Materials Today: Proceedings 68 (2022) 1280–1287

Contents lists available at ScienceDirect

Materials Today: Proceedings

journal homepage: www.elsevier.com/locate/matpr

Drilling parameter analysis of hybrid composites (Al/B4C/graphite) using grey relational and Taguchi techniques

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ARTICLE INFO

Article history:
Available online 1 July 2022

Keywords:
Thrust Force
Torque
Roughness
Drilling
Hybrid Composites
Grey Relational Analysis

ABSTRACT

Application of composite materials has been increasing worldwide especially in production industries. In drilling operation, standard of hole is the basic demand in numerous applications. The choice of optimized drilling parameters is extremely vital for good hole quality. Our objective is to optimize the parameters involved in drilling of aluminium /boron carbide/ graphite hybrid composite materials to get good quality holes. A series of drilling experiments are conducted in CNC machining centre on the hybrid composite specimen slabs of size 100 mm × 100 mm × 10 mm, made-up by stir casting technique. Our work is to analyse the consequences of drilling parameters like spindle speed, feed and drill tool diameter on thrust force, torque, surface roughness and roundness error. The experimental results are collected individually on L27 orthogonal array and analysed by Signal – Noise (S/N) quantitative relation and grey rational analysis with an objective to optimize the drilling parameters to reveal the dominant factors that have an effect on the responses mentioned.

Selection and peer-review under responsibility of the scientific committee of the International Conference on Advanced Materials and Modern Manufacturing

1. Introduction

Aluminum Hybrid Composites (AHCs) see a category of light mass with high-performance aluminium reinforced material systems. Good strength like tenuity, high strength with low weight quantitative relation, smart resistance to corrosion and better properties at high temperature are the most important benefits of aluminium composites over metallic element and non – metallic elemental materials [1].

The reinforcement in Aluminium Hybrid Composites might be a type of continuous or broken fibres or particulates. Properties of Aluminium Hybrid Composites will be custom-made to the necessity of various modern utilizations by making acceptable blending of matrix material and reinforcements and also by using different processing techniques. [2].

Generally, for the metal matrix composites to be hybrid, there should be more than one reinforcement material in the metal matrix [3]. Al/SiC/Gr is one such hybrid composites, in which, the silicon carbide and graphite are used to strengthen the base metal. Graphite particles also increase the wear resistance of the material, which make it useful for applications in automotive sectors.

On the other hand, these materials are having a drawback of poor machinability and so machining / drilling of these materials become a challenging task for the field operators [4]. On account of the application of hybrid composites, the parameters for machining or drilling must be optimized to improve the quality of production [5].

The base metal picked for the study is Al 6061, various ingredients of Al6061 is given in Table 1. The strengthening materials used for reinforcement in this specimen is 5% of boron carbide powders and 5% of graphite powder which was made by stir casting methodology since stir casting is the most effortless and least expensive methodology for producing the metal matrix hybrid composites [6].

Drilling operation is one of the standard manufacturing processes primarily followed for making variety of products using hybrid aluminium composites. Fulfilment of these products for their corresponding applications are based on the standard of the drilled hole surface and its precision. Geometry of the twist drill and the drilling factors like drill feed and the spindle speed, governing the quality of the drilled surface [7]. Wrong choice of twist drill and the factors of drilling lead to overheat of the tool, increas-

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https://doi.org/10.1016/j.matpr.2022.06.236
2214-7853/
Selection and peer-review under responsibility of the scientific committee of the International Conference on Advanced Materials and Modern Manufacturing

Table 1
Chemical ingredients of Al6061.

Element	Al	Mg	Si	Fe	Cu	Cr	Zn	Mn	Others
%	96.85	0.9	0.7	0.6	0.3	0.25	0.2	0.05	0.05

ing wear rate of the tool and excessive drilling force, that cause poor standard of the drilled holes and damage the inner surface of the drilled holes [8].

Generally, multi objective functions, including all the factors, can be analysed successfully using GRA technique [9] by converting multi attributes of the drilling into a single value known as grey relational grade. On the basis of this grade, the ideal parameters can be achieved. In Taguchi analysis, S/N ratios are used to determine the influence of various factors affecting the responses.

Our objective in this experimental study is to determine the impact of drilling factors affecting the standard and precision of the drilled hole while drilling Al/B4C/Gr hybrid composites and also to find the ideal parameters of drilling using GRA and Taguchi techniques.

2. Materials and methods

2.1. Specimen preparation

Various ingredients of the base metal Al6061 is given in Table 1. Al6061 homogeneously mixed with 5% weight proportion of boron carbide and 5% of graphite powders with the help of stir casting process is the hybrid material chosen for our investigation. The sample of the material is cast into square blocks of size 10 cm × 10 cm × 1 cm. %.

2.2. Drilling experiments

For our experimental investigations, to determine the extent of the impact of drilling variables, we have chosen three different parameters of drilling, viz diameter of the twist drill, drilling speed and tool feed rate, at three levels and is listed in Table 2. Taguchi's experimental design of L27 orthogonal array was selected to conduct the trial of experiments using Titanium Aluminium Nitride coated tools in CNC machining centre. Roughness in the drilled hole surface, roundness or circularity error in the drilled holes, thrust force and drilling torque induced are the four responses to be measured.

2.3. Measurement of responses

The responses of our experiments, drilling force and torque are recorded during drilling process using drill tool dynamometer mounted on the vertical CNC machining centre, BFW Surya VF-30 Vertical Machining Center which is interfaced with a PC using Dynaware software. Surface roughness inside the holes drilled is measured using surface roughness tester SURFCOM 1400G and the error in roundness are measured using Coordinate measuring machine - Contura G2 (Carl Zeiss).

Table 2
Process Parameters and their levels.

Factor	Level 1	Level 2	Level 3
Tool Diameter A (mm)	5	7.5	10
Speed B (rpm)	1000	2000	3000
Feed C (mm/rev)	0.05	0.10	0.15

2.4. Analysis of responses

Highly influenced factors and the ideal factors of drilling can be determined by analysing the four responses measured from all the experiments. The techniques used for analysis in our investigations are GRA and Taguchi's analysis.

GRA technique is applied to optimise our multi objective function, that is to minimise the drilling thrust, drilled hole roughness, torque induced and the roundness error in the drilled holes.

In Taguchi analysis, signal to noise ratio for all the four responses of all the 27 experiments were found out and the influencing parameter for each and every response can be determined.

2.4.1. Grey relational analysis

The GRA technique is utilized for concluding the best machining / drilling variables. Data pre-processing, that is Normalization is important here, because the span and unit of one data arrangement could contradict from the other. There are various techniques of data pre-processing presented for the grey relational investigation (10).

In grey relational analysis, initially, our experimental results are normalized in the range of 0 to 1. There are three different approaches to do this normalization.

If our target value is infinite, then "larger the better" strategy is to be followed and the sequence can be normalized using the formula [11]:

$$x_i(k) = \frac{y_i(\mathrm{k}) - \min y_i(\mathrm{k})}{\max y_i(\mathrm{k}) - \min y_i(\mathrm{k})} \tag{1}$$

For, "smaller the better" strategy, the sequence can be normalized using the following formula [11]:

$$x_i(k) = \frac{\max y_i(\mathrm{k}) - y_i(\mathrm{k})}{\max y_i(\mathrm{k}) - \min y_i(\mathrm{k})} \tag{2}$$

Following the data pre-processing, the following stage is to calculate the GR coefficient, to make the relationship between the actual and best normalized experimental results more precise. The GR coefficient can be expressed as follows [11].

$$\chi_i(k) = \frac{\Delta_{min} + \xi\Delta_{max}}{\Delta_{oi}(k) + \xi\Delta_{max}} \tag{3}$$

Where, $\Delta_{oi}(k)$ is the difference in the absolute values of xo(k) and xi(k).

$0 \leq \xi \leq 1$ is the distinguishing coefficient, and generally ξ is assumed to be 0.5.

Δ_{min} is the smallest value of Δ_{oi}.

Δ_{max} is the largest value of Δ_{oi}.

For every experiment, the grey relational grade can be calculated by accumulating the grey relational coefficient of each quality characteristic. The average grey grade for the ith experimental run for all 'n' responses is given below [11].

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n}\chi_i(k) \tag{4}$$

Where, n represents the number of process responses and χi (k) represents the grey relational coefficient of kth response in i^{th} experiment.

2.4.2. Taguchi's analysis

Taguchi's analysis is a kind of statistical technique to determine the influence of various parameters on the responses considered [12]. In this technique, the ratio of signal to noise (S/N) shows the variation of the measured values from the desired value.

As our objectives are to minimise the thrust force, roughness, torque and roundness error, SN Ratio for smaller is better has been chosen, and the corresponding formula is given in the equation (5).

$$\text{S/N ratio (smaller is better)} = -10log_{10}\left(\left(\sum y^2\right)/n\right) \quad (5)$$

Here, y is the observed values for a particular trial and n represents the number of outputs for the same trial.

3. Results and discussion

The experimental results and normalised values of all the responses are given in Table 3. The experimental results for the thrust force, drilling torque, surface roughness and roundness error are listed in Table 3. Basically, thrust force, drilling torque, surface roughness and roundness error belong to the "smaller-the-better" methodology and the equation (2) is utilized for data pre-processing. Once normalizing the experimental values, the grey relational coefficients are calculated with the help of equation (3) and they are shown in the same table.

Then the Grey relational coefficients and Grey relational grades for each experiment can be calculated using the equations (3) and (4) respectively and the values are shown in the Table 4..

The mean Grey relational grades of each response at each level are calculated and mean of all these mean values are calculated as mean grey relational grade as shown in the Table 5..

The best level of drilling parameters is the level with highest Grey Relational Grade and so the optimal parameter values are given as (A1 B3 C1) and is shown graphically in the Fig. 1. The predicted grey relational grade 'Ɛ' using the optimal level of the process parameters can be expressed [11] as.

$$\epsilon = \epsilon_m + \sum_{k=1}^{q} \epsilon_k^{'} - \epsilon_m \quad (6)$$

Where Ɛm denotes the mean grey relational grade and Ɛk' denotes the grey relational grade at optimum level. k represents the response and q, the number of parameters. Using this relation, the predicted grey relational grade for our experiments is found to be 0.8480.

3.1. Test for confirmation

To ensure the results, another experiment is organized to examine the enhancement of the process. The ideal variables have been chosen for this experiment, that is the diameter of the drill as 5 mm, drilling speed of 3000 rpm and feed rate of 0.05 mm/rev. The response output for the test is given in the Table 6..

From the results of the confirmation test, the actual GRG is calculated as 0.8260, which is nicely corelated with the anticipated GRG of 0.8480.

3.2. Taguchi results

Next the responses measured from all the experiments were tabulated and are investigated using Taguchi's analysis. S/N ratios for all the trials and for all the four responses are evaluated and entered as SNR1, SNR2, SNR3 and SNR4 in the Table 7.

Main effect plots, the graphical form of the response tables, are drawn for the obtained SN ratios for all the responses using Minitab19 software. Fig. 2 shows the main effect plots for the thrust force induced on drilling and the corresponding response table is shown in Table 8. From the delta values of response table, it was found that the spindle speed is the most influencing factor for thrust force followed by feed rate and then drill diameter.

The main effect plots indicated that the ideal parameters to minimize the thrust force are 1000 rpm of speed, 0.15 mm/rev of feed with 10 mm diameter drilling tool.

Table 3
Experimental Results and Normalised Values of Responses.

Trial No	Experimental Results				Normalised values of responses			
	Thrust Force (N)	Roughness (µm)	Torque (N.m)	Roundness error (mm)	Thrust Force (N)	Roughness (µm)	Torque (N.m)	Roundness error (mm)
1	255.06	6.41	1.32	0.0562	0.3572	0.0769	0.7522	0.0555
2	304.11	6.15	1.94	0.0634	0.1681	0.1678	0.5672	0.0533
3	338.45	4.7	2.55	0.0543	0.0357	0.6748	0.3851	0.0561
4	191.3	4.82	1.1	0.0642	0.6029	0.6329	0.8179	0.0531
5	137.34	4.64	1.64	0.0822	0.8109	0.6958	0.6567	0.0477
6	255.06	4.26	1.96	0.0599	0.3572	0.8287	0.5612	0.0544
7	107.91	4.42	0.49	0.0508	0.9244	0.7727	1.0000	0.0571
8	88.29	4.08	1.37	0.0711	1.0000	0.8916	0.7373	0.0510
9	132.44	3.77	2.26	0.0529	0.8298	1.0000	0.4716	0.0565
10	272.29	6.63	2.41	0.0639	0.2908	0.0000	0.4269	0.0532
11	304.11	5.84	3.84	0.0776	0.1681	0.2762	0.0000	0.0491
12	312.5	4.83	3.81	0.1061	0.1358	0.6294	0.0090	0.0406
13	222.04	5.35	1.83	0.0617	0.4844	0.4476	0.6000	0.0539
14	150.6	4.91	2.87	0.0676	0.7598	0.6014	0.2896	0.0521
15	277.22	4.66	2.5	0.0573	0.2717	0.6888	0.4000	0.0552
16	140.89	5.09	0.54	0.0617	0.7972	0.5385	0.9851	0.0539
17	110.36	4.57	1.43	0.1135	0.9149	0.7203	0.7194	0.0384
18	175	4.03	2.48	0.0628	0.6658	0.9091	0.4060	0.0535
19	286.08	5.91	2.26	0.0902	0.2376	0.2517	0.4716	0.0453
20	334.1	5.41	3.66	0.1808	0.0525	0.4266	0.0537	0.0183
21	347.72	5.08	3.54	0.0799	0.0000	0.5420	0.0896	0.0484
22	249.36	5.38	1.73	0.1086	0.3791	0.4371	0.6299	0.0399
23	183.46	4.88	2.72	0.2421	0.6332	0.6119	0.3343	0.0000
24	321.97	4.45	2.65	0.2046	0.0993	0.7622	0.3552	0.0112
25	179.85	4.91	0.74	0.1385	0.6471	0.6014	0.9254	0.0309
26	149	4.47	2.11	0.1779	0.7660	0.7552	0.5164	0.0192
27	236.5	4.11	2.89	0.0897	0.4287	0.8811	0.2836	0.0455

Table 4
Grey Relational Coefficients and Grey Relational Grades.

Trial No	Grey Relational Coefficients				Grey Relational Grade
	Thrust Force (N)	Roughness (µm)	Torque (N.m)	Roundness error (mm)	
1	0.4375	0.3514	0.6687	0.9968	0.6136
2	0.3754	0.3753	0.5360	0.9925	0.5698
3	0.3415	0.6059	0.4485	0.9979	0.5984
4	0.5574	0.5766	0.7330	0.9921	0.7148
5	0.7256	0.6217	0.5929	0.9816	0.7305
6	0.4375	0.7448	0.5326	0.9946	0.6774
7	0.8686	0.6875	1.0000	1.0000	0.8890
8	1.0000	0.8218	0.6556	0.9880	0.8664
9	0.7461	1.0000	0.4862	0.9987	0.8078
10	0.4135	0.3333	0.4659	0.9922	0.5512
11	0.3754	0.4086	0.3333	0.9843	0.5254
12	0.3665	0.5743	0.3353	0.9680	0.5610
13	0.4923	0.4751	0.5556	0.9935	0.6291
14	0.6755	0.5564	0.4131	0.9901	0.6588
15	0.4071	0.6164	0.4545	0.9961	0.6185
16	0.7115	0.5200	0.9710	0.9935	0.7990
17	0.8546	0.6413	0.6405	0.9639	0.7751
18	0.5994	0.8462	0.4570	0.9929	0.7239
19	0.3961	0.4006	0.4862	0.9770	0.5650
20	0.3454	0.4658	0.3457	0.9280	0.5212
21	0.3333	0.5219	0.3545	0.9829	0.5482
22	0.4461	0.4704	0.5746	0.9666	0.6144
23	0.5768	0.5630	0.4289	0.8975	0.6166
24	0.3570	0.6777	0.4368	0.9159	0.5968
25	0.5862	0.5564	0.8701	0.9502	0.7408
26	0.6812	0.6714	0.5083	0.9295	0.6976
27	0.4667	0.8079	0.4110	0.9773	0.6657

Table 5
Response Table for Overall Grey Relational Grade.

Factors	Level 1	Level 2	Level 3
A	**0.7186**	0.6491	0.6185
B	0.5615	0.6508	**0.7739**
C	**0.6797**	0.6624	0.6442

Mean Grey Relational Grade = 0.6621

Fig. 3 shows the main effect plots for drilled hole surface roughness and the corresponding response table is shown in Table 9. For roughness also the spindle speed is the most influencing factor followed by feed rate and drill diameter.

Table 6
Confirmation test results.

Response	Thrust force	Roughness	Torque	Roundness error
Value	103.01	3.6	2.94	0.0379

The main effect plots shown in Fig. 3 indicated that the ideal parameters to minimize the roughness are 1000 rpm of speed, 0.05 mm/rev of feed with 7.5 mm diameter drilling tool.

Fig. 4 shows the main effect plots for the drilling torque induced and the corresponding response table is shown in Table 10. For

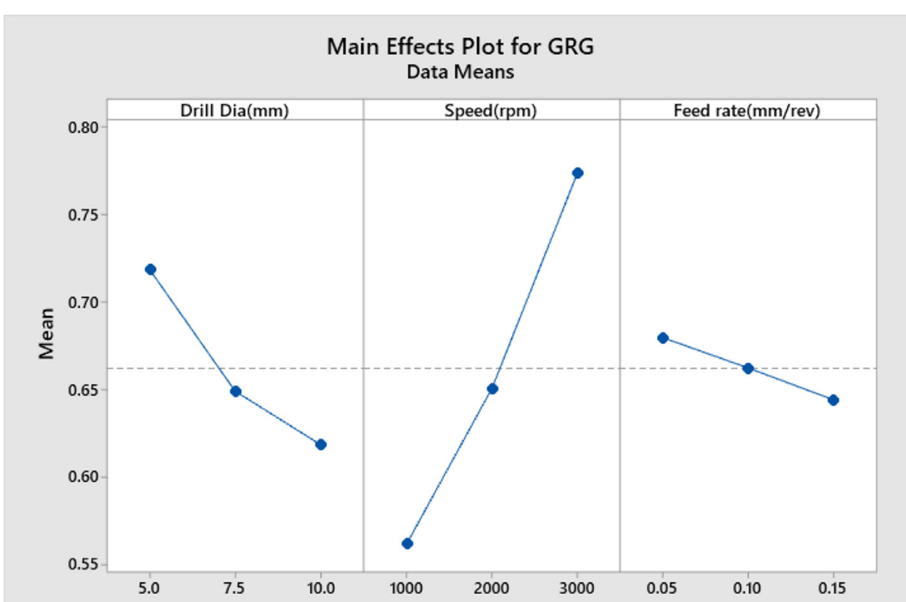

Fig. 1. Effect of parameters on drilling characteristics.

Table 7
Experimental Results and S/N Ratios.

Trial No	Drill Dia (mm)	Speed (rpm)	Feed (mm/rev)	Thrust force (N)	Roughness (µm)	Torque (N.m)	Roundness error (mm)	SNR1	SNR2	SNR3	SNR4
1	5	1000	0.05	255.06	6.41	1.32	0.0562	−48.133	−16.137	−2.411	25.005
2	5	1000	0.1	304.11	6.15	1.94	0.0634	−49.661	−15.778	−5.756	23.958
3	5	1000	0.15	338.45	4.7	2.55	0.0543	−50.590	−13.442	−8.131	25.304
4	5	2000	0.05	191.3	4.82	1.1	0.0642	−45.634	−13.661	−0.828	23.849
5	5	2000	0.1	137.34	4.64	1.64	0.0822	−42.756	−13.330	−4.297	21.703
6	5	2000	0.15	255.06	4.26	1.96	0.0599	−48.133	−12.588	−5.845	24.451
7	5	3000	0.05	107.91	4.42	0.49	0.0508	−40.661	−12.908	6.196	25.883
8	5	3000	0.1	88.29	4.08	1.37	0.0711	−38.918	−12.213	−2.734	22.963
9	5	3000	0.15	132.44	3.77	2.26	0.0529	−42.440	−11.527	−7.082	25.531
10	7.5	1000	0.05	272.29	6.63	2.41	0.0639	−48.701	−16.430	−7.640	23.890
11	7.5	1000	0.1	304.11	5.84	3.84	0.0776	−49.661	−15.328	−11.687	22.203
12	7.5	1000	0.15	312.5	4.83	3.81	0.1061	−49.897	−13.679	−11.618	19.486
13	7.5	2000	0.05	222.04	5.35	1.83	0.0617	−46.929	−14.567	−5.249	24.194
14	7.5	2000	0.1	150.6	4.91	2.87	0.0676	−43.556	−13.822	−9.158	23.401
15	7.5	2000	0.15	277.22	4.66	2.5	0.0573	−48.856	−13.368	−7.959	24.837
16	7.5	3000	0.05	140.89	5.09	0.54	0.0617	−42.978	−14.134	5.352	24.194
17	7.5	3000	0.1	110.36	4.57	1.43	0.1135	−40.856	−13.198	−3.107	18.900
18	7.5	3000	0.15	175	4.03	2.48	0.0628	−44.861	−12.106	−7.889	24.041
19	10	1000	0.05	286.08	5.91	2.26	0.0902	−49.130	−15.432	−7.082	20.896
20	10	1000	0.1	334.1	5.41	3.66	0.1808	−50.478	−14.664	−11.270	14.856
21	10	1000	0.15	347.72	5.08	3.54	0.0799	−50.825	−14.117	−10.980	21.949
22	10	2000	0.05	249.36	5.38	1.73	0.1086	−47.937	−14.616	−4.761	19.283
23	10	2000	0.1	183.46	4.88	2.72	0.2421	−45.271	−13.768	−8.691	12.320
24	10	2000	0.15	321.97	4.45	2.65	0.2046	−50.156	−12.967	−8.465	13.782
25	10	3000	0.05	179.85	4.91	0.74	0.1385	−45.098	−13.822	2.615	17.171
26	10	3000	0.1	149	4.47	2.11	0.1779	−43.464	−13.006	−6.486	14.996
27	10	3000	0.15	236.5	4.11	2.89	0.0897	−47.477	−12.277	−9.218	20.944

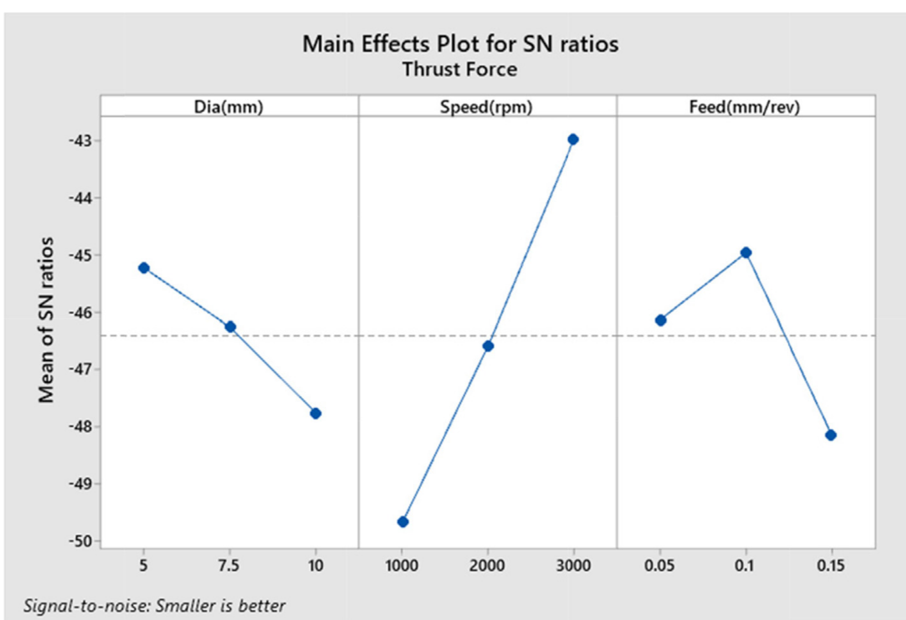

Fig. 2. Main effect Plots for thrust force.

torque, the feed rate is the most influencing factor followed by spindle speed and drill diameter.

The main effect plots indicated that the ideal parameters to minimize the drilling torque are 0.15 mm/rev of feed, 1000 rpm of speed with 10 mm diameter drilling tool.

Fig. 5 shows the main effect plots for the roundness error in the drilled holes and the corresponding response values are shown in Table 11. The drill tool diameter is highly influencing the roundness error, subsequently the drill tool feed and drilling speed.

Table 8
Response Table for Thrust force.

Level	Dia(mm)	Speed(rpm)	Feed(mm/rev)
1	−45.21	−49.67	−46.13
2	−46.25	−46.58	−44.96
3	−47.76	−42.97	−48.14
Delta	2.55	6.70	3.18
Rank	3	1	2

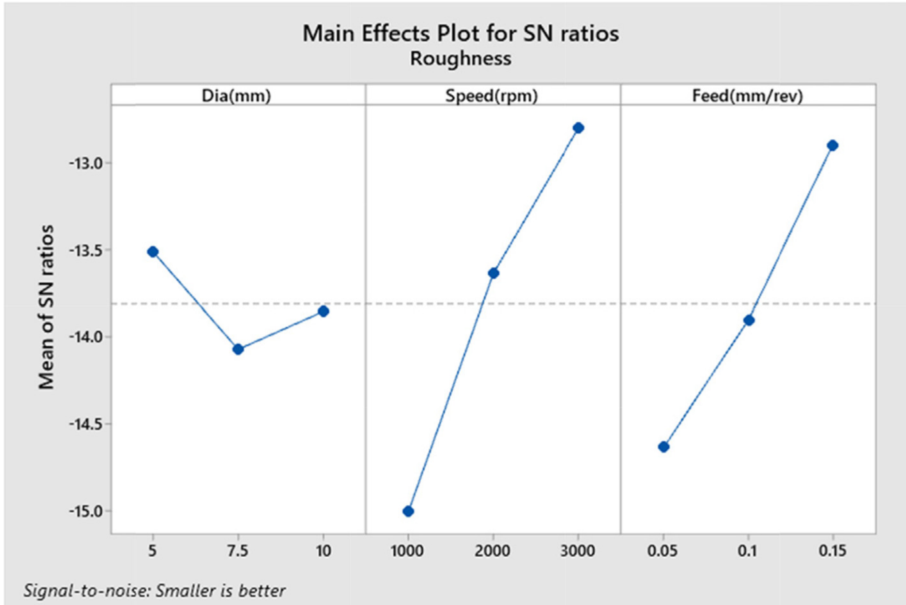

Fig. 3. Main effect Plots for Roughness.

Table 9
Response Table for Roughness.

Level	Dia(mm)	Speed(rpm)	Feed(mm/rev)
1	−13.51	−15.00	−14.63
2	−14.07	−13.63	−13.90
3	−13.85	−12.80	−12.90
Delta	0.56	2.20	1.74
Rank	3	1	2

Table 10
Response Table for Torque.

Level	Dia(mm)	Speed(rpm)	Feed(mm/rev)
1	−3.432	−8.508	−1.534
2	−6.551	−6.139	−7.021
3	−7.149	−2.484	−8.576
Delta	3.717	6.025	7.042
Rank	3	2	1

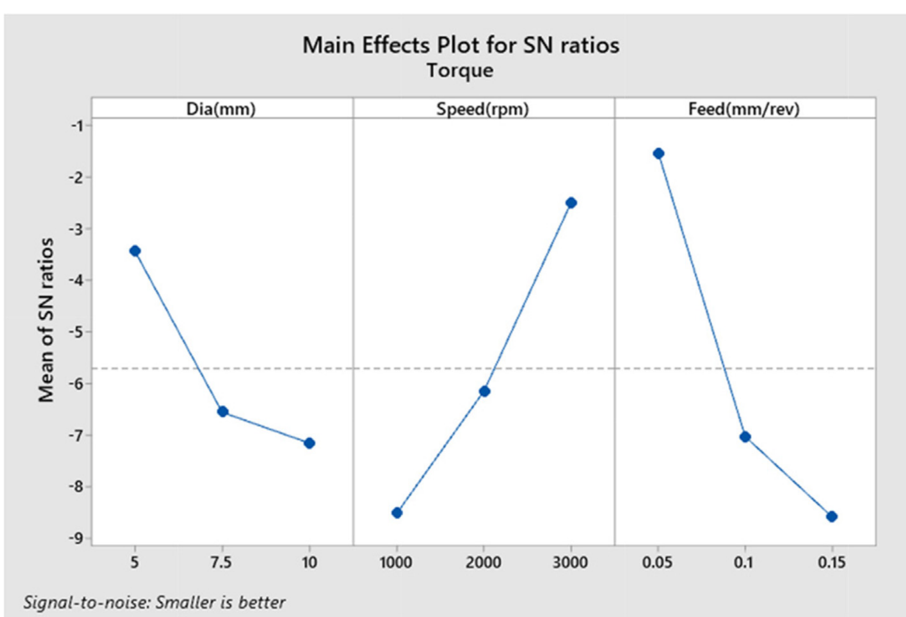

Fig. 4. Main effect Plots for Drilling torque.

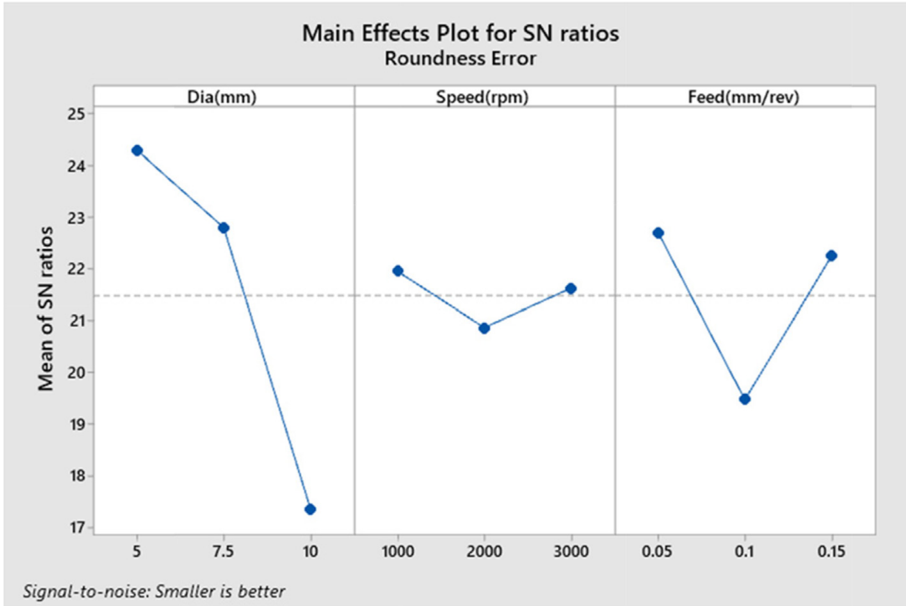

Fig. 5. Main effect Plots for Roundness Error.

Table 11
Response Table for Roundness Error.

Level	Dia(mm)	Speed(rpm)	Feed(mm/rev)
1	24.29	21.95	22.71
2	22.79	20.87	19.48
3	17.36	21.62	22.26
Delta	6.94	1.08	3.23
Rank	1	3	2

The main effect plots indicated that the ideal parameters to minimize the roundness error in the drilled holes are 10 mm diameter drilling tool, 0.1 mm/rev of feed and 2000 rpm of speed.

4. Conclusion

To drill holes effectively in Al/B4C/Graphite composite materials, the analysis to determine the ideal drilling variables is carried out and the conclusions at the end of our investigations are listed here.

The required 5% B4C and 5% Graphite reinforced Al6061 hybrid MMC specimens were prepared with the help of mechanical stirring type casting technique.

Drilling trials were organized as per Taguchi's L27 array in the VMC by changing the drilling variables like tool diameter, drilling speed and feed.

The ideal and effective drilling variables were acquired by GRA technique and the ideal parameters are determined as 5 mm of tool diameter, 3000 rpm of drilling speed and 0.05 mm/rev of tool feed.

To ensure the results of grey analysis, a confirmation experiment was carried out using the ideal drilling factors mentioned above and it is concluded that the real grey value is very close to the predicted grey value.

The same experimental results are also analysed using Taguchi's technique and the optimum parameters for each response are found out separately and the main effect plots are drawn for the same.

CRediT authorship contribution statement

S. Senthil babu: Conceptualization, Methodology, Writing – original draft, Investigation, Validation. **C. Dhanasekaran:** Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to acknowledge the support of Vels Institute of Science, Technology and Advanced Studies, Chennai, Met Mech Lab, Chennai and Kosaca calibrations lab, Chennai.

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Further Reading

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