MULTIPLE PERFORMANCE OPTIMIZATION OF MACHINING PARAMETERS OF DRILLING HYBRID MICA COMPOSITES USING TAGUCHI BASED GREY RELATIONAL ANALYSIS

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Abstract

This paper focuses on the multiple performance analysis in machining characteristics of drilling Hybrid Metal Matrix Composites (MMC) produced through stir casting route. Taguchi based Grey relational analysis is used for the optimization of the machining parameters on drilling hybrid composites. Experiments are conducted on AA 356-aluminium alloy reinforced with silicon carbide of size 25 microns and Mica of size 45 microns. Drilling test is carried out in VMC Machining centre using solid carbide drills of 6 mm diameter. An L_{27}, 3-level orthogonal array was chosen for the experiments with three drilling parameters namely spindle speed, feed rate, and wt % of SiC and have been optimized based on the multiple performance characteristics for thrust force, surface roughness, and torque. The level of importance of the drilling parameters is determined by using Analysis Of Variance (ANOVA). Experimental results show that the performance in drilling process can be improved effectively by using this approach.

Key words: Drilling, Hybrid composites, Grey relational analysis, ANOVA, Optimization.

I. INTRODUCTION

Metal matrix composites (MMC) are materials which combine a tough metallic matrix with hard ceramic reinforcement. The inclusion of an additional reinforcement phase makes them hybrid composites. Metal matrix composites, in general possess certain superior properties like low density, high specific gravity, stiffness and strength, controlled coefficient of thermal expansion, superior wear resistance and corrosion resistance. But their poor machinability is attributed to the presence of ceramic reinforcements, resulting in very high rates of tool wear, which in turn restricts their wider spread. The effect of the various cutting parameters on the surface quality and microstructure on drilling of Al/17% SiC particulate MMC by using various drills were investigated by Tosun [20, 21]. Drilling of metal matrix composites of type A356/20% SiC-T6 was investigated by Davim et al [3] based on the Taguchi technique with the objective of establishing the correlations between cutting velocity, feed rate and cutting time with the evaluation of tool wear, specific cutting pressure and hole surface roughness using PCD drill. Shew and Kwong [17] have used the optimization technique to obtain an extended tool life and better productivity, which are influenced by cutting force and torque. The tool life, surface roughness and burr formation were investigated in high speed drilling of stainless steel using TiN-coated carbide drill [6]. Mohan et al [10] have discussed the influence of process parameters were studied on cutting force and torque during drilling of glass-fiber polyester reinforced composite using Taguchi technique with the objective of minimization of cutting force and torque.

Grey relational analysis based on grey system theory was used for solving the complicated interrelationships among the multi responses [1, 5, 12]. The grey relational grade was obtained to evaluate the multiple responses. As a result, optimization of the multiple responses can be converted into optimization of a single relational grade [4, 13].

Traditionally, Mica is a natural lubricant which eases machining. Most of the researches on the machining of Al/SiC metal matrix composite have been focused, while machining of Al/SiC-Mica has received less attention. Little research has been done on the incorporation of mica in SiC composites. The proposed methodology of combining grey relational analysis and Taguchi method has wide applications in the multi response problems like optimization of machining parameters in drilling of hybrid MMC's using the solid carbide drills.

In the present study experimental details using the Taguchi method of parameter design have been employed for optimizing multiple performance characteristics such as surface roughness, thrust force and torque for drilling Al/Sic-Mica composites. Grey relational analysis has been considered for optimization of multiple response characteristics. Finally analysis of variance (ANOVA) and confirmation test have been conducted to verify the test results.

II. EXPERIMENTAL

A. Materials and methods

Aluminium alloy Al 356 was used as a matrix material and its chemical composition is as shown in Table 1.

The silicon carbide particles of size 25 microns and Mica, an average size of 45 microns were used as the reinforcement materials. The composites were fabricated with 5-15 weight % of the Sic particle in steps of the 5 weight % and a fixed quantity of 3 weight % of Mica.

The Al 356 alloy, which was in the form of ingot, was cut into small pieces to accommodate into the Silica Crucible. The Mica for the study has been procured from Premier Mica Company, Chennai. Aluminium alloy was first melted in an electric furnace. Mica and SiC, preheated to a temperature of about 620°C, were added to the molten metal at 750°C and stirred continuously. The stirring was done at 500 rpm for 5-7 min. Magnesium was added in small amounts during stirring to increase the wetting. The melt with reinforcement was poured into permanent metallic mould.

B. Experimental Design

Taguchi design of experiments was used to plan experimental design [14, 16, 19] This method can dramatically reduce the number of experiments required to gather necessary data. Although many factors affect the machining process, the cutting variables such as cutting speed and feed rate are important parameters which has been considered first. Apart from the cutting parameters, work piece also plays an important role. The machinability of metal matrix composite is influenced by the wt % of reinforcement embedded in the matrix. Table 2 shows the machining parameters considered, its symbol and its level. In the present study the machining parameters has been evaluated by the following responses thrust force, torque and surface roughness.

C. Experimental Procedure

Drilling tests were conducted on vertical CNC machining centre. The machining samples were prepared in the form of 150 mm × 150 mm × 10 mm blocks for each material. The solid carbide drill bits of 6 mm diameter were used. The surface roughness of the work piece was measured with a Mitutoyo portable Surftest SJ-201 P/M contact profilometer. The computer controlled data acquisition system was used to collect and record the data of the experiments. The Kistler dynamometer was used to record the thrust force and torque. The dynamometer is connected to a 3-channel charge amplifier type through a connecting cable type, which in turn is connected to the PC by a

Table 1. The chemical composition of Al 356 alloy materials

Material	Chemical composition (wt.%)							
	Copper	Silicon	Magnesium	Manganese	Iron	Titanium	Zinc	Al
Composite matrix	<0.0005	7.27	0.45	<0.002	0.123	0.08	0.005	Balance

Table 2. Machining parameter and levels

Machining parameters	units	symbol	Level		
			1	2	3
Spindle Speed	rpm	*A*	1000	2000	3000
Feed rate	mm/min	*B*	50	100	150
Wt fraction of Sic	%	*C*	5	10	15

37-pin cable from the A/D board. The experiments were repeated twice to circumvent the possible experimental errors. A schematic arrangement of experimental setup is shown in Figure 1. The sample outputs of the dynamometer (variation of thrust force, Torque with acquisition time) at different spindle speeds are given in Figures 2-4.

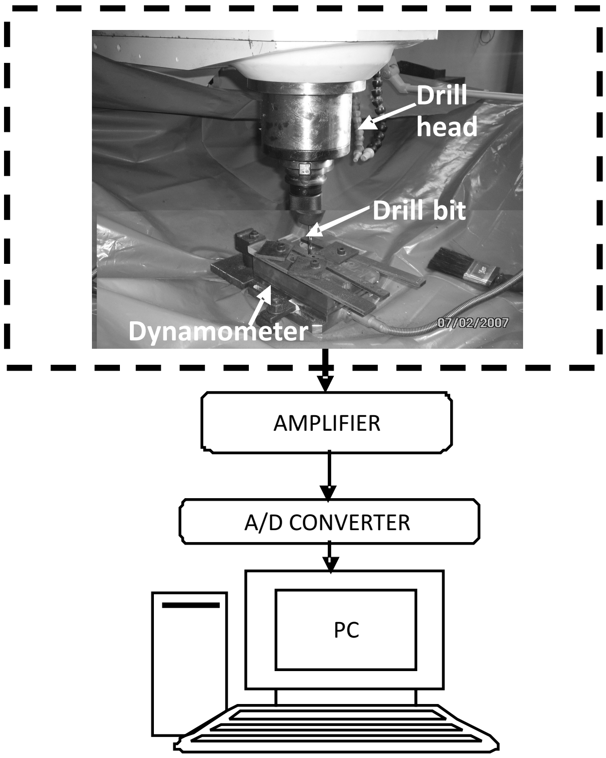
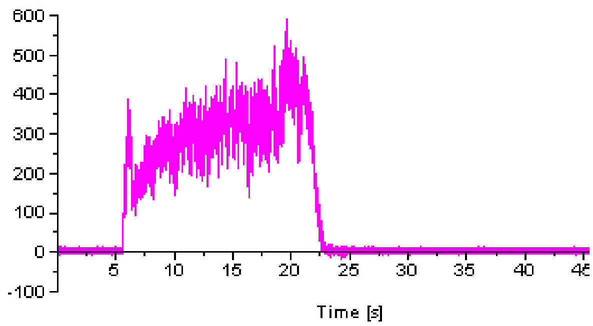
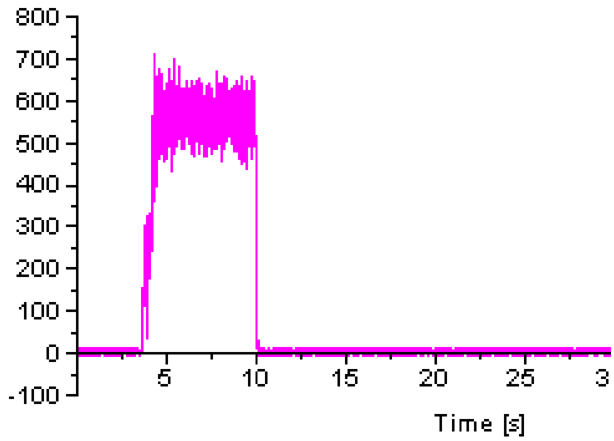


Fig. 1. Schematic representation of experimental set-up



Mean Value = 610 N

Fig. 2. Typical thrust force observed when spindle speed = 1000 rpm feed rate = 50 mm/min and work piece contains 15% Sic_p + 3% Mica



Mean Value = 710 N

Fig. 3. Typical thrust force observed when spindle speed = 1000 rpm feed rate = 150 mm/min and work piece contains 5% Sic_p + 3% Mica

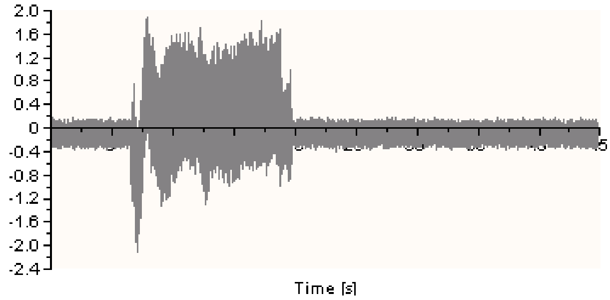


Fig. 4. Typical Torque value observed when spindle speed = 1000 rpm feed rate = 50 mm/min and work piece contains 15% Sic_p + 3% Mica

The experimental results of the thrust force, surface roughness and torque are shown in Table 3

III. GREY RELATIONAL ANALYSIS

The Taguchi method is a systematic approach for design and analysis of experiments to improve the product quality and the grey relational analysis. It can highly simplify the optimization of process parameters for multiple performance characteristics. To get optimized results, Taguchi loss function was used to measure the performance characteristics deviation from the desired value [12]. In grey relational analysis, grey relational coefficient for different process characteristics were calculated and average of these coefficients was considered which is called grey relational grade and was used as a single response for the Taguchi's experimental plan. A statistical analysis of variance (ANOVA) is performed to see which process

Table 3 Experimental results

Trail No	Spindle speed (rpm)	Feed rate (mm/min)	Wt of SiC (%)	Thrust force (N)	Surface Roughness (microns)	Torque (Nm)
1	1000	50	5	510	2.4	2.1
2	1000	50	10	545	2.1	2.2
3	1000	50	15	568	1.8	2.4
4	1000	100	5	585	3.8	2.7
5	1000	100	10	605	3.4	2.9
6	1000	100	15	625	3.2	3.2
7	1000	150	5	640	4.8	2.6
8	1000	150	10	680	4.3	2.8
9	1000	150	15	710	4.0	3.0
10	2000	50	5	525	2.0	2.8
11	2000	50	10	560	1.8	2.9
12	2000	50	15	585	1.5	3.2
13	2000	100	5	600	3.3	3.0
14	2000	100	10	625	3.0	3.2
15	2000	100	15	640	2.7	3.4
16	2000	150	5	650	4.0	2.8
17	2000	150	10	695	3.7	3.0
18	2000	150	15	720	3.4	3.1
19	3000	50	5	535	1.7	3.1
20	3000	50	10	580	1.6	3.3
21	3000	50	15	585	1.5	2.8
22	3000	100	5	610	2.8	3.1
23	3000	100	10	635	2.5	3.4
24	3000	100	15	660	2.2	3.6
25	3000	150	5	665	3.6	3.0
26	3000	150	10	710	3.2	3.1
27	3000	150	15	745	2.7	3.2

parameters are statistically significant. With the grey relational analysis and statistical analysis of variance, the optimum combination of the process parameters can be predicted. Finally, a confirmation experiment is conducted to verify the optimal process parameters obtained from the process parameter design [1].

A. S/N ratio to compute drilling characteristics

During drilling of hybrid MMCs, thrust force, surface roughness and torque has been considered as smaller-the-better type. These considerations have been made with respect to greater quality characteristics of interest.

Hence, the S/N ratio of the quality characteristics (smaller-the-better type) are computed by using the following formula

$$\text{S/N ratio } \eta = -10 \log \left[\frac{1}{n} \sum_{i=1}^{n} y_i^2 \right] \quad (1)$$

The S/N ratios of output responses are shown Table 4.

Table 4. Multi response S/N ratio for experimental results

Exp No	Thrust force (N)	Surface roughness (um)	Torque (Nm)
1	– 54.1514	– 7.60422	– 6.44439
2	– 54.7279	– 6.44439	– 6.84845
3	– 55.0870	– 5.10545	– 7.60422
4	– 55.3431	– 11.5957	– 8.78665
5	– 55.6351	– 10.6296	– 9.24796
6	– 55.9176	– 10.1030	– 10.1030
7	– 56.1236	– 13.6248	– 8.29947
8	– 56.6502	– 12.6694	– 8.94316
9	– 57.0252	– 12.0412	– 9.54243
10	– 54.4032	– 6.0206	– 8.94316
11	– 54.9638	– 5.10545	– 9.39644
12	– 55.3431	– 3.52183	– 10.103
13	– 55.563	– 10.3703	– 9.5424
14	– 55.9176	– 9.54243	– 10.103
15	– 56.1236	– 8.62728	– 10.7564
16	– 56.2583	– 12.0412	– 8.94316
17	– 56.8397	– 11.364	– 9.54243
18	– 57.1466	– 10.6296	– 9.82723
19	– 54.5671	– 4.60898	– 9.96621
20	– 55.2686	– 4.0824	– 10.3703
21	– 55.563	– 3.52183	– 10.8814
22	– 55.7066	– 8.94316	– 9.96621
23	– 56.0555	– 7.9588	– 10.6296
24	– 56.3909	– 7.04365	– 11.1261
25	– 56.4564	– 11.1261	– 9.54243
26	– 57.0252	– 10.103	– 9.82723
27	– 57.4431	– 8.81818	– 10.103

B. Grey Relational Analysis for the S/N Ratio

In the grey relational analysis, a data pre-processing is performed in order to normalize the raw data, and a linear normalization of the S/N ratio is performed. The normalized S/N ratio means, when the range of the series is too large or the optimal value of a quality characteristic is too enormous, it will cause the influence of some factors to be ignored and the original experimental data must be normalized to eliminate such effect. So the normalized S/N ratio x_{ij} for the i^{th} performance characteristic in the j^{th} experiments can be expressed as follows;

$$x_{ij} = \frac{\eta_{ij} - \min_j \eta_{ij}}{\max_j \eta_{ij} - \min_j \eta_{ij}} \quad (2)$$

Table 5 shows the normalized S/N ratio for thrust force, surface roughness and torque. Basically, the larger normalized S/N ratio corresponds to the better performance and the best-normalized S/N ratio is equal to unity. Next, the grey relational coefficient is calculated to express the relationship between the ideal (best) and actual normalized S/N ratio. The grey relational coefficient ξ_{ij} for the i^{th} performance characteristic in the j^{th} experiment can be expressed as follows

$$\xi_{ij} = \frac{\min_k \min_j |x_i^0 - x_{ij}| + \zeta \max_i \max_j |x_i^0 - x_{ij}|}{x_i^0 - x_{ij}| + \zeta \max_i \max_j |x_i^0 - x_{ij}|} \quad (3)$$

Where x_i^0 is the ideal normalized S/N ratio for the i^{th} performance characteristic and ξ distinguishing coefficient which is in the range $0 \le \zeta \le 1$.

A weighting method is then used to integrate the grey relational coefficients of each experiment into the grey relational grade. The overall evaluation of the multiple performance characteristics is based on the grey relational grade, i.e.,

$$\gamma_j = \frac{1}{m} \sum_{i=1}^{m} \omega_i \zeta_{ij} \quad (4)$$

Table 5 shows the normalized S/N ratio for thrust force, surface roughness and torque.

Assume that $\omega_1 = \omega_2 = \omega_3 = 1$, where Y_j is the grey relational grade for the j^{th} experiment, ω_i the weighting factor for the i^{th} performance characteristic, and m the number of performance characteristics. Table 6 shows the grey relational grade for each experiment using the L_{27} orthogonal array. A higher grey relational grade indicates that the corresponding S/N ratio is closer to the indicates normalized S/N ratio [13].

Table 5

Expt No	Thrust force (N)	Torque (Nm)	Surface roughness (m)
1	0	0	0.364
2	0.226	0.533	0.294
3	0.355	0.752	0.199
4	0.385	0.501	0.699
5	0.599	0.660	0.626
6	0.766	0.752	0.547
7	0.627	0.396	1
8	0.766	0.533	0.928
9	0.875	0.660	0.871
10	0.126	0.0875	0.218
11	0.307	0.631	0.178
12	0.444	0.837	0.093
13	0.429	0.599	0.547
14	0.679	0.780	0.518
15	0.864	0.893	0.460
16	0.729	0.533	0.789
17	0.875	0.660	0.810
18	1	0.722	0.800
19	0.108	0.247	0.047
20	0.291	0.780	0.0931
21	0.416	0.946	0
22	0.400	0.780	0.397
23	0.653	0.921	0.413
24	0.851	1	0.330
25	0.716	0.660	0.652
26	0.851	0.722	0.723
27	0.967	0.780	0.652

Table 6 Grey relational coefficient and grey grade for each experiment

Exp no	Grey relation coefficient			Grey grade
	Thrust force (N)	Torque (Nm)	Surface roughness (μm)	
1	0.333	0.333	0.440	0.369
2	0.392	0.517	0.414	0.441
3	0.436	0.669	0.384	0.496
4	0.448	0.500	0.624	0.524
5	0.555	.595	0.572	0.574
6	0.682	0.669	0.524	0.625
7	0.573	0.453	1	0.575
8	0.682	0.517	0.874	0.591
9	0.801	0.595	0.795	0.631
10	0.363	0.353	0.390	0.369
11	0.419	0.575	0.378	0.457
12	0.473	0.755	0.355	0.528
13	0.466	0.555	0.524	0.516
14	0.609	0.694	0.509	0.604
15	0.787	0.824	0.480	0.647
16	0.649	0.517	0.704	0.523
17	0.801	0.595	0.725	0.607
18	1	0.643	0.714	0.646
19	0.359	0.399	0.344	0.367
20	0.413	0.694	0.355	0.488
21	0.461	0.983	0.333	0.666
22	0.454	0.694	0.453	0.534
23	0.590	0.863	0.460	0.638
24	0.771	1	0.427	0.633
25	0.638	0.595	0.589	0.508
26	0.771	0.643	0.644	0.586
27	0.938	0.694	0.589	0.640

IV. ANALYSIS OF EXPERIMENTAL RESULTS AND DISCUSSIONS

From the results it is known that the mechanism of drilling of metal matrix composite is due to the combination of plastic deformation, shearing and bending rupture. The occurrence of the above mechanism depends on the weight % of ceramic particles embedded in the matrix. Normally the roughness of the drilled composite surface was highly influenced by the feed rate and is followed by the spindle speed. The thrust force also play a vital role in deciding the performance of the product produced, while considering the above aspects it is very difficult to attain good performance during the drilling operation. If one of its characteristic improves the performance and other reduces it and hence achieving multiple performances is a difficult task [11].

In order to obtain the optimal drilling parameter for multiple performance characteristics, statistical analysis must integrate some other numerical method like regression and mathematical modeling. However, it is quite different and efficient to obtain the optimal machining parameter by grey relational analysis. The grey relational generating data of 27 experiments are shown in table. Surface roughness, torque, Thrust force are taken as the lower the better characteristic. Grey relational grade can be calculated by using equation 1, 2, 3. It is found that experiment 21 drilling parameter setting has the highest grey relational grade from

Table 7 ANOVA for Grey grade

Source	Sum of Squares	Degrees of freedom	Mean Square	F Value	p-value Prob > F	contribution % of
Model	0.180333	6	0.030055	21.3085	< 0.0001	
A-Spindle speed rpm	0.021199	2	0.0106	1.133909	0.3416	10.1653
B-Feed rate mm/min	0.092927	2	0.046463	32.94116	< 0.0001	44.55994
C-Wt % of SiC	0.084208	2	0.042104	29.85043	< 0.0001	40.37907
Residual	0.018	20	0.0009			8.631324
Cor Total	0.208543	26				

table 6. Therefore experiment drilling parameter setting is the optimal parameter setting for attaining multiple performance simultaneously among 27 experiments.

However, the relative importance among the machining parameters for the multiple performance characteristics still needs to be analyzed so that the optimal combinations of the machining parameter levels can be determined more clearly [6,19]. For analyzing the results, statistical analysis of variance (ANOVA) is used.

ANOVA is a standard statistical technique to interpret the experimental results. It is extensively used to identify the performance of a group of parameters under investigation. The purpose of ANOVA is to investigate the parameters, whose combination to total variation is significant. In ANOVA, the total sum of squares deviations (SS_T) is calculated by

$$SS_T = \Sigma (m_i - m)^2 \quad (5)$$

Where m is the overall mean of S/N ratio.

The total sum of squared deviations, SS_T, is divided into two sources

$$SS_T = \sum_{i=1}^{np} SS_j + SS_e \quad (6)$$

Where, SS_j is the sum of squared deviations for each design parameter and is given by

$$SS_j = \sum_{i=1}^{l} (\eta_{ji} - m)^2 \quad (7)$$

Where n_p is the number of significant parameters and l is the number of levels of each parameter. SS_e is the sum of squared error without or with pooled factor, which is the sum of squares corresponding to the insignificant factors. Mean square of a factor (MS_j) or error (MS_e) is found by dividing its sum of squares with its degree of freedom. Percentage contribution (ρ) of each of the design parameters is given by following equation [8, 15]

$$\rho_j = \frac{SS_j}{SS_T} \quad (8)$$

The analysis of variance is presented in Table 7 Based on the results of analysis of variance (Table 7) it has been understood that feed rate and spindle speed are the most significant machining parameters which were found to affect the multiple performance characteristics.

From the Fig. 5 (a-c) it clear that feed rate is the most significant factor that affects the grey relational grade. The results indicate that low feed rate is preferred in drilling of hybrid Al356/SiC Mica MMC. Increase in feed rate increases the thrust force and it leads to poor surface finish. Also, the increase in feed rate increases the heat generation during drilling which increases the surface roughness. The increase in wt % of SiC decreases the surface roughness. It is evident that the surface roughness values for Al356/SiC-Mica reinforced composites decreases with increase in spindle spindle speed. This is due to the polishing effect produced by the rubbing of small SiC particles trapped between the flank face of the tool and the work piece surface. The optimal level of machining parameters are achieved based on highest average.

Since the experimental design is orthogonal, it is then possible to separate out the effect of each machining parameter on the Grey relational grade at different levels. For example, the mean of the Grey relational grade for spindle speed at levels 1 and 2 can be calculated by averaging Grey relational grade

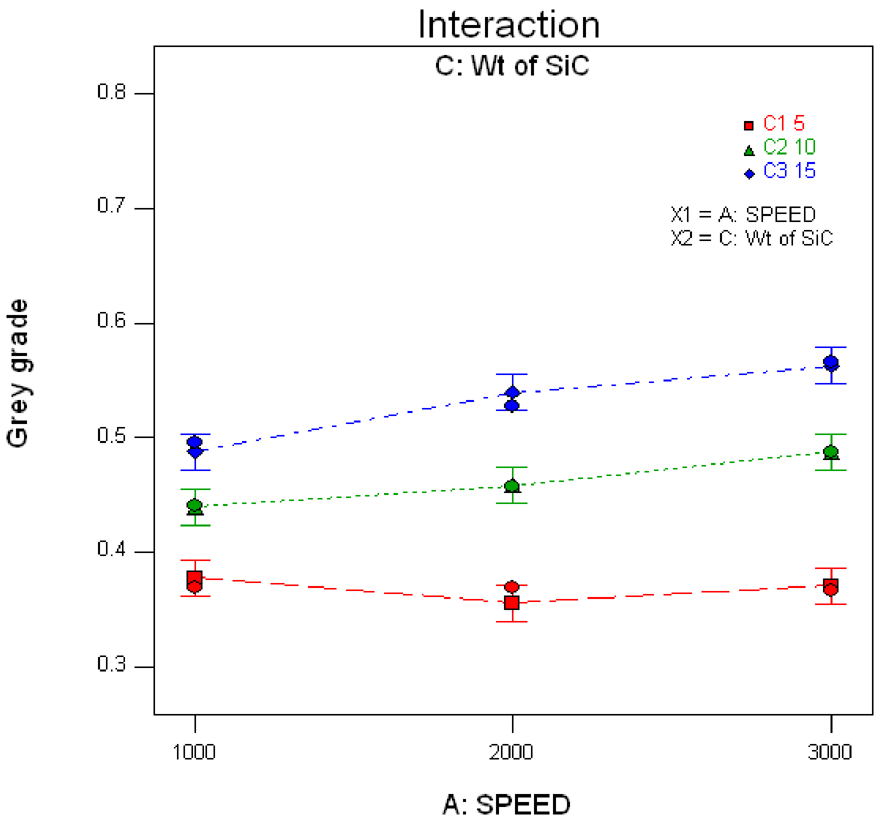


Fig. 5 (a) Spindle speed Vs Wt % SiC interaction plot at Feed rate = 150 mm/min

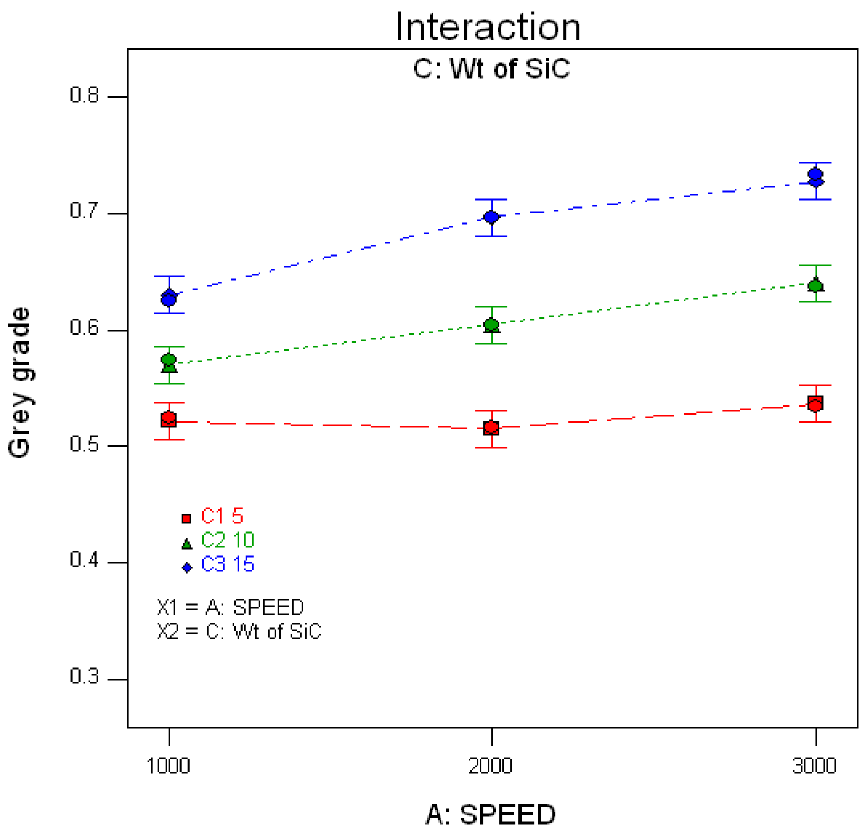


Fig. 5 (b) spindle speed Vs Wt % SiC interaction plot at Feed rate = 50 mm/min

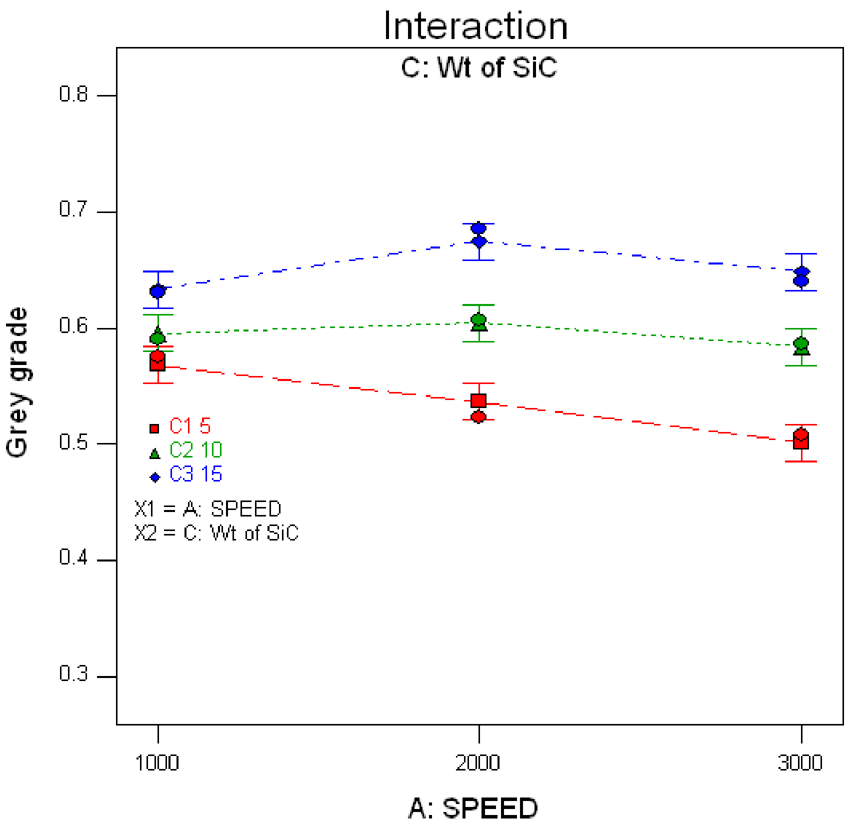


Fig. 5 (c) Spindle speed Vs Wt % SiC interaction plot at Feed rate = 100 mm/min

for the experiments 1 to 9 and 10 to 18 respectively. The influence of each machining parameter can be more clearly presented by means of the grey relational grade graph. The response table for grey relational grade is presented in Table 8.

Table 8 Response table for grey relational grade

Symbol	Machining parameter	Grey relational Grade		
		1	2	3
A	Spindle speed m/min	0.536	0.553	0.562
B	Feed rate mm/min	0.6	0.58	0.453
C	Wt of SiC %	0.475	0.585	0.622

Based on the response graph (Fig 6) and response table (Table 8), the optimal drilling parameters for the Al356/SiC-Mica composites can be achieved. In the present study, number of levels considered is three. If more than three levels are used, the number of experiments required to arrive the results will be high. The authors attempted to arrive at the optimal solution within three levels of parameters. For non-linearity three levels are sufficient. But if more levels are considered, the results will be better. The results obtained may not be optimal results. The results have been considered as near-optimal results and have been confirmed by using confirmation tests. Since the confirmation test has been done, the optimum solution may be a feasible one and is discussed in the next section.

Table. 9 Results of machining performance using the initial and optimal machining parameters

	Initial Machining parameter	Optimal machining parameter	
		Prediction	Experimental
Setting level	$A_2B_2C_2$	$A_3B_1C_3$	
Thrust force	600		580
Torque	3.2		2.8
Surface roughness	3.3		1.5
Grey relational grade	0.516	0.713	0.667

Referring to the average response table and average response graph, the variable settings for near-optimal machining parameters are

- ❖ Spindle speed at level three A_3
- ❖ Feed rate at level one B_1
- ❖ wt % Sic_p at level three C_3

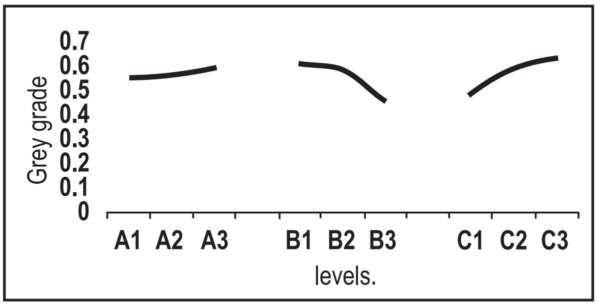


Fig. 6. Response graph for grey grade

Scanning electron microscope (SEM) was used to observe and analyze the machined surface. The SEM micrographs of the drilled surface are given in Fig. 7.

V. CONFIRMATION TESTS

The final step involved is to predict and verify the improvement in the performance characteristic for drilling of Al356/SiC-Mica composites with respect to the chosen initial parameter setting. The predicted Grey relational grade, using the optimal level of the machining parameters, can be calculated from following equation:

$$\alpha_{predicted} = \alpha_m + \sum_{i=1}^{N} (\alpha_0 - \alpha_m) \quad (9)$$

where α_m is the total mean of the Grey relational grade, α_0 is the mean Grey relational grade at optimal level and n is the number of main design parameters that affect the Multiple performance characteristics. Table 9 shows the comparisons of predicted and actual machining performance for multiple performance characteristic using their optimal cutting parameters. The confirmation experimental results at optimal level (A_3B_1C3) shows that Thrust force is reduced from 600N to 580 N, surface finish is improved from 3.3 to 1.5 μm, and torque is reduced from 3.2 Nm to 2.8 Nm It is clearly evident from these results that the multiple performance characteristics in the composite machining process are greatly improved through this approach.

Fig. 7. SEM image illustrating the drilled surface when Spindle speed = 3000 rpm, Feed rate = 50 mm/min

VI. CONCLUSIONS

- Orthogonal array with Grey relational analysis was employed to optimize the multiple performance characteristics of machining process. The work piece used was Al356/SiC-Mica composites and the tool material used was solid carbide drills of 6 mm diameter.
- The experimental results for optimal settings shows that there was a considerable improvement in the performance characteristics of machining process. The confirmation experiment results at optimal level ($A_3B_1C_3$) shows that shows that thrust force is reduced from 600 N to 580 N, surface finish is improved from 3.3 to 1.5 μm, and torque is reduced from 3.2 Nm to 2.8 Nm. It is clearly evident from these results that the multiple performance characteristics in the composite machining process are greatly improved through this approach.

- Feed rate is the factor which has great influence on machining of Al356/SiC-Mica composites, followed by spindle speed.
- This technique will be more convenient and economical to predict the effects of different influential combinations of parameters within the levels studied.
- The Grey relational analysis technique converts the multiple performance characteristics into single performance characteristics and therefore simplifies the optimization procedure. The accuracy can be improved by including more number of parameters and levels.

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