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Prediction of Optimal Drilling Parameters of Aa6063/Sic/B_4c/Fa Hybrid Composites using Taguchi and Topsis Techniques

Thirupathaiah C[a], Sanjeev Reddy K Hudgikar *[b]

[a,] *Research Scholar, Department of Mechanical Engineering, Visvesvaraya Technological University (VTU) Recognized Research Centre, Visvesvaraya Technological University, Belgaum, Karnataka, India – 590018, India.*

Email: cblthiru@gmail.com, *Orcid iD: https://orcid.org/ 0000-0002-5145-6417.*

[*b,] *Professor, Faculty of Engineering &Technology (Co-Edu), Sharnbasva University, Kalaburagi, Karnataka - 585103, India.*

Corresponding Email: drhudgikar@gmail.com

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ABSTRACT

This research explores the optimal machining parameters for drilling AA6063/SiC/B4C/FA hybrid composites using a novel multi-response optimization approach that TOPSIS with a Taguchi-based technique. AA6063, an architectural alloy, is characterized by limited strength, surface hardness, and moderated machinability. To enhance these properties, ceramic particles such as SiC, B_4C, and FA are incorporated into the base AA6063 using a stir-casting process. This study aims to optimize the drilling conditions to improve the performance and durability of the resulting hybrid composites. A Taguchi L-32 experimental array was employed to assess the effects of drilling parameters, including spindle speed (1000, 1250, 1500 and 1750 rpm), feed rate (0.1, 0.15, 0.2, and 0.25 mm/rev), point angle (60°, 90°, 118°, and 135°), and tool type (HSS and carbide). The study evaluated the surface roughness (Ra), and material removal rate (MRR) of drilled holes using ANOVA and TOPSIS analysis. The results indicate that the ideal drilling parameters are1500 rpm (speed), 0.25 mm/rev (feed), 90° (point angle) with carbide tool for optimal Ra and MRR.

Keywords: AA6063, TOPSIS, Taguchi, ANOVA, MRR, Surface Roughness, delamination

1.0 INTRODUCTION

AA6063 is widely recognized architectural alloy that finds applications across various industries, including automotive, aerospace, and construction (structural), particularly for the fabrication of components like doors, windows, roofs and others [1, 2]. AA6063 possess moderate strength and excellent extrudability, making it an ideal choice for lightweight structures where high strength is not the primary concern [3, 4]. Also, AA6063 possess good corrosion resistance and ability to achieve smooth surface finishes. However, while AA6063 serves well in many contexts; its mechanical properties may limit its use in more demanding environments where enhanced durability and performance are required[5]. To overcome these limitations, researchers and manufacturers have rapidly focused on the incorporation of ceramic particles (both micro and nano particles), such as borides (TiB_2, WB, ZrB_2), carbides (B_4C, SiC, TiC, W_2C, WC, ZrC and so on), nitrides (AlN, BN, Si_3N_4, TiN, ZrN and many), oxides (Al_2O_3, Cr_2O_3, CeO_2, SiO_2, ZrO_2 and others) and others, into the AA6063 matrix [6, 7]. The addition of these ceramic materials not only enhances mechanical properties (strength and toughness), thermal stability, tribological properties (wear and friction), but also aids to reduced weight and improved longevity of the resultant composite material.

There are various techniques are available to produce AA6063 MMCs including liquid-state (stir-casting, squeeze casting, centrifugal casting and so on) and solid-state (powder metallurgy, compo-casting, and others) processing techniques [8]. Among these methods, stir casting is considered one of the most pioneering techniques due to its simplicity and effectiveness in achieving uniform dispersion of ceramic reinforcements within the molten metal matrix [9, 10]. This process helps to minimizing agglomeration and ensuring that the composite material possesses enhanced mechanical properties throughout its volume. Selvan et al. (2023) optimized stir-casting variables such as the percentage of reinforcements (Gr and MoS_2), stirring speed, and pouring temperature, all of which significantly influence the hardness and wear resistance of hybrid composites. The experiments were designed using a Taguchi L9 matrix, and statistical analysis identified the optimal parameters: a stirring speed of 400 rpm, a reinforcement percentage of 1.5 wt% for Gr and MoS_2, and a pouring temperature of 760°C, as determined by the Data Envelopment Analysis Ranking (DEAR) method. Under these optimal conditions, the hybrid composite demonstrated a reduced wear rate of 1.65×10^{-3} mm^3/min and an increased hardness of 128 HV [11].

Aircraft structural applications require precise drilling of tons of holes for rivets and bolts, where both accuracy and surface finish are critical for structural integrity and performance. The machinability of hybrid metal matrix composites (MMCs) poses significant challenges such as leading to increased tool wear, cutting forces, and energy consumption during machining processes like turning, milling, and drilling because of the presence of hard reinforcement particles [12, 13]. As drilling accounts for about 33% of machining operations, optimizing parameters such as spindle speed, feed rate, and drill point angle is essential to improve surface quality and reduce tool wear. Advanced tooling solutions and innovative strategies, including coated tools and adaptive machining, are vital to overcoming these challenges, ensuring efficient and high-quality machining of hybrid MMCs for aerospace applications [14, 15].

In this connection, the Data Envelopment Analysis Ranking (DARE) method was employed to determine the optimal drilling conditions for AA2219/B_4C/Gr/MoS_2 MMCs, focusing on burr height (BH), material removal rate (MRR), and thrust force (TF). The optimal drilling parameters identified were a feed rate (FR) of 0.25 mm/rev, drilling speed (DS) of 20 m/min, and drill tool material (DM) as a coated carbide tool. These conditions resulted in an optimal MRR of 645 mm^3/min, TF of 2.95 kN, and BH of 0.16 mm, respectively [11]. The Grey Relational Approach was utilized to assess the influence of drilling parameters on LM/B_4C composites. The results revealed that a feed rate of 50 mm/min, spindle speed of 3000 rpm, and drill material as HSS, combined with LM/9wt.%B_4C composite, achieved the top ranking compared to designed L27 experimental combinations. Additionally, statistical analysis indicated that feed rate (33.3%) is the most significant parameter, trailed by reinforcement (26.3%), spindle speed (11.3%), and drill material (5.9%) [16, 17]. Composites reinforced with graphite (Gr) demonstrated superior drilling performance compared to those reinforced with MoS2 in AA2219 composites. Graphite reinforcement emerged as the most significant factor influencing surface roughness across all test conditions. The findings also revealed that the best surface finish was achieved at a higher drilling speed (1600 rpm) and a lower feed rate (75 mm/min) using a 6 mm drill bit, [18]. Using the Taguchi L27 Orthogonal Array (OA), experiments were designed to determine the optimal drilling parameters for Al5059/SiC/2%MoS_2 MMCs using the NSGA-II algorithm. The results showed that the best MRR was 0.078166 g/min, and the optimal temperature was 34.52 °C. These optimal outcomes were achieved with a drilling speed of 610.5484 rpm, a feed rate of 25.01983 mm/min, and 5.84 wt.% of SiC with a particle size of 23.5 µm [19].

Chakraborty et al., (2023) applied newly developed multi-criteria decision making (MCDM) tool, known as ordinal priority approach (OPA), to address two parametric optimization problems related to drilling operations of Al-MMCs. In the first case, the optimal combination of drilling parameters are cutting speed of 87.96 mm/min, feed rate of 0.050 mm/rev, and point angle of 140°, resulted in balanced values for average surface roughness (Ra - 6.01 µm), cutting force (Fc - 274.57 N), and torque (T - 0.69 Nm). On the other hand, in the second example, the optimal parametric combination of spindle speed at 2000 rpm, feed rate of 0.2 mm/rev, and a carbide drill bit led to the most favourable results for thrust force (TF - 368.910 N), average surface roughness (Ra - 2.030 µm), and burr height (BH - 0.11 mm) [20]. Further, the Reference Ideal Method (RIM) was applied to solve a multi-objective optimization problem aimed at determining the optimal spindle speed and feed rate to achieve the maximum MRR, minimum diameter error (DE), and minimum roundness error (RE) simultaneously. The results indicated that a spindle speed of 1280 rpm and a feed rate of 0.16 mm/rev ensure the highest MRR, the lowest DE, and minimal RE [21]. The drill point angle had the greatest influence on minimizing hole surface roughness and roundness error, followed by drilling speed and feed rate for Al7075/SiC/WC MMCs. For unconstrained optimization, the finest conditions were found to be a 128°-point angle, a feed rate of 0.05 mm/rev, and a drilling speed of 1000 rpm. In contrast, for constrained optimization, the finest conditions were a 118°-point angle, a feed rate of 0.05 mm/rev, and a drilling speed of 1000 rpm [22]. Drilling experiments on LM5/ZrO2 composites were conducted using Taguchi's Design of Experiments (DoE) and analyzed through Grey Relational Analysis (GRA). The results revealed that the thrust force (TF), surface roughness (SR), and burr height (BH) decreased as the feed rate was reduced across all specimens. The most statistically significant parameter affecting the Grey Relational Grade (GRG) was drill material (29.08%), followed by feed rate (24.24%) and spindle speed (19.52%). The predicted GRG was 0.824, while the experimental GRG was 0.856, resulting in a minimal error of 3.7% [23]. Following this, the process variables in the drilling of LM6/B4C composites were successfully optimized, as confirmed by validation studies. Thrust force (TF), surface roughness (SR), and burr height (BH) decreased as the feed rate decreased similarly as spindle speed increased for all specimens. The TiN-coated carbide drill bit provided the best surface roughness and burr height values across all composites. The predicted Grey Relational Grade (GRG) was 0.846, while the experimental GRG was 0.865, resulting in a minimal error of 2.2%, confirming the validity of the optimization process [24]. The influence of rotational speed, feed rate, and mica reinforcement percentage on thrust force and torque was investigated for Al/B4C/Mica hybrid composites, with the analysis conducted using multi-objective optimization through a non-dominated sorting genetic algorithm (NSGA-II). The results indicated that a rotational speed of 1840 rpm, a feed rate of 25.3 mm/min, and 5.83% mica reinforcement provided the optimal parameters for achieving the lowest thrust force of 339.68 N and torque of 68.98 N.m. The Al/10 wt.% B4C/5.83 wt.% mica composite is recommended for automotive applications, [25]. A study using the Box–Behnken design optimized the drilling of AA2024/GFRP/AA2024 metal-composite laminates for aeronautical structures. It found that using the 85C uncoated carbide drill with a 0.05 mm/rev feed rate and 20 m/min cutting speed minimized delamination factors (FdaE = 1.18, FdaS = 1.33) and thrust force (67.3 N), [26]. The optimized drilling parameters are spindle speed of 1448.50 rpm, feed rate of 48.09 mm/min, cutting angle of 135°, and 1.16% nano SiC were determined using the Teaching–Learning-Based Optimization (TLBO) technique. The experiments were designed using response surface methodology (RSM) based on a Box-Behnken design. The results showed a 44% reduction in thrust force (Tf), a 40.4% decrease in surface roughness (Ra), an 85% reduction in burr height, and a temperature reduction of over 100% during LN2-assisted drilling.

Machining attributes can be forecasted and optimized using hybrid models like artificial neural network-simulated annealing (ANNSA) and artificial neural network-genetic algorithm (ANN-GA). However, training backpropagation networks is complex, and genetic algorithms often struggle with ambiguity in multi-response optimization[27–29]. To address these challenges, alternative methods such as Grey Relational Analysis (GRA), Principal Component Analysis (PCA), Data Envelopment Analysis (DEA), and neural networks have been developed [30–33]. Among these, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is particularly effective for multi-response optimization. It ranks solutions based on multiple criteria, offering a simple and intuitive approach for selection challenges where minimal changes are needed [34, 35]. TOPSIS is valued for its ease of implementation and ability to solve complex optimization problems. In summary, while hybrid models like ANNSA and ANN-GA are promising, the complexity of their training makes methods like GRA, PCA, and TOPSIS valuable alternatives for optimizing machining attributes [36].

From the extensive literature it is observed that there is a limited research work is obtained on the optimization of drilling process parameters on the AAs, particularly on AA6063. Though the available research used the ANNSA, ANN-GA, GRA, PCA, and DEA techniques to find the optimal parameters which were not upto the extend. Therefore, in this work novel TOPSIS technique is used to predict the multi-response optimization of Ra and MRR of Al6063/SiC/B4C/FA hybrid composite co-relating with the ANOVA.

2.0 MATERIALS AND METHODS

2.1 Materials

In this work, Al6063 base metal was procured from the M/s. Perfect Metals, Bangalore. Its chemical composition was shown in the Table-1. The ceramic particles (reinforcements) like SiC, B_4C and fly-ash of sizes 70, 65 and 90 microns respectively were purchased with 99 % purity.

Table 1 Chemical composition of Al6063

Cu	Mg	Si	Fe	Mn	Ni	Zn	Sn	Ti	Al
0.1	0.2-0.6	6.5-7.5	0.5	0.5	0.1	0.1	0.1	0.05	Remains

2.2 Stir-casting process

Before producing Al6063/SiC/B_4C/FA hybrid composite, the stir-casting machine (ref. Figure 1) was cleaned, and lubricants were applied to prevent Al6063 from sticking to the furnace and other surfaces. One kilogram of Al 6063 alloy was heated in an electric furnace up to 800 °C, ensuring that the ingots were completely melted. Then, preheated reinforcement (1.0 wt.% of SiC, 1.0 wt.% of B_4C, and 1.0 wt.% of fly-ash) at 400 °C was gradually added into the molten Al6063 alloy at 700 °C of maintained temperature. A zirconia-coated, two-blade stainless steel stirrer mixed the reinforcement into the molten Al6063 at 500 rpm for 5 minutes, moving up and down to prevent particle agglomeration. To improve wetting, 1% pure Mg was added to the molten metal, and slags (unwanted materials) were manually removed using tongs [37]. Argon gas was supplied during the process to prevent oxide formation[4]. The molten metal was then poured into the preheated die (350 °C) of 200 X 60 X 25 mm size through the pre-heated pathway (300 °C), and the Al6063/SiC/B_4C/FA hybrid composite sample were die-cooled for an hour to ensure a consistent cooling rate. Finally, the samples were prepared using wire-cut electric discharge machining for further analysis and testing.

Figure 1 Stir-casting set-up used to produce Al6063/SiC/B_4C/FA hybrid composites

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2.3 Drilling of Al6063/SiC/B_4C/FA hybrid composites

The Al6063/SiC/B4C/FA hybrid composite was machined to dimensions of 150 mm x 50 mm x 20 mm. The selected process parameters and their levels for the experiments are shown in Table 2. Experiments were conducted using a vertical drilling machine (AMS MCV- 400) based on the L32 orthogonal array designed in MiniTab. Each hole was drilled with unique variable combinations across the plate. Following the drilling process, delamination, material removal rate, and surface waviness were recorded as key outcomes. For each sample, three measurements were taken, and an average value was considered as the Ra value. Surface quality was assessed using a Talysurf III analyser, with a 0.8 mm cut-off length to examine surface texture. To ensure uniformity, holes were drilled with equal spacing and positioned adequately away from the plate boundaries. The MRR during drilling was measured using the equation (1).

$MRR = \frac{\pi D^2 f N}{4}$ --------Eq (1)

Where, D - Diameter of the drilled hole (mm); f - Feed rate (mm/rev); N - Spindle speed (RPM) and π - Constant (3.1416)

Table 2: Levels of Input factors

Factor	Levels			
	Level 1	Level 2	Level 3	Level 4
Tool type	HSS	Carbide	-	-
Speed (rpm)	1000	1250	1500	1750
Feed (mm/rev)	0.1	0.15	0.2	0.25
Point of angle (Deg)	60	90	118	135

Figure 2.AMS-MCV-400 CNC Vertical Milling Centre

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Research Article

2.4 Signal-to-noise (S/N) ratio analysis

The performance characteristics are influenced by process conditions and variations, particularly in surface roughness (Ra) and material removal rate (MRR) values. To analyze these factors, Taguchi's Design of Experiments (DOE) is employed to determine the number of experiments and compute the S/N ratio for optimization [38]. The S/N ratios are calculated using three performance characteristics: larger-the-better, nominal-the-better, and lower-the-better [39–41]. Maximizing the S/N ratio enhances the desired output while minimizing noise factors. This study aims to achieve a minimum Ra and maximum MRR for superior surface finish and efficient machining. Specifically, the Ra of Al6063/SiC/B_4C/FA composites is analyzed using a 'smaller-the-better' approach to minimize Ra, while the MRR is assessed with a 'larger-the-better' approach to maximize MRR. A higher S/N ratio indicates better performance. The significant parameters for Ra and MRR are estimated using Taguchi's mathematical equations, with the experimental results and their corresponding S/N ratios presented in Table 3.

Table 3. Drilling investigational results with respective DOE on Al6063/SiC/B_4C/FA hybrid composite.

S.No.	Tool type	Speed (rpm)	Feed (mm/rev)	Point of angle (Deg)	Surface Roughness Ra (μm)	S/N Ratio of Ra	MRR (mm3/min)	S/N Ratio of MRR
1	HSS	1000	0.1	60	3.686	-11.331	5024	74.021
2	HSS	1000	0.15	90	3.785	-11.561	7536	77.543
3	HSS	1000	0.2	118	3.923	-11.872	10048	80.042
4	HSS	1000	0.25	135	4.102	-12.260	12560	81.980
5	HSS	1250	0.1	60	3.521	-10.933	6280	75.959
6	HSS	1250	0.15	90	3.665	-11.281	9420	79.481
7	HSS	1250	0.2	118	3.525	-10.943	12560	81.980
8	HSS	1250	0.25	135	3.451	-10.759	15700	83.918
9	HSS	1500	0.1	90	2.659	-8.494	7536	77.543
10	HSS	1500	0.15	60	3.106	-9.844	11304	81.065
11	HSS	1500	0.2	135	2.667	-8.520	15072	83.563
12	HSS	1500	0.25	118	2.552	-8.138	18840	85.502
13	HSS	1750	0.1	90	2.448	-7.776	8792	78.882
14	HSS	1750	0.15	60	3.124	-9.894	13188	82.404
15	HSS	1750	0.2	135	2.534	-8.076	17584	84.902
16	HSS	1750	0.25	118	2.756	-8.806	21980	86.841
17	Carbide	1000	0.1	135	2.632	-8.406	5024	74.021
18	Carbide	1000	0.15	118	2.786	-8.900	7536	77.543
19	Carbide	1000	0.2	90	3.523	-10.938	10048	80.042
20	Carbide	1000	0.25	60	3.625	-11.186	12560	81.980
21	Carbide	1250	0.1	135	1.889	-5.525	6280	75.959
22	Carbide	1250	0.15	118	1.753	-4.876	9420	79.481
23	Carbide	1250	0.2	90	2.828	-9.030	12560	81.980
24	Carbide	1250	0.25	60	3.454	-10.766	15700	83.918

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Research Article

25	Carbide	1500	0.1	118	1.552	-3.818	7536	77.543
26	Carbide	1500	0.15	135	1.495	-3.493	11304	81.065
27	Carbide	1500	0.2	60	2.553	-8.141	15072	83.563
28	Carbide	1500	0.25	90	2.672	-8.537	18840	85.502
29	Carbide	1750	0.1	118	1.254	-1.966	8792	78.882
30	Carbide	1750	0.15	135	1.535	-3.722	13188	82.404
31	Carbide	1750	0.2	60	1.972	-5.898	17584	84.902
32	Carbide	1750	0.25	90	2.032	-6.158	21980	86.841

2.5 TOPSIS methodology

TOPSIS is a powerful multi-criteria decision-making tool, ideal for complex manufacturing scenarios where numerous criteria and options interact, significantly influencing outcomes. This method efficiently identifies optimal drilling conditions by evaluating actual criteria measures and their relative importance, making it applicable to any decision-making problem. TOPSIS ranks alternatives by choosing the one closest to the positive ideal solution and farthest from the negative ideal, thus ensuring the best possible decision[42–44].

Step 1: In TOPSIS, the initial phase is the decision matrix, which consists of n criteria and m alternatives, represented as:

$D_m = [x_{11}\ x_{12}\ \cdots\ x_{1n}\ x_{21}\ x_{22}\ \cdots\ x_{2n}\ \cdots\ \cdots\ \cdots\ \vdots\ x_{m1}\ x_{m2}\ x_{m1}\ x_{mn}\ ]$ ------------- Eq (2)

Step 2: The normalized matrix id generated using the following equation:

$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}$, j=1,2,3, ...n ------------- Eq (3)

Step 3: The weight of each attribute is denoted as Wj (where j=1, 2, ... n). The weighted normalized values can be computed as:

$V = w_j r_{ij}$ ------- Eq (4),

where $\sum_{j=1}^{n} w_j = 1$

Step 4: The following expressions were used to find the ideal (best) and negative (worst) solutions.

V+ = $\{ (\sum_i^{max} v_{ij}\ j \in J), (\sum_i^{min}\ j \int\ j\ \ i = 1,2,3 \ldots\ldots m)\}$ - - - - - Eq (5)

which results in $v_1^+, v_2^+, v_3^+, \ldots \ldots \ldots, v_n^+$

Similarly, the negative ideal solution is given by:

V- = $\{ (\sum_i^{min} v_{ij}\ j \in J), (\sum_i^{max}\ j \int\ j\ i = 1,2,3 \ldots\ldots m)\}$ - - - - - Eq (6)

which results in $v_1^-, v_2^-, v_3^- \ldots \ldots \ldots, v_n^-$

Step 5: The difference of each alternative from the ideal solution is calculated as follows:

$S_i^+ = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^+)^2}$, $i = 1,2,3, \ldots \ldots, m$ - - - - - Eq (7)

For the negative ideal solution, it is:

$S_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2}$, $i = 1,2,3, \ldots \ldots, m$ - - - - - Eq (8)

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Step 6: The closeness of a specific alternative to the ideal solution is calculated using the following formula:

$$Ci = \frac{S_i^-}{S_i^+ + S_i^-}, \quad i = 1,2,3, \dots \dots m$$ ------Eq (9)

Step 7: Finally, to identify the most preferred and least preferred alternatives, the Pi values are ranked in descending order.

3.0 RESULTS AND DISCUSSIONS

The drilling experimental results (S/N ratios of Ra and MRR) with respective DOE data of Al6063/SiC/B_4C/FA hybrid composites are presented in Table 3.

3.1 Analysis of variance analysis (ANOVA) for Ra and MRR

ANOVA is a widely used statistical tool for analyzing the influence of independent factors on the dependent parameters. In this study, ANOVA was employed to evaluate the contributions of key process parameters, namely tool type, spindle speed, feed rate, and point angle, on Ra and MRR during the drilling of Al6063/SiC/B_4C/FA hybrid composite. Table 4 presents the ANOVA results for Ra and MRR, highlighting the influence of these parameters.

The ANOVA results for Ra indicate the relative importance of each drilling parameter based on the F-value and P-value, analysed at a confidence level greater than 95%. The F-values show that tool type is the most influential parameter, with the highest F-value of 110.17, contributing nearly 60.44% to the total probability in Ra. This is followed by spindle speed (F = 42.95, contributing ~23.56%), point angle (F = 15.89, contributing ~8.72%), and feed rate (F = 13.28, contributing ~7.29%). The P-values further confirm the statistical significance of these factors, with tool type ($P = 8.24 \times 10^{-10}$), spindle speed ($P = 1.27 \times 10^{-5}$), point angle ($P = 4.42 \times 10^{-5}$), and feed rate ($P = 1.27 \times 10^{-5}$) all being much smaller than the threshold of 0.05. Additionally, the standard error of regression (S = 0.8275) indicates that the predicted values are closely aligned with the observed data. The coefficient of determination (R-Sq = 94.0%) demonstrates that the model explains a substantial portion of the variability in the response variable, while the adjusted R-Sq (91.1%) accounts for model complexity, further confirming its robustness. These findings underscore the reliability of the developed model in capturing the effects of the process parameters on the Ra responses.

Table 4. Analysis of variance (ANOVA) results for Ra and MRR of Al6063/SiC/B_4C/FA hybrid composite

	ANOVA for Ra						ANOVA for MRR					
Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
Tool type	1	75.43	75.43	75.43	110.17	8.24e−10	1	0	0	0	*	*
Speed (rpm)	3	88.22	88.22	29.41	42.95	3.87e−9	3	105.26	105.26	35.09	*	*
Feed (mm/rev)	3	27.27	27.27	9.091	13.28	4.42e−5	3	283.36	283.36	94.45	*	*
Point of angle (Deg)	3	32.63	32.63	10.88	15.89	1.27e−5	3	0	0	0	*	*
Residual Error	21	14.38	14.38	0.69			21	0	0	0		
Total	31	237.94					31	388.62				

Table 5. Ranking of Ra and MRR for Al6063/SiC/B_4C/FA hybrid composite

	Ranking of Ra				Ranking of MRR			
Level	Tool type	Speed (rpm)	Feed (mm/rev)	Point of angle (Deg)	Tool type	Speed (rpm)	Feed (mm/rev)	Point of angle (Deg)
1	-10.031	-10.807	-7.281	-9.749	80.98	78.4	76.6	80.98
2	-6.96	-9.264	-7.946	-9.222	80.98	80.33	80.12	80.98
3	-	-7.373	-9.177	-7.415	-	81.92	82.62	80.98
4	-	-6.537	-9.576	-7.595	-	83.26	84.56	80.98
Delta	3.071	4.27	2.295	2.335	0	4.86	7.96	0
Rank	2	1	4	3	4	2	1	3

For MRR, feed rate and spindle speed emerge as the most dominant parameters. This dominance can be attributed to their direct involvement in determining the MRR, as described in Eq. (1). The feed rate dictates the depth of material removed per revolution, while spindle speed controls the cutting speed, both of which play critical roles in the mechanics of material removal of Al6063/SiC/B_4C/FA hybrid composite. Their importance is clearly reflected in the high sequential sum of squares (Seq SS) and adjusted mean square (Adj MS) values for feed rate and spindle speed (Table 4). In contrast, tool type and point angle exhibit negligible or no influence on MRR, as their Seq SS and Adj MS values are zero. This lack of contribution can be attributed to their minimal role in directly altering the MRR. While these parameters might affect other performance metrics such as surface quality or tool wear, their impact on MRR remains insignificant under the investigated conditions. The deterministic nature of the relationship between MRR and the drilling parameters ensures that the observed trends are consistent and repeatable across all experimental trials. The absence of residual variance in the model further underscores its reliability. Such consistency is critical for optimizing drilling performance, as it enables precise control over the key parameters such as feed rate and spindle speed to achieve higher productivity.

3.2 Interaction of drilling parameters on the analysis of SN ratio and means for Ra and MRR

The interactions of drilling parameters on the signal-to-noise (S/N) ratios and their effects on surface roughness (Ra) and material removal rate (MRR) for Al6063/SiC/B_4C/FA hybrid composites were analyzed using ANOVA, and the results are depicted in Figures 2 and 3. The main effects plots illustrate the influence of tool type, spindle speed, feed rate, and point angle (x-axis) on the corresponding S/N ratios (y-axis), while the counterplots display parameter interactions such as feed vs. speed, point angle vs. speed, and point angle vs. feed at different levels. The parameter influence and their respective rankings for Ra and MRR are summarized in Table 5.

Based on the main effects plot (Fig. 2a), the optimal conditions for minimizing Ra were observed at a spindle speed of 1750 rpm (level 4), a feed rate of 0.10 mm/rev (level 1), and a point angle of 118° (level 3) when using a carbide tool. The parameter ranking from Table 5 indicates that spindle speed (rank 1) is the most influential factor in achieving a smoother surface finish, followed by tool type (rank 2), point angle (rank 3), and feed rate (rank 4). This trend is further corroborated by the average S/N ratios for each parameter level, where higher S/N ratios consistently align with better surface quality. The counterplots (Fig. 2b) highlight the interaction effects of parameters on Ra. Regions of lower Ra are represented by light blue shades, transitioning to darker shades with increasing Ra. The findings reveal that increasing spindle speed reduces Ra. This is because higher speeds generate greater thermal energy during drilling, softening the Al6063/SiC/B_4C/FA hybrid composite and facilitating smoother shearing with fewer surface irregularities. Conversely, lower speeds fail to generate sufficient thermal softening, leading to irregular material removal and higher Ra. The feed rate also significantly influences Ra of Al6063/SiC/B_4C/FA hybrid composite. Higher feed rates increase the depth of cut per revolution, resulting in prominent tool marks and increased surface roughness. In contrast, lower feed rates ensure controlled material removal, reducing chatter and surface defects, thereby achieving lower Ra values. The point angle plays a critical role in determining surface finish of Al6063/SiC/B_4C/FA hybrid composite. A smaller point angle concentrates cutting forces on a smaller area, leading to uneven MRR and increased drill bit tool wear, which deteriorates the surface quality. In comparison, a moderate point angle ensures a balanced distribution of cutting forces, reducing drill bit tool wear and facilitating smoother material removal, which results in lower Ra. The superior wear resistance and rigidity of the carbide tool also contribute to better surface finish compared to the HSS tool, as carbide tools maintain their sharpness for longer durations under varying machining conditions.

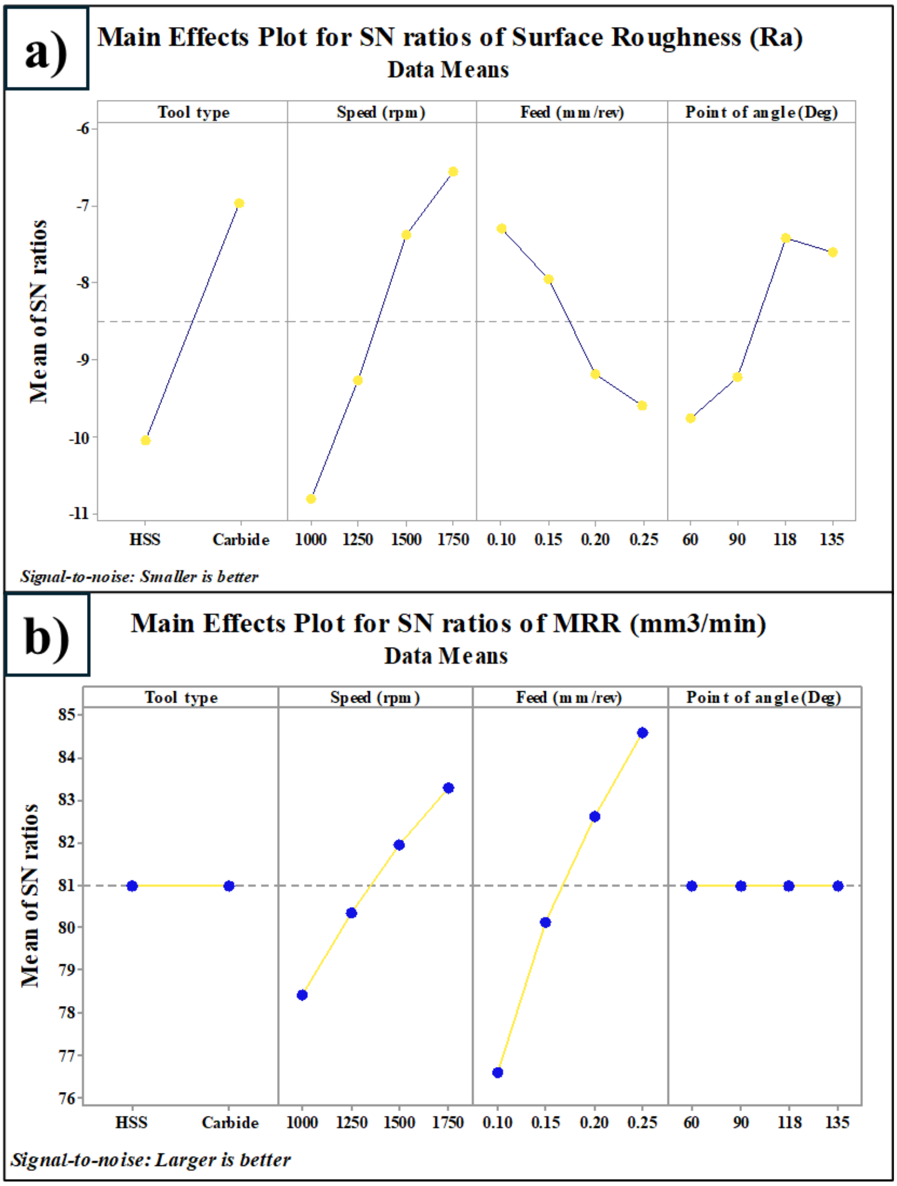

Fig. 3: Main effect plots for drilling Al6063/SiC/B4C/FA hybrid composite (a) Surface Roughness and (b) Material Removal Rate

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From the S/N ratios (Fig. 4a), the maximum MRR for Al6063/SiC/B_4C/FA hybrid composite was achieved at a feed rate of 0.25 mm/rev (level 4) and a spindle speed of 1750 rpm (level 4). Where the drill bit tool type and point angle displays constant (neutral). The ranking table confirms that feed rate (rank 1) is the most influential factor in determining MRR, followed by spindle speed (rank 2), point angle (rank 3), and tool type (rank 4). The consistent superiority of the carbide tool over the HSS tool in achieving higher MRR was observed across various parametric conditions. The counterplots (Fig. 4b) reveal that higher feed rates and spindle speeds combined with a larger point angle result in significantly higher MRR. At higher feed rates, the cutting depth per revolution increases, leading to a greater volume of material removed. Similarly, higher spindle speeds enhance the cutting energy and shearing action, further boosting the MRR of Al6063/SiC/B_4C/FA hybrid composite. A larger point angle reduces tool deflection and improves chip evacuation, enabling uninterrupted and efficient material removal. In contrast, lower feed rates and spindle speeds reduce the cutting action and material removal, directly correlating with lower MRR values. A smaller point angle further limits cutting efficiency, increasing tool wear and reducing the overall material removal rate. The counterplots vividly depict these trends, with regions of lower MRR shown in light blue shades, transitioning to darker blue shades as MRR increases under optimal parameter settings. The deterministic relationship observed across trials ensures that these trends are consistent and reproducible, leaving minimal unexplained variance in the model. This analysis underscores the critical importance of feed rate and spindle speed as dominant parameters for optimizing both surface finish (Ra) and material removal rate (MRR) of Al6063/SiC/B_4C/FA hybrid composite, while tool type and point angle contribute to secondary effects on Al6063/SiC/B_4C/FA hybrid composite, which further refine the machining process.

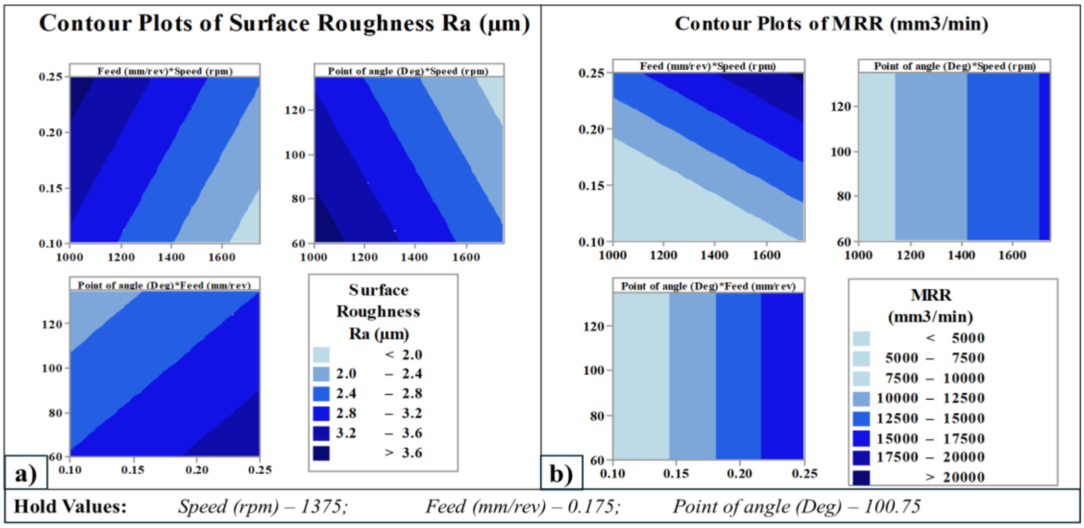

Fig. 4: Counter plots for drilling Al6063/SiC/B4C/FA hybrid composite (a) Surface Roughness and (b) Material Removal Rate

3.3 TOPSIS Analysis for prediction of optimal drilling parameters for Al6063/SiC/B4C/FA hybrid composite

TOPSIS methodology is one of the multi-criterion decisions making (MCDM) techniques used to rank better preference for drilling parameters predicted for Ra and MRR under different machining conditions. The relative closeness value (higher probability value) is used to rank the top substitute, which indicates the optimum values. As per the calculated results, the closeness values of ranking of the alterative is found as 32 – 30 – 28 – 23 – 31 – 29 – 20 – 12 – 24 – 21 – 9 – 4 – 19 – 17 – 6 – 3 – 26 –

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25 – 27 – 22 – 18 – 14 – 16 – 13 – 15 – 10 – 8 – 5 – 11 – 7 – 2 – 1. The experiment run 32 is high value of relative closeness values among 32 experimental runs and indicated as the optimal predicted run as per out-put parametric combination of Ra and MRR. According to higher relative closeness value as 0.847, which was predicted at the input parameters of carbide tool, 1750 rpm of speed, 0.25 mm/rev of feed, and 90° point of angle.

Table 6: TOPSIS predictions with respective to drilling experimentation out-comes for Al6063/SiC/B_4C/FA hybrid composite

S. No	Separation measure of positive ideal solution (S_i^+)	Separation measure of negative ideal solution (S_i^-)	Relative closeness (Ci)	Rank
1	0.138	0.013	0.085	32
2	0.125	0.020	0.136	30
3	0.115	0.035	0.232	28
4	0.108	0.051	0.322	23
5	0.128	0.020	0.134	31
6	0.113	0.033	0.225	29
7	0.095	0.054	0.365	20
8	0.080	0.076	0.487	12
9	0.108	0.047	0.305	24
10	0.092	0.053	0.363	21
11	0.064	0.081	0.560	9
12	0.045	0.106	0.701	4
13	0.097	0.057	0.369	19
14	0.083	0.063	0.433	17
15	0.049	0.098	0.666	6
16	0.046	0.123	0.728	3
17	0.123	0.045	0.267	26
18	0.110	0.041	0.270	25
19	0.107	0.039	0.265	27
20	0.097	0.053	0.356	22
21	0.109	0.068	0.385	18
22	0.087	0.078	0.472	14
23	0.080	0.064	0.445	16
24	0.080	0.076	0.486	13
25	0.099	0.080	0.446	15
26	0.073	0.090	0.553	10

27	0.062	0.083	0.575	8
28	0.048	0.104	0.683	5
29	0.090	0.091	0.502	11
30	0.061	0.096	0.613	7
31	0.037	0.108	0.743	2
32	0.024	0.132	0.847	1

Overall, the different parametric combination runs the carbide tool is the best drill bit tool to obtain higher MRR with minimal Ra than that of HSS drill bit tool. Also, the higher speed and feed with 90° point of angle provides higher MRR with minimal Ra. Further, the experimental confirmation test also provides nearby values of SR and MRR using carbide tool, 1750 rpm of speed, 0.25 mm/rev of feed, and 90° point of angle drilling parameters. These results shown a less than 6% deviation to the predicted results, which indicates that predicted parameter values of TOPSIS are within the limit.

4.0 CONCLUSIONS

Optimization of drilling parameters for AA6063/SiC/B4C/FA hybrid composites using Taguchi and TOPSIS methodology was investigated successfully in the present research work. The key inferences derived from the experimental investigations are summarized as follows:

- The ANOVA results indicate that tool type (carbide tool) is the most influential parameter on Ra contributing 60.44%, followed by spindle speed (23.56%), point angle (8.72%), and feed rate (7.29%) of AA6063/SiC/B4C/FA hybrid composites. Whereas, for the MRR the feed rate emerged as the dominant parameter, followed by the spindle speed, while type and point angle exhibits minimal influence.

- The counter-plots shows that higher spindle speed combined with lower feed rates with moderate point angle yields superior surface finish and maximum MRR. The carbide tool consistently exhibits better performance in obtaining lower Ra and maximum MRR compared to HSS tool. These optimal machining conditions ensured uniform distribution of cutting forces, minimized tool wear, and improved overall drilling characteristics.

- The TOPSIS methodology effectively ranked the experimental trials based on relative closeness values, with the optimal combination of machining parameters identified as carbide tool, spindle speed of 1750 rpm, feed rate of 0.25 mm/rev, and point angle of 90°.

- The experimental confirmation tests showed a deviation of less than 6% from the predicted results, validating the robustness of the optimization model.

In future work, the utilization of coated tools with advanced cooling techniques can be explored to further enhance the machinability and performance of hybrid composites in drilling applications.

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