Simultaneous optimization of drilling responses using GRA on Al-6063/TiC composite

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Abstract

The aim of the current work is to optimize the drilling constraints simultaneously during drilling of an Al6063/TiC composite based on grey relational analysis. Drilling trials were performed on Al-6063 reinforced with 15 wt% titanium carbide (TiC) of size 50 μm . HSS twist drills with diameter of 10 mm under lubricated condition were utilized for performing drilling tests. Drilling parameters explicitly helix angle, spindle speed, feed rate and responses such as surface roughness, cutting force and temperature are considered in the study. Grey relational grades were calculated to find the optimum levels of parameters, and moreover major involvement of constraints was dogged by ANOVA. The drilled composite specimen surface was analyzed under scanning electron microscopy (SEM). SEM metaphors of the drilled composite face specified the charisma of grooves, micro-cracks and dents.

Keywords MMCs · Drilling · GRA · ANOVA · Optimization

1 Introduction

Ceramic-reinforced metal matrix composites (MMCs) are highly capable materials for many functions with a combination of various desirable properties. MMCs possess the blend of contradicting properties of the base material (metallic alloys) and the ceramics. Thus, they have high toughness; lightweight–high strength and moduli, combinations of better properties of both [1, 2]. Thus, reinforcements usually improve the properties of base material. Demand for better, advanced and improved materials in the fields like automobile and aerospace industries led to a rapid development of MMCs [3, 4]. Waku and Nagasawa [5] found that monolithic materials are inferior to MMCs in many facets. Methods to fabricate ceramics and MMCs are discussed by Rosso [6]. Numerous methods are developed for manufacturing MMCs. Stir casting is regarded as

an accepted method because of its unique features. Several metals and their alloys have been used as matrix in the research works for producing MMCs. The most worked on material is aluminum and its admixtures [7–9]. Many research studies suggested the suitability of Al-based composites for structural applications. Uvaraja and Natarajan [10] have conducted experiments on the hardness of Al-7075 alloy with B_4C kept as constant at 3 wt% and wt% of SiC varying between 0 and 15. The highest hardness for the composite was obtained at wt% for SiC at 15. Composites with SiC and flyash reinforced with aluminum and hybrid composite with aluminum SiC and flyash were experimentally investigated by Boopathi et al. [11] for the determination their hardness. It was proven that the hybrid composite with 10% of both SiC and fly ash has been the hardest when compared to Al-SiC and Al-fly ash composites.

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AA 5052 reinforced with different volume proportions of ZrB_2 particles were studied by Kumar et al. [12]. From the study, it was observed by the author that there is an improvement in mechanical properties because of the formation of ZrB_2 particles. Hardness improved continuously with ZrB_2 content, whereas tensile properties enlarged up to 9 vol% ZrB_2 . Fracture behavior of the Al 7075/SiC composite was studied by Kalkanli and Yilmaz [13] using the three-point bend test. It was observed that flexural strength and reinforcement in wt% of SiC were directly related till a wt% of 10, where the flexural strength was reported to be 580 MPa. From the wt% of 10 till wt% of 30, the above parameters were observed to be inversely related. At wt% of 30, flexural strength was observed to be 300 MPa. Sliding wear tests have been employed by Suresh [14] to investigate the wear of Al-based MMCs reinforced with particles of B_4C , SiC, TiC and TiB₂. The tests were conducted for 80 N and 160 N loading using a pin-on-disc apparatus. The wear rate for the above Al-MMC is observed to be lower than that for the pure Al. Negligible influence of reinforcement size and type was noticed on the wear rate. But volume has a marginal consequence on wear rate.

Reinforcement particles present in the MMCs make the tools blunt and wear the tools with reduction in tool life. Most of the hard tools like carbide and HSS reduce their tool life while machining MMCs as explained by Aramesh et al. [15] in their work. Challenging on machining of MMCs increased due to the presence and development of hard reinforcements day by day. So far, most of the developed MMCs are machined using the conventional methods like turning, drilling, milling etc. keeping the cost aspects into the consideration. But high abrasive wear of tools are observed by the conventional machining methods, which again results to higher cost addition with poor machinability. Optimizing the machining parameters is required improve the machinability of the composites. Most of the researchers concluded that PCD tools are better suitable tools for machining the composite materials than the HSS and carbide tools as explained in the literature [16–18]. Munia raj and Manoharan [19] investigated the torque produced during drilling of the aluminum-based MMC with 15 wt% SiC and wt% graphite as reinforcements. The work concluded that the feed rate is the highly influenced factor to control the torque during the drilling of MMCs. From the work, it was also concluded that spindle speed is the least influencing factor during dry drilling of MMCs.

From the exceeding works, it is examined that assessment of mechanical properties and the machining of

MMCs reinforced with SiC, TiC and Al_2O_3 were carried out, but only few researchers concentrated on the machining of MMCs with such reinforcements. From the literature, it was also understood that the factors like weight fraction of reinforcements along with its distribution and properties of the matrix affect the machining of MMCs highly. The present study is aimed to expose the optimum drilling parameters of Al-6063 matrix reinforced with TiC composites. In order to determine the effects of drilling parameters on the surface roughness, cutting force and drilling temperature, three different helix angle, spindle speed and feed rate were used. The experimental consequences were interpreted by the help of GRA and ANOVA for the simultaneous optimization and influence of drilling parameters on responses. The most effective drilling parameters on machinability characteristics of MMCs were determined.

2 Materials and methods

This section presents the details of the materials and methods used to investigate the machining parameters effect on the MMCs. The mechanical as well as machinability properties of the MMCs depend on the ceramic (TiC) wt% used in the composite sample.

2.1 Work piece material

The composite used in the study was Al-6063 with 15 wt% of TiC MMC which were made up by the liquid processing technique with a thickness of 10 mm. The reinforcement wt% used in the current study was based on the previous study of the author [20]. The base metal Al-6063 aluminum alloys chemical composition is tabulated in Table 1. The stir casting setup is shown in Fig. 1. Table 2 shows the physical and its mechanical properties of Al-6063/TiC composites [20].

2.2 Drilling of composite

Drilling tests were performed under soluble oil (1:10) as a lubricant on Al-6063 with 15 wt% TiC-reinforced composites using a Universal drilling machine (GPREC Kurnool, A.P., India). In the current work, three controlling factors (helix angle, spindle speed and feed rate) with three levels each and HSS drill bits with a diameter of 10 mm have been considered. The composite tested for drilling is having a length of 160 mm and 60 mm

Table 1 Chemical composition of matrix material (Al-6063) aluminum alloy

Elements	Al	Fe	Si	Cu	Mg	Mn	Cr	Ti	Zn	Others
Composition (wt%)	97.5	0.35	0.60	0.1	0.9	0.1	0.1	0.1	0.1	0.15

Fig. 1 Stir casting setup

Table 2 Physical and tensile properties of composites with different reinforcement content [20]

Sample designation	Density (g/cc)	Microhardness (HV)	UTS (MPa)	Elongation (%)
Al 6063 + 5 wt% TiC	2.81	59.6	127	9
Al 6063 + 10 wt% TiC	2.86	73.8	132	7
Al 6063 + 15 wt% TiC	2.93	99.6	144	5

width with a constant thickness of 10 mm. Full factorial design was considered for performing the drilling experiments. Experimental test setup with dynamometer and used drill bits are shown in Fig. 2. The dynamometer connected to the drilling machine was an armed wheel strain gauge type which is capable of measuring both thrust force and torque during the drilling of composite specimens. Considered constraints and their ranks are listed in Table 3. Responses like cutting force were deliberated using a dynamometer, and surface roughness by a Talysurf roughness tester. Drilling tool–work interface temperature was examined using a pyrometer.

3 Results and discussion

The main purpose of the work is to optimize the drilling parameters simultaneously to achieve lower surface roughness (SR), cutting force (CF) and temperature (Temp.) in the drilling of the TiC-reinforced Al-6063 MMC. The drilled specimen with various test conditions is shown in Fig. 3. Experimental run conditions and its corresponding responses are tabulated in Table 4.

It is observed from Table 4 that increase in helix angle improved the surface roughness. This is due to the fact that surface flaws and irregularities get smeared out by raising helix angle at the drilling region. Similar results were observed by other peers who are working in the similar area [21, 22]. Higher helix angle decreases the temperature at the tool, which can be observed by Table 4. Increase in feed rate increased the surface roughness and cutting force similar to others researches [23, 24]. Enhance in feed rate decreased the temperature slightly during drilling of AMMC under the lubricated condition. Lower feed rate develops higher temperatures; thereby, the decrease in shear strength of work-piece at the cutting region takes place and let effortless shearing of the composite specimen during drilling.

3.1 Grey relational analysis procedure

Grey relational study is a way of converting two or more output parameters into a single output parameter so as to change the multi-response problem into a single-response one [25]. The method of grey relational study is explained in the subsections [26, 27].

3.1.1 Normalization of the test results

The experimental response values for punch force, thinning ratio and dome height have to be normalized in the range from 0 to 1 using Eqs. 1 and 2.

The normalized value for the *larger the better* type of response is

$$Z_i(K) = \frac{Y_i(k) - \min Y_i(k)}{\max Y_i(k) - \min Y_i(k)} \quad (1)$$

The normalized value for the *smaller the better* type of response is

$$Z_i(K) = \frac{\max Y_i(k) - Y_i(k)}{\max Y_i(k) - \min Y_i(k)} \quad (2)$$

$Z_i(K)$ is the normalizing value.

Fig. 2 Experimental test setup with dynamometer and drill bits

Table 3 Process parameters and its levels considered in the work

Factors	Parameters	Units	Level 1	Level 2	Level 3
A	Helix angle	degrees	20	30	40
B	Spindle speed	RPM	400	500	600
C	Feed rate	mm/rev	0.1	0.2	0.3

Fig. 3 MMC after drilling holes at various test conditions

3.1.2 Grey relation coefficient (GRC)

The grey relational coefficient values were calculated by Eq. 3.

$$\varepsilon_i(K) = \frac{\Delta_{\min} + \varphi \Delta_{\max}}{\Delta_{oi}(K) + \varphi \Delta_{\max}} \quad (3)$$

where Δ_{oi} is the quality loss function $= \Delta_{oi}(K) = (Z_o(K) - Z_i(K))$ and $\Delta_{\min}$ and $\Delta_{\max}$ are the min. and max. values of the differences of Δ_{oi} . The distinguish coefficient can be accustomed by the choice maker to exercise the judgment, and various distinguish coefficients produce various results in GRA. Based on the best results obtained in the literature, the distinguishing coefficient was set as 0.5 initially in the present work. The value of φ lies between 0 and 1 and is taken preferably to be 0.5 since all the responses are given equal importance.

3.1.3 Grey relation grade (GRG) and order

The grey relation coefficients shown in Table 5 are averaged in order to obtain the grey relation grade. By calculating the grey relational grades using Eq. 4, the multiple reactions are converted into single reactions.

$$\text{Grey relation grade } (\gamma_i) = \frac{1}{n} \sum_{k=1}^n \varepsilon_i(K) \quad (4)$$

Table 4 Experimental run conditions and their responses

Test no.	Helix angle (°)	Spindle speed (rpm)	Feed rate (mm/rev)	Surface roughness (μm)	Cutting force (N)	Temperature (°C)
1	20	450	0.1	0.426	570.78	29.5
2	30	450	0.1	0.567	470	29.3
3	40	450	0.1	0.263	422.22	28.3
4	20	450	0.2	0.54	653.78	29.4
5	30	450	0.2	0.66	435.78	29.0
6	40	450	0.2	0.39	454	28.7
7	20	450	0.3	0.806	774.78	29.2
8	30	450	0.3	0.953	553.78	29.6
9	40	450	0.3	0.463	535.78	28.9
10	20	500	0.1	0.416	525.75	29.0
11	30	500	0.1	0.48	411	29.2
12	40	500	0.1	0.203	392.22	28.7
13	20	500	0.2	0.426	653.78	29.3
14	30	500	0.2	0.643	435.78	29.3
15	40	500	0.2	0.273	414	28.9
16	20	500	0.3	0.656	653.78	30.0
17	30	500	0.3	0.853	544.89	29.7
18	40	500	0.3	0.326	490.21	28.8
19	20	560	0.1	0.38	530.78	30.2
20	30	560	0.1	0.47	424	29.6
21	40	560	0.1	0.193	392.22	29.0
22	20	560	0.2	0.43	658.78	31.7
23	30	560	0.2	0.51	435.78	29.7
24	40	560	0.2	0.256	414	29.8
25	20	560	0.3	0.53	721.78	33.9
26	30	560	0.3	0.56	573.78	31.9
27	40	560	0.3	0.256	544.89	29.8

where n is the no. of responses and ϵ_i (K) is the grey relation coefficient. Grey relational grades along with their rank (1st rank for the largest GRG) are shown in Table 5.

Here, by means of “grey relational analysis,” various responses are united to solo response, i.e., GRG, for tone down in optimization. Three drilling parameters are considered for optimizing and also three responses, i.e., surface roughness (SR), cutting force (CF) and tool temperature (Temp.) simultaneously. The procedure for the computation of GRG is talked about in Sect. 3.1. The experimental test results in Table 4 are utilized for calculating the normalized SR, CF and Temp., which are shown in Table 5. The calculated normalized value by Eq. 2 is used to work out GRCs for all the three outcomes using Eq. (3). Later, GRG is estimated from GRCs for all the experimental results using Eq. (4). As per the GRG conventions, the test conditions are correlated with ‘higher is better policy’ [28]. The optimal value, highest GRG, was originated to be the 12th experimental test condition, and the corresponding test set can be observed in

Table 4. By maximizing the grade values (Table 5), minimum SR, CF and Temp. can be simultaneously obtained at the helix angle of 40°, spindle speed of 500 rpm and feed of 0.1 mm/rev optimal drilling conditions. Figure 4 represents the main effects plots of GRG. From Fig. 4, similar results are observed as grey relational analysis, i.e., high helix angle, medium speed and lower feed for better GRG. Increase in spindle speed and feed leads to the increase in drilling temperature. This also led to an increase in adverse effect on the cutting edge; thereby, wear and burning scars around the drilling area increase. Increase in helix angle increases the cutting edge such that the reduction in chip thickness and chip width. Meanwhile thrust force decreases by this increase in helix angle. Lower helix angle had an adverse effect on wear of the composite sample (workpiece) during the drilling operation; in other words, higher helix angle also induces less wear of drill bit also. Higher spindle speed and feed rate impart higher wear of the drill bit and cutting edge angle.

Table 5 Estimated grey relational grades and their rankings

Test no.	Normalized			Grey relational coefficient			GRG (Expt.)	GRG predicted	Rankings of GRG (Expt.)
	SR	CF	Temp.	SR	CF	Temp.			
1	0.69	0.53	0.79	0.62	0.52	0.70	0.612	0.63300	18
2	0.51	0.80	0.82	0.50	0.71	0.74	0.651	0.76390	16
3	0.91	0.92	1.00	0.84	0.86	1.00	0.903	0.89480	3
4	0.54	0.32	0.80	0.52	0.42	0.72	0.554	0.53530	20
5	0.39	0.89	0.88	0.45	0.81	0.80	0.688	0.66620	11
6	0.74	0.84	0.93	0.66	0.76	0.88	0.763	0.79710	6
7	0.19	0.00	0.84	0.38	0.33	0.76	0.491	0.43760	25
8	0.00	0.58	0.77	0.33	0.54	0.68	0.519	0.56850	22
9	0.64	0.62	0.89	0.58	0.57	0.82	0.660	0.69940	15
10	0.71	0.65	0.88	0.63	0.59	0.80	0.673	0.63010	13
11	0.62	0.95	0.84	0.57	0.91	0.76	0.746	0.76100	8
12	0.99	1.00	0.93	0.97	1.00	0.88	0.950	0.89190	1
13	0.69	0.32	0.82	0.62	0.42	0.74	0.593	0.53240	19
14	0.41	0.89	0.82	0.46	0.81	0.74	0.670	0.66330	14
15	0.89	0.94	0.89	0.83	0.90	0.82	0.849	0.79420	4
16	0.39	0.32	0.70	0.45	0.42	0.62	0.498	0.43470	23
17	0.13	0.60	0.75	0.37	0.56	0.67	0.529	0.56560	21
18	0.83	0.74	0.91	0.74	0.66	0.85	0.750	0.69650	7
19	0.75	0.64	0.66	0.67	0.58	0.60	0.615	0.62662	17
20	0.64	0.92	0.77	0.58	0.86	0.68	0.706	0.75752	9
21	1.00	1.00	0.88	1.00	1.00	0.80	0.933	0.88842	2
22	0.69	0.30	0.39	0.62	0.42	0.45	0.495	0.52892	24
23	0.58	0.89	0.75	0.55	0.81	0.67	0.675	0.65982	12
24	0.92	0.94	0.73	0.86	0.90	0.65	0.802	0.79072	5
25	0.56	0.14	0.00	0.53	0.37	0.33	0.410	0.43122	27
26	0.52	0.53	0.36	0.51	0.51	0.44	0.486	0.56212	26
27	0.92	0.60	0.73	0.86	0.56	0.65	0.688	0.69302	10

Fig. 4 Main effect plot for GRG

3.2 ANOVA for GRG

The implication and percentage convince of process parameters over the worth and individuality was found

out by performing analysis of variance (ANOVA) [29–31]. Table 6 shows the ANOVA results of GRG. Based on the contribution entitlement, the most highly influenced feature for drilling operation is helix angle of the drilling tool with 63.2% contribution and feed rate with 34.02% contribution. Speed is not influencing parameter for drilling the Al-6063/TiC composites. Similar results in line with the present results were observed in the literature as well [32]. The drilling of composite specimen with higher helix angle generates less cutting force and cutting temperature due to the increase in flute volume for emigration of chips and temperature distribution [33]. The decrease in helix angle leads to the increase in the cutting length edge such that cutting edge increases. Increase in helix angle leads to the decrease in undeformed chip height and width so that the cutting edge decreases during the drilling operation.

Table 6 ANOVA of GRG

Source	DF	Adj SS	Adj MS	F-value	P-value	% Contribution
Helix angle	2	0.32360	0.161801	135.10	0.000	63.2
Spindle speed	2	0.01391	0.006955	5.81	0.010	2.78
Feed rate	2	0.17407	0.087036	72.67	0.000	34.02
Error	20	0.02395	0.001198			
Total	26	0.53554				
<i>Model summary</i>						
S	R-sq	R-sq(adj)	R-sq(pred)			
0.0346064	95.53%	94.19%	91.85%

Fig. 5 Contour plot of GRG versus feed and helix angle

3.3 Regression analysis

Correlation between independent, dependent and unknown parameters can be made possible with the help of regression analysis. An Eq. 5 shows the regression model generated for the GRG using MiniTab-16. The regression equation can be used to predict the GRG values for various levels of process parameters within the lower and higher limits. The drilling parameters with *P* value less than 0.05 indicated that the model terms significantly affected the response in the design space. Equation 5 indicates the relationship between the GRG and the drill process parameters, i.e., helix angle, spindle speed and feed rate. Figure 5 illustrates the contour plot of GRG for two highly influenced parameters (helix angle and feed rate) during the drilling of composite specimens which can be observed from Table 6. From Fig. 5, it is experiential that the increase in helix angle and the decrease in feed rate attained a higher GRG value at a steady speed of 505 rpm.

Interactions among the drilling parameters are not much influencing the response which is clearly observed from Table 6.

$$\text{GRG} = 0.495 + 0.01309 \text{ Helix angle} - 0.000058 \text{ Spindle speed} - 0.977 \text{ Feed rate} \quad (5)$$

Figure 6 illustrates the scatter plot of GRG with all the three considered drilling parameters. From Fig. 6, it is clearly understood that GRG increased with the increase in helix angle and decreased with the increase in feed rate. The influence of the spindle speed on GRG is very small which can be observed in Fig. 6b. ANOVA of GRG (Table 6) specified the similar results that speed is the least influencing factor among the three considered drilling factors. Similar results like influence of feed is more in drilling the MMCs were observed by others researchers as well [34].

3.4 Confirmation test

The validation of the experimental test results was carried out by performing the confirmation test with three repetitions. The results obtained by the confirmation test are shown in Table 7, and the confirmation tested sample is shown in Fig. 7. The average values were utilized to validate the prediction of GRG.

The GRG calculated from confirmation experiments was 0.901, whereas the GRG by experimental calculated value is 0.891. The confirmation of the GRG is valid since the error value is less than 1%.

3.5 SEM analysis

The drilled composite surface was observed by SEM to analyze the morphology of the machined surface. The SEM morphology of the drilled surface composite specimens is exposed in Fig. 8. Mostly in the drilling procedure, mutual rubbing of abrasive particles takes place, which

Fig. 6 Scatter plot **a** GRG versus helix angle, **b** GRG versus speed and **c** GRG versus feed

Table 7 Confirmation test results

S. no	Drilling parameters			Responses		
	Helix angle (°)	Spindle speed (rpm)	Feed rate (mm/rev)	Surface roughness (μm)	Cutting force (N)	Temperature (°C)
1	40	500	0.1	0.205	396.2	28.9
2	40	500	0.1	0.202	392.1	28.5
3	40	500	0.1	0.208	390.4	28.1
Average				0.205	392.9	28.5

smoothens the surface of the composite. When compared to Fig. 8a and b, Fig. 8b shows smooth surface due to the higher helix angle with less feed rate. After thorough examination of the SEM images, morphology of the drilled surface reveals that a higher feed rate causes the wide surface dent in the composite specimens which may be because of higher contact pressure. Moreover, high feed rate increases the tool–workpiece interface can be observed from Table 4 as well. This leads the composite specimen soften due to plastic deformation. More pulling

out of particles was observed in Fig. 8 a & b. The occurrence of the cracks on the machined surface is due to the strain hardening of the composite specimen. Enlarge in micro-cracks leads to the voids in the composites [35, 36] which is observed in Fig. 8a. Figure 8a shows lot of scratches because of more contact pressure due to elevated feed rate. Once the particles start pulling out from the composite specimens, crack and pits form over the surface which leads to the reduced surface finish of the drilled surface.

Fig. 7 Confirmation test composite sample

4 Conclusion

In this study, grey relational analysis was tailored to discover the cause of drilling parameters on fabricated aluminum Al-6063 reinforced with 15 wt% TiC composites. A multi-objective function named full factorial design based grey relational analysis were tailored to get the optimal parameter setting of the drilling parameters, for minimizing the surface roughness, cutting force and tool temperature in drilling operation.

1. GRA is an extremely valuable procedure to optimize the SR, CF and Temp., during the drilling of aluminum-based MMCs since it does not entail several complex mathematical presumptions and simulation can be easily used by the practitioners or engineers in the industry.
2. In the present study, the optimal arrangement of drilling parameters identified by GRA is higher helix angle (40°), medium spindle speed (500 rpm) and lower feed (0.1 mm/rev).
3. ANOVA of the GRG revealed that helix angle is the most influencing parameter with 63.2% contribution followed by feed with 34% contribution. Speed is the least contribution with 2.7% for optimizing the drilling parameters for drilling AMMC.
4. The SEM description of the drilled surface confirms the proof of honing result, debris and trimmed surface of the composite material.

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Compliance with ethical standards

Conflict of interest The authors declare that there is no conflict of interest regarding the publication of this paper.

Fig. 8 SEM images of the drilled surface at speed of 500 rpm with **a** helix angle 20 and feed rate 0.3 and **b** helix angle 40 and feed rate 0.1

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