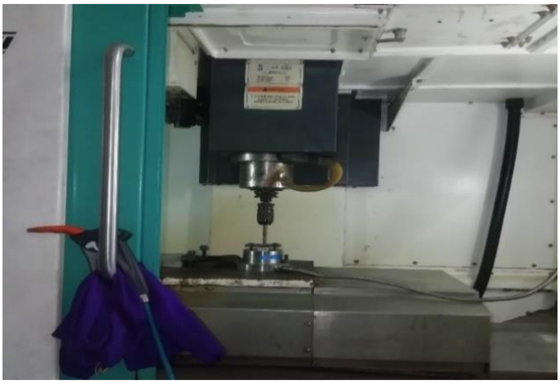

Fig. 1 Experimental Set up on VMC

Fig. 2 Workpieces after Drilling operation

2.3 Design of Experiments

The Taguchi method, recognized as an effective instrument in parameter design, was employed to carry out the experiments. An L18 orthogonal array, consisting of 18 rows corresponding to the number of experiments, was utilized for this purpose. This approach facilitated a straightforward, efficient, and systematic means of optimizing design with respect to performance, quality, and cost. The study incorporated six workpiece materials, which included five unique combinations of hybrid metal matrix composites (MMCs) alongside one conventional base matrix material. Furthermore, three varying levels of drilling spindle speed and drill diameter were established as additional process parameters. Table 2 lists the drilling parameters used as process control factors and the respective levels.

Table 2 Drilling parameter and levels

Parameters		Levels					
		1	2	3	4	5	6
A	Composition-%wt of reinforcements of Hybrid MMC	B_4C 0%-TiB_2 0%	B_4C 3%-TiB_2 9%	B_4C 6%-TiB_2 9%	B_4C 9%-TiB_2 3%	B_4C 9%-TiB_2 6%	B_4C 9%-TiB_2 9%
B	Drilling speed (RPM)	800	1000	1200	--	--	--
C	Drill tool diameter (mm)	8	10	12	--	--	--

2.4 Taguchi Analysis

The Taguchi method is an established framework for addressing optimization in engineering contexts; however, it is essentially a mono-optimization technique. This approach employs a statistical indicator known as the signal-to-noise (S/N) ratio to evaluate the effects of various process parameters, considering both the mean and the data variability. The S/N ratio is is vital for providing insights into the optimization needs. The calculation of the signal-to-noise ratio

(S/N) for each control factor is essential for understanding the effects of drilling parameters on response characteristics. Signals indicate the average response effects, while noises measure the discrepancies from these averages, which illustrate the sensitivity of the experimental results to noise factors. In this study, the S/N ratio was selected following the 'the smaller-the-better' approach to minimize the response effectively [7] .

Taguchi's S/N ratio: Smaller -is-better

$$\eta = -10\log_{10}\frac{1}{n}\sum_{i=1}^{n} {y_i}^2 \qquad (1)$$

3 Results and Discussions

Table 3 illustrates the L18 orthogonal array, highlighting thrust force and surface roughness as the key response parameters with S/N ratios.

Table 3 Experimental Results and S/N ratios

Experiment No.	Drilling Process Parameters			Responses and S/N ratios			
	Composition	Drilling Speed (RPM)	Drill Tool Dia. (mm)	Thrust Force (N)	S/N Ratio for Thrust Force (dB)	Surface Roughness (μm)	S/N Ratio for Surface Roughness (dB)
1	1	800	8	741.311	-57.400	1.347	-2.587
2	1	1000	10	685.491	-56.720	1.163	-1.311
3	1	1200	12	690.788	-56.786	1.390	-2.860
4	2	800	8	849.321	-58.581	1.411	-2.990
5	2	1000	10	641.311	-56.141	1.482	-3.416
6	2	1200	12	741.311	-57.400	1.509	-3.573
7	3	800	10	886.743	-58.956	1.865	-5.413
8	3	1000	12	910.788	-59.188	1.769	-4.954
9	3	1200	8	680.788	-56.660	1.268	-2.062
10	4	800	12	949.743	-59.552	1.729	-4.755
11	4	1000	8	852.592	-58.614	1.649	-4.344
12	4	1200	10	724.446	-57.200	1.473	-3.364
13	5	800	10	1049.743	-60.421	1.864	-5.408
14	5	1000	12	810.788	-58.178	1.978	-5.924
15	5	1200	8	741.311	-57.400	1.043	-0.365

16	6	800	12	1092.356	-60.767	1.946	-5.782
17	6	1000	8	741.311	-57.400	1.628	-4.233
18	6	1200	10	971.833	-59.751	1.981	-5.937

3.1 Effect on Thrust Force

The drill force acting along the direction of drill feed rate is called thrust force. During drilling of metals, the uniform thrust force is induced over a period due to the constant uncut chip thickness. Drilling triggers the push-out debonding, which is caused largely by a catastrophic breakdown of the composites due to thrust force. The forces acting on the workpiece must be analysed to attain better drilling characteristics, and it must be optimized to avoid adverse effect on the drilling process [12].

In Figure 3, the main effect plot for thrust force is displayed, whereas Figure 4 showcases the main effect plot for the S/N ratio related to thrust force. It is worth mentioning that the criteria for the S/N ratio is based on the principle of 'smaller is better'. It is observed that with increase in reinforcement particles thrust force also increases. Figure 3 indicated increase in weight percentage of reinforcement particles there is increase in thrust force. Any machining process is not just bringing two surfaces together to remove metals, but also breaking molecular bonds. This will create an incredible frictional heat between surfaces. It is obvious that the thrust force is a function of friction between tool and the workpiece. The higher the level of ceramic reinforcement, the higher the friction that will occur during the drilling and hence a higher thrust force .Moreover, as the weight percentage of reinforcement increases, the hardness of the developed composites also rises. This increased hardness poses challenges during machining, particularly in drilling, which consequently leads to an increase in the cutting force needed. The high-strength and hard reinforcement particles, even when they are extracted from the matrix, tend to remain in the cutting area and effectively resist the axial penetration of the tool. This interaction contributes to a greater thrust force as the percentage of reinforcement increases [13] [14].

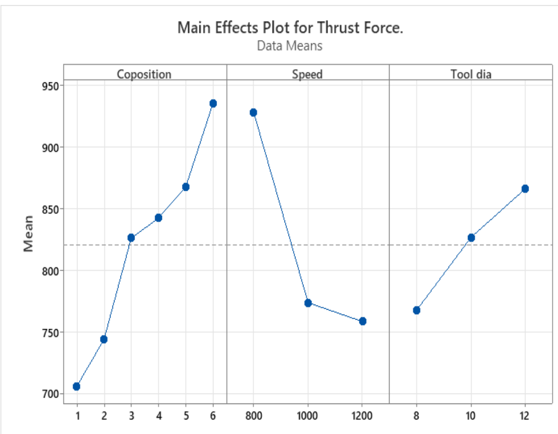

Fig. 3 Main effect plot of Thrust force

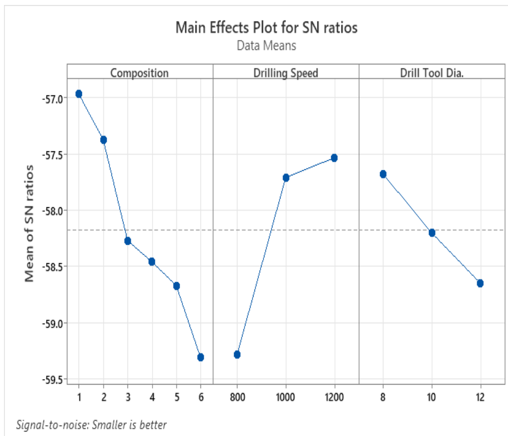

Fig. 4 Plot for S/N Ratios for Thrust force

From the Figure 5.13 it is seen that thrust force reduces with the increase of the drilling speed.

These changes are due to the coefficient of thermal expansion of the B4C and TiB2 particles into aluminum matrix, which caused an immense dislocation in the composite material. These changes are also vulnerable to heat intensity or temperature. Indeed, the influence of the cutting speed may impact the heat generation and increased the magnitude of heat on the drilling surface. This increase induced the portion of dislocation and caused thermal distress and hence the lower cutting force was observed at higher cutting speed [15]. Another reason for decrease in thrust for with speed is for given tool diameter and material hardness the increase in rotational speed increases the peripheral velocity and momentum of the tool. The tool edge covers greater cutting length in given time. Hence, with feed remaining constant the thrust force required for drilling is expected to reduce.

The drill diameter is one of the important factors as the drill diameter increases, the thrust force increases for the composite. For given rotational speed and material hardness with increase in tool diameter, the area to be cut increases. The drill diameter increases the area of contact between the tool and workpiece and the load on the tool subsequently increases the thrust force in drilling of hybrid composites. [16]

Table 4 Response Table of S/N Ratios for Thrust Force - Smaller is better

Level	Composition	Drilling Speed	Drill Tool Dia.
1	-56.97	-59.28	-57.68
2	-57.37	-57.71	-58.20
3	-58.27	-57.53	-58.65
4	-58.46		
5	-58.67		
6	-59.31		
Delta	2.34	1.75	0.97
Rank	1	2	3

In the S/N ratio analysis for thrust force, the 'smaller is better' criterion is applied. The response table in Table 4 illustrates the outcomes of this analysis. Notably, the composite material composition is rated the highest, followed by drilling speed, with drill tool diameter ranking the lowest. According to the S/N ratio analysis, the optimal levels are Composition 1 (Al 7075/ 0% B_4C/ 0%TiB_2 - level 1), 1200 rpm (level 3), and 8 mm diameter tool (level 1), as indicated in the main effect plot.

3.2 Effect on Surface Roughness

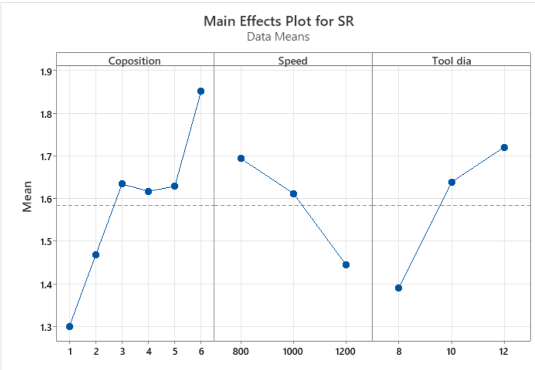

Fig. 5 Main effect plot of Surface Roughness

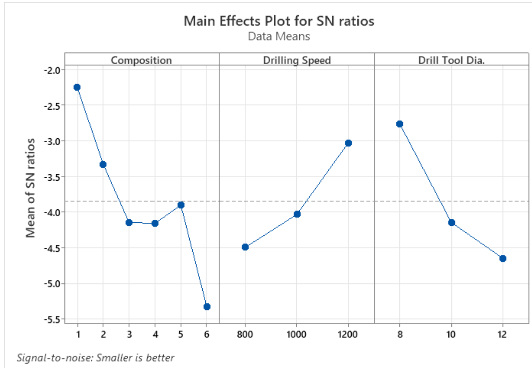

Fig. 6 Plot for S/N Ratios for Surface Roughness

In Figure 5, the main effect plot of surface roughness is depicted, while Figure 6 exhibits the main effect plots for S/N ratios related to surface roughness. When the tool diameter increases with the same hardness and rotational speed, the surface roughness also increases.

From the Figure 5 it is observed that with increase in reinforcement particles as per composition, the surface roughness increases. It is understood that the increase of the reinforcement particles in the composite affects the surface finish substantially. When the harder ceramic particles are included into matrix material, a poor surface finish is observed. This is due to the various mechanisms involved during machining: (i) breaking of the reinforcements particles, (ii) pulling out of particles from the matrix leading to the formation of voids, and (iii) formation of microcracks [17] . It is also observed from the figure 5 that the increase in spindle speed reduces the surface roughness in drilling of the hybrid composites. This is because that at high spindle speed, the force induced in cutting has been increased which in turn cuts the hybrid MMCs smoothly and produces lesser surface roughness than slow speed [18] [15]. Figure 5 indicates that the surface roughness is proportionate to the drill diameter. The increase of the drill diameter increases the surface roughness on drilling. This may be due to increase in drill diameter increases the surface area having harder particles for machining causes increase in surface roughness [19] .

Table 5 Response Table of S/N Ratios for Surface Roughness - Smaller is better

Level	Composition	Drilling Speed	Drill Tool Dia.
1	-2.253	-4.490	-2.764
2	-3.327	-4.031	-4.142
3	-4.144	-3.027	-4.642
4	-4.155		
5	-3.900		
6	-5.318		
Delta	3.065	1.463	1.878

Rank	1	3	2

The S/N ratio analysis for surface roughness employs the 'smaller is better' criterion. The outcomes of this analysis are presented in Table 5, which illustrates the response table. Notably, the composite material composition is rated the highest, followed by the drilling tool diameter, while the drilling speed is ranked the lowest. The S/N ratio analysis indicates that the best combination includes Composition 1 (Al 7075/ 0% B_4C/ 0%TiB_2 - level 1), 1200 rpm (level 3), and an 8 mm diameter tool (level 1), as outlined in the main effect plot.

3.3 Grey Relational Analysis Optimisation

Consequently, researchers often utilize Grey Relational Analysis (GRA) in conjunction with Taguchi Analysis to achieve the simultaneous optimization of multiple responses [20]. The process of Grey analysis consists of a coherent collection of statements regarding system solutions. Generally, one extreme presents no viable solution, whereas the other extreme showcases a system with exceptional data that leads to a specific solution. In the central region, Grey systems can facilitate a practical solution. Grey Relational Analysis (GRA) does not aim to highlight the simplest answer; instead, it offers approaches to identify a suitable and applicable solution for real-world problems [21]. The outcomes of our experiments are scrutinized for optimization by employing the Grey–Taguchi technique, a combined methodology designed for effective optimization.

An evaluation of the two output responses from the 18 drilling experiments was conducted using their corresponding signal-to-noise ratio (S/N) values, applying the "smaller the better" formula for thrust force and surface roughness. It is essential to normalize the data through equation (2) to lessen the variation present. In pursuit of minimizing surface roughness and , the "lower is better" aspect of grey relational analysis was utilized for the normalization procedure. The original sequence can be normalized as demonstrated below .

In instances where the original sequence exhibits the characteristic of "lower is better," it is necessary to normalize the original sequence as follows:

$$X_i = \frac{\max \gamma_i - \gamma_i}{\max \gamma_i - \min \gamma_i} \qquad (2)$$

Xi represents the normalized S/N value and Y_i represents S/N value for any particular response for an experiment.

Within the framework of hybrid Grey–Taguchi analysis, the calculation of the Grey relational coefficient (GRC) is performed using the normalized signal-to-noise ratio (S/N) values, as specified in Equation (3). Following this calculation, the Grey relational grade (GRG) can be determined, which aids in elucidating the relationship between the most favorable experimental results and the actual outcomes [22] [23].

The sequences of deviation were computed by taking the difference between the normal sequence values and 1, with the findings presented in Table 6 [24].

The grey relational coefficient can be determined as :

$$\xi_i(k) = \frac{\Delta_{min} + \xi\Delta_{max}}{\Delta_{0i}(k) + \xi\Delta_{max}} \qquad (3)$$

Where, $\Delta_{0i}=|x_0(k) - x_i(k)|$ = difference of the absolute value

between $x_0(k)$ and $x_i(k)$;

ξ = distinguishing coefficient in between zero and one, assuming value 0.5.

$\Delta_{min} = \min||x_0(k) - x_i(k)||$ = smallest value of Δ_{0i}

$\Delta_{max} = \max ||x_0(k) - x_i(k)||$ = largest value of Δ_{0i}.

The determination of the grey relational grade γi is accomplished through the averaging of the grey relational coefficients, as illustrated in the equation presented below.

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n}\xi_i(k) \qquad (4)$$

Table 6 presents the computed grey relational coefficient along with the corresponding grey relational grade.

Table 6 Grey Relational Grade

Exper. No.	Normalizing sequence		Deviation sequence		Grey relational coefficient		GRG
	Thrust force	Surface Roughness	Thrust force	Surface Roughness	Thrust force	Surface Roughness	
1	0.272	0.399	0.728	0.601	0.407	0.454	0.431
2	0.125	0.170	0.875	0.830	0.364	0.376	0.370
3	0.139	0.448	0.861	0.552	0.367	0.475	0.421
4	0.527	0.471	0.473	0.529	0.514	0.486	0.500
5	0.000	0.548	1.000	0.452	0.333	0.525	0.429
6	0.272	0.576	0.728	0.424	0.407	0.541	0.474
7	0.609	0.906	0.391	0.094	0.561	0.842	0.701
8	0.659	0.824	0.341	0.176	0.594	0.739	0.667
9	0.112	0.305	0.888	0.695	0.360	0.418	0.389
10	0.737	0.788	0.263	0.212	0.656	0.702	0.679
11	0.535	0.714	0.465	0.286	0.518	0.636	0.577
12	0.229	0.538	0.771	0.462	0.393	0.520	0.457
13	0.925	0.905	0.075	0.095	0.870	0.840	0.855
14	0.440	0.998	0.560	0.002	0.472	0.995	0.734

15	0.272	0.000	0.728	1.000	0.407	0.333	0.370
16	1.000	0.972	0.000	0.028	1.000	0.947	0.974
17	0.272	0.694	0.728	0.306	0.407	0.620	0.514
18	0.780	1.000	0.220	0.000	0.695	1.000	0.847

The average GRGs for all three responses have been calculated at each of the three levels and are presented in a response table, as illustrated in Table 7. Additionally, the overall mean of these nine GRGs is denoted as the mean GRG within the same table.

Table 7. Response Table For Grey Relational Grade

Level	Composition	Drilling speed	Drill tool dia.
1	0.407	0.690	0.464
2	0.468	0.548	0.610
3	0.586	0.493	0.658
4	0.571		
5	0.653		
6	0.778		
Delta	0.371	0.197	0.195
Rank	1	2	3
Mean Grey relational grade = 0.577			

The grey relational grade indicates the extent to which drilling process parameters affect performance characteristics. A larger grey relational value correlates with higher quality performance. Therefore, the optimal drilling parameters correspond to a higher grey relational grade. The key factors influencing drilling, which are vital for optimizing thrust force and surface roughness, include the composition or weight percentage of the reinforcement material, followed by spindle speed and drill tool diameter, as demonstrated by their ranking in the response table. The optimal levels for the input factors in drilling operations are identified as the maximum grey relational grade for each factor, leading to the conclusion that the best parameters are level 6 for the composition (Al/9% B_4C/9% TiB_2), level 1 for spindle speed (800 rpm), and level 3 for drill tool diameter (12 mm).

4 Conclusions

The aluminum-based hybrid composite (Al7075/B_4C/TiB_2) specimens were fabricated using the stir casting technique and then subjected to machining. Drilling operations were performed based on Taguchi's L18 orthogonal array, incorporating six different workpiece materials, three distinct drilling speeds, and three varying drill tool diameters. The conclusions drawn from the experimental studies are outlined below. The outcomes of the diverse examinations reveal the following insights:

1. The evaluation of the main effect plot across all responses indicates that thrust force and surface roughness tend to increase with higher weight percentages of B_4C and TiB_2 particle reinforcement. In contrast, an increase in speed generally leads to a reduction in these responses. Furthermore, the trend in responses is positively correlated with an increase in drill diameter.

2. According to the Taguchi analysis focused on the signal-to-noise (S/N) ratio, the composition or weight percentage of reinforcements stands out as the most critical factor impacting thrust force and surface roughness. For thrust force, the drilling speed ranks as the second most significant parameter, whereas for surface roughness, the drill diameter plays a crucial role.

3. Taguchi S/N ratio analysis indicate that the parameters most effective for minimising thrust force and surface roughness are Composition level 1 (Al 7075/ 0% B4C/ 0%TiB2), level 3 of speed 1200 rpm , and an level 1 drill tool diameter of 8 mm.

4. The results of the grey relational analysis for the optimization of various properties show that Experiment 16 attains the highest grey relational grade associated to input parameters of coposition- Al 7075/ 9% B_4C/ 9% TiB_2 and drilling speed of 800 rpm and drill diameter of 12 mm.

5. The findings from the grey relational grade analysis indicate that the composition of hybrid metal matrix composites (MMCs) is the most critical parameter, with speed serving as the second most influential factor, and drill diameter being the least significant in terms of its effect.

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