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Multi Response Optimization in Drilling Al6063/SiC/15% Metal Matrix Composite

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Abstract**—**This investigation proposes a grey-based Taguchi method to solve the multi-response problems. The grey-based Taguchi method is based on the Taguchi's design of experimental method, and adopts grey relational analysis (GRA) to transfer multi-response problems into single-response problems. In this investigation, an attempt has been made to optimize the drilling process parameters considering weighted output response characteristics using grey relational analysis. The output response characteristics considered are surface roughness, burr height and hole diameter error under the experimental conditions of cutting speed, feed rate, step angle, and cutting environment. The drilling experiments were conducted using L27 orthogonal array. A combination of orthogonal array, design of experiments and grey relational analysis was used to ascertain best possible drilling process parameters that give minimum surface roughness, burr height and hole diameter error. The results reveal that combination of Taguchi design of experiment and grey relational analysis improves surface quality of drilled hole.

Keywords**—**Metal matrix composite, Drilling, Optimization, step drill, Surface roughness, burr height, hole diameter error.

I. Introduction

COMBINATION of a high strength ceramic reinforcement in a soft metal matrix is the technological innovation in the field of composites; the designers have the choice to choose suitable materials for particular applications. The composites have yet to exhibit a major role into high volume automotive and aerospace applications [1]-[3]. But composites are not easy to machine as compared to conventional materials. Drilling is most widely used for joining different materials, due to the economic reason and applicability. Since the metal matrix composites contain SiC in particulate form, a cutting tool must be able to drill composites with high quality. Therefore, it is necessary to understand the relationship among the various controllable parameters and to identify the important parameters that influence the quality of drilling.

A number of studies have been performed by various researchers worldwide in the last few decades. Initially, researchers introduced the concept of optimum speed for metal cutting operations. Many approaches have been proposed for optimizing machining parameters for better economic performance [4]. A study was done on drilling metal matrix composites of type A356/20% SiC-T6 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, the specific cutting pressure and the hole surface roughness using PCD drill [5]. The effect of various cutting parameters was investigated on the surface quality and microstructure on drilling of Al/17% SiC particulate MMC by using various drills, and it was suggested that TiN coated HSS drills can be used for drilling Al/SiC-MMC rather than solid carbide tools [6], [7]. Chin reported that the holes obtained during drilling of aluminum-silicon alloys with 7% silicon (SAE 323) using uncoated and diamond coated K10 carbide tools with MQL technique presented either similar or better quality than those obtained with flood lubricant system [8]. Lin presented an investigative study on dry and semi-dry drilling of 12% silicon aluminum alloy (JISADC12) with finely crystallized smooth surface of diamond coatings. The study revealed that smooth surface diamond coating could lead to longer durability of drills as compared to conventional rough surface diamond coating in both dry and semi-dry cutting conditions [9]. Kuo et al. investigated the tool life, surface roughness and burr formation in high-speed drilling of stainless steel using TiN-coated carbide drill [10]. Mohan et al. studied the influence of process parameters 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 [11]. Most of the applications of Taguchi method concentrate on the optimization of single response problems [12]. The grey relational analysis based on grey system theory can be used for solving the complicated interrelationships among the multiple responses [13], [14].

Critical review of literature in the present investigation revealed that burr formation was the major issue while drilling. To minimize the problem, a step drill was proposed for drilling. Taguchi L27 OA was implemented to plan the experimentation. Four drilling process parameters, cutting speed, feed rate, step angle, and cutting environment with three levels each, were selected. The effect of these process parameters on quality characteristics, surface roughness (SR), burr height (BH) and hole diameter error (HDE) was examined using Taguchi based grey relational analysis (GRA).

II. Experimental Procedure

A. Material

Aluminum alloy Al6063 was used as a matrix material. Silicon carbide particles of average size 30-40 microns were used as the reinforcement materials. The composite with 15wt% of SiC particles was fabricated by the mechanical stir

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casting Process. The Al6063 alloy, which was in section, was cut into small pieces in order to be used into the graphite crucible. The aluminum alloy was first melted in an electric furnace. SiC particulates, preheated to a temperature of about 720°C, were added to the molten metal at 760° C and stirred continuously for uniform distribution. The stirring was done at 750rpm for 7–9min. The melt with reinforcement was poured into a permanent metallic mould. The microstructure of uniformly distributed SiC particulates is shown in Fig. 1.

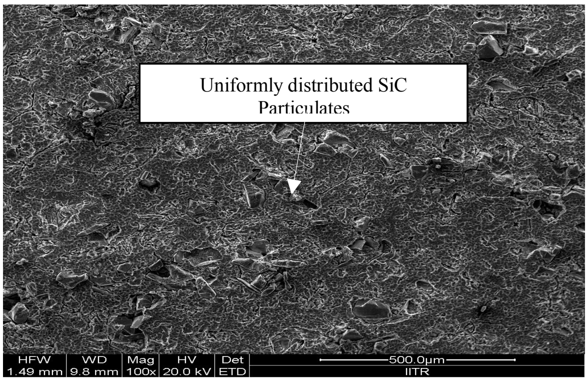

Fig. 1 Microstructure of the AA6063/15%SiC composite

B. Drilling Parameter Selection

The Taguchi method, developed by Dr. Genichi Taguchi, refers to the technique of quality engineering. Taguchi's parameter design not only can reduce product cost, improve quality, but also reduce experimental time interval. In this study, L27 (3^{13}) orthogonal array is chosen due to its capability to check the interactions among the parameters [15]. Process parameters A, B, C, D and their range are shown in Table I. Signal-to-noise ratio (S/N), for each control factor is calculated to find the effect of drilling parameters on the response characteristic. The signals are indicators of the effect on the average responses. The noises are measures of the influence on the deviations from the average responses, which accounts for the sensitiveness of the experiment output to the noise factors. In this study, the S/N ratio was chosen according to the criterion 'the smaller-the-better', in order to minimize the response. The S/N ratio of the smaller-the-better can be expressed as follows [15]:

$$S/N = -10\log\frac{1}{n}\left(\sum_{i=1}^{n} yi^2\right) \quad (1)$$

where, n is the number of repetitions of the experiment and yi is the average measured value of experimental data i.

C. Experimental Setup

Drilling tests were conducted on a BFW 30 CNC VS three axis vertical machining centre with 5 kW driver motor.

TABLE I
PROCESS PARAMETERS AND THEIR RANGES

Symbol	Factor	Level-1	Level-2	Level-3
A	Cutting speed (m/min)	37.68	103.62	150.72
B	Feed rate (mm/rev)	0.05	0.15	0.25
C	Step angle (Degree)	90	118	135
D	Cutting environment	Dry	Water soluble oil	Synthetic oil

The machining samples were prepared in the form of 300mm×25mm×25mm blocks. The experimentation was carried out with three step twist drill bits (8mm smaller, 12mm larger diameter) of HSS manufactured by Addison as shown in Fig. 2. The surface finish of each drilled hole was measured with the aid of a Mitutoyo Surftest-4 (Japan) type instrument. The burr height (BH) of each drilled hole was measured with the aid of a TRIMOS, a height gauge with least count 0.001mm. The hole error of each drilled hole was measured with the aid of a Mitutoyo Crystal-Apex C (Japan) coordinate measuring machine (CMM). The response was taken at three positions spaced at 120° intervals around the hole circumference.

(a) (b) (c)

Fig. 2 Photographs of step drills used for the investigations (a: step angle 135^0, b: step angle 118^0, c: step angle 90^0).

D. Optimization Steps Using Grey Relational Analysis

Step 1: Calculate S/N Ratio for the Corresponding Responses Using (1).

Step 2: Normalize the Data

Normalize the data using (1) to reduce the variation in data. As we have to minimize the surface roughness, burr height and hole diameter error, so "lower is better" characteristic of grey relational analysis was used for data normalizing. The original sequence can be normalized as follows [13].

When the "lower is better" is a characteristic of the original sequence, then the original sequence should be normalized as:

$$x_i^*(k) = \frac{\max x_i^0(k) - x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \quad (2)$$

where i = 1. . . . m; k = 1, . . . , n; m is the number of experimental data items and n is the number of parameters. $x_i^0(k)$ denotes the original sequence, $x_i^*(k)$ the sequence after the data pre-processing, max $x_i^0(k)$ the largest value of $x_i^0(k)$, min $x_i^0(k)$ the smallest value of $x_i^0(k)$. The responses measured using Taguchi L27 orthogonal array are converted into S/N values using (1), since objective of the study is to minimize the responses for better quality of drilled holes.

Step 3: Calculate the Grey Relational Co-Efficient for the Normalized S/N Ratio Values.

After data pre-processing, the grey relation coefficient ξi(k) was calculated for performance characteristics and is expressed as [13], [14]:

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

where, Δoi is the deviation sequence.

$$\Delta_{0i} = \|x_0^*(k) - x_i^*(k)\| \quad (4)$$

$$\Delta_{min} = \min_{\forall j \epsilon i} \min_{\forall k} \|x_0^*(k) - x_j^*(k)\| \quad (5)$$

$$\Delta_{max} = \max_{\forall j \epsilon i} \max_{\forall k} \|x_0^*(k) - x_j^*(k)\| \quad (6)$$

$x_0^*(k)$ denotes the reference sequence and $x_i^*(k)$ denotes the comparability sequence. ζ is distinguishing or identification coefficient: ζϵ[0, 1] (the value may be adjusted based on the actual system requirements). ζ = 0.5 is used in this study. The normalized response data is converted in to grey relational coefficient using (3). These calculated grey relational coefficients are tabulated in Table II.

Step 4: Generate the Grey Relational Grade.

After the grey relational coefficient is calculated, it is usual to take the average value of the grey relational coefficients as the grey relational grade [13], [14]. The grey relational grade is defined as follows:

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n} \xi_i(k) \quad (7)$$

The average values of the grey relational coefficients known as grade are tabulated in Table II.

TABLE II
GREY RELATIONAL COEFFICIENT AND GRADE

Trial No.	Grey coefficient			Grade
	SR	B H	HDE	
1	0.673752	0.85405	0.593	0.70693
2	0.638081	0.745353	0.515	0.63281
3	0.577131	0.621371	0.467	0.55516
4	0.558938	0.741636	0.556	0.61885
5	0.525568	0.568824	0.493	0.52913
6	0.462962	0.398729	0.437	0.43289
7	0.367048	0.421032	0.417	0.40169
8	0.355065	0.372549	0.361	0.36287
9	0.333333	0.333333	0.333	0.33322
10	0.825304	0.766638	0.815	0.80231
11	0.773516	0.602114	0.729	0.70154
12	0.558938	0.401422	0.686	0.54878
13	0.541779	0.721418	0.583	0.61539
14	0.502866	0.592417	0.508	0.53442
15	0.444888	0.446904	0.473	0.45493
16	0.397999	0.666478	0.461	0.50849
17	0.384184	0.464135	0.372	0.40677
18	0.362975	0.384755	0.361	0.36957
19	1	1	1	1
20	0.825304	0.872625	0.855	0.85097
21	0.638081	0.797322	0.796	0.74380
22	0.596456	0.778639	0.556	0.64369
23	0.517795	0.602439	0.486	0.53541
24	0.462962	0.505033	0.461	0.47633
25	0.550234	0.706745	0.449	0.56865
26	0.495695	0.565397	0.417	0.49269
27	0.439146	0.438919	0.402	0.42668

TABLE III
RESPONSE TABLE FOR GREY RELATIONAL GRADE

Drilling parameters	Level 1	Level 2	Level 3	Max-min
Cutting speed	0.5082	0.5491	0.6376	0.1294
Feed rate	0.7269	0.5379	0.4301	0.2969
Step angle	0.6518	0.5607	0.4824	0.1694
Cutting environment	0.5706	0.5770	0.5473	0.0297
Overall mean grade 0.5649				

III. RESULTS AND DISCUSSIONS

From Table IV, it was observed that trial number 19 (A3, B1, C1 and D1) has highest grey relational grade.

Therefore, parametric values at trial number 19 give minimum surface roughness, burr height and hole diameter error among all trial runs. But it does not give exact optimal setting of drilling process parameters for optimum performance. As per Taguchi methodology, response table was used to calculate average grey relational grade for each input process parameter at different levels. The calculated grey relational grade for drilling parameters at levels 1–3 is reported in Table III.

The response table data is graphically presented in Fig. 3. The grey relational grade reflects the impact of drilling process parameters on performance characteristics. In other words, larger grey relational value corresponds to high quality performance. Therefore, optimal drilling process parameters are corresponding to larger value of grey relational grade. Therefore, the combination of cutting speed at level 3, feed rate at level 1, step angle at level 1 and cutting condition at level 2 (Table III) shows largest value of average grey relational grades. Therefore, A_3, B_1, C_1, D_2 with a cutting speed of 150.72 m/min, feed rate of 0.05 mm/rev, step angle of 90^0 and cutting environment of water soluble oil is the optimum combination of process parameters for multi response optimization in drilling of composites. The similar findings are drawn from the Fig. 3.

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TABLE IV
POOLED - ANOVA RAW DATA

Source	SS	DOF	V	F-Ratio	P%
A	0.0787	2	0.03937	37.65	11.48
B	0.4064	2	0.20321	194.37	60.59
C	0.1293	2	0.06469	61.87	19.07
D	0.0044	2	0.00220	2.10	
AXB	0.0374	4	0.00936	8.95	4.98
AXC	0.0029	4	0.00073	0.70	
AXD	0.0015	4	0.00039	0.37	
error (pooled)	0.0062	6	0.00104		3.84
Total	0.6672	26			100

The difference between maximum and minimum average grey relational grade of each input process parameter gives an idea about most important controllable factors. So analysis of variance (ANOVA) was implemented. The purpose of ANOVA is to investigate the effect of parameters and their influence on the process. ANOVA analysis was carried out for a level of significance of 5%, i.e. for 95% level of confidence. If the calculated F-ratio is more than the tabulated value i.e. 5.14 for parameter and 4.53 for interactions at confidence level, then the effect is significant. P% gives the significant percentage contribution on response i.e. grey relational grade. Further the grey relational grade in Table III is analyzed with ANOVA. The ANOVA of the grey relational grade is tabulated in Table IV. Table clearly shows that feed rate has maximum contribution (60.59%) followed by step angle (19.07%) and cutting speed (11.48%). It can be seen from table that AXB interaction has only significant influence of 4.98% compared to other interactions.

At higher cutting speed surface roughness decreases. This is due to decrease in thermal influence in cutting region. Furthermore, thermal heating in cutting region decreases due to low interaction time between chip tools interfaces at high cutting speed. It has also been reported that during the drilling process, effect of cutting speed on drilling forces is very small as compared to feed rate. Thus, higher grey relational grade is derived at higher cutting, as presented in Fig. 3 (a). It was observed from Fig. 3 (b) that there is a steep decrease in grey relational grade with increase in feed rate. The cutting forces were low at smaller feed of 0.05mm/rev and increased continuously with increase in feed rate. Thus, higher grey relational grade is derived at higher cutting, as presented in Fig. 3 (a). It was observed from Fig. 3 (b) that there is a steep decrease in grey relational grade with increase in feed rate. The cutting forces were low at smaller feed of 0.05mm/rev and increased continuously with increase in feed rate.

At lower feed, lower value of surface roughness, burr height and hole diameter error was observed.

Therefore, overall drilling performance is better at lower feed rate of 0.05mm/rev, which was reflected by higher grey relational grade in Fig. 3 (b). This is also supported by the microstructure of drilled surface shown in Fig. 4. Fig. 4 (a) reflects the drilled surface with micro cracks, pulled out particles and rough surface finish at higher feed rate. Fig. 4 (b) shows, drilled surface with lower surface roughness at low feed rate (0.05mm/rev).

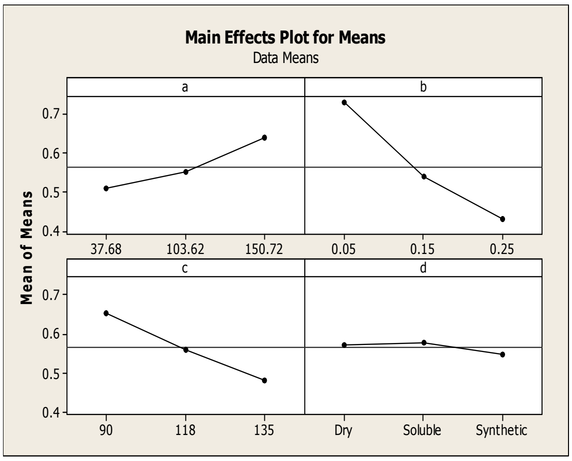

Fig. 3 Effects of Process Parameters on Grey Relational Grade

The lower level of step angle gives higher value of grey relational grade for burr height and hole diameter error as shown in Fig. 3 (c). This level of step angle shows decrease in burr height and hole diameter error, which may be due to the thermal softening of material in cutting region.

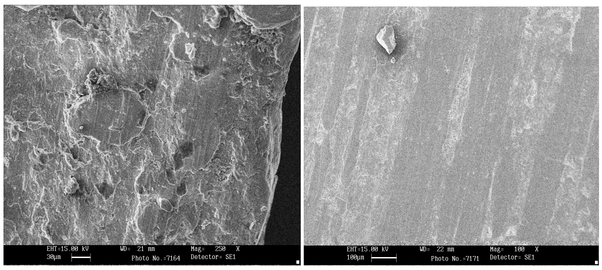

Fig. 4 SEM microstructure of drilled surface at a cutting speed 150.72m/min (a) 0.25mm/rev, (b) 0.05mm/rev

The secondary cutting edges of drill geometry are exposed to this thermally softened material and may cause overall decrease in the cutting forces, which decreases the burr height. Decrease in cutting forces also decreases the vibrations which reduces hole diameter error.

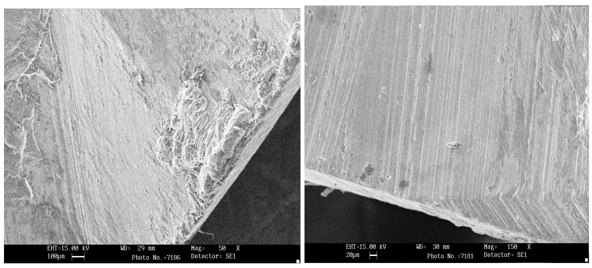

Fig. 5 SEM microstructure of drills at a cutting speed of 50.72m/min and feed rate of 0.05mm/rev for (a) 135^0 and (b) 90^0step angle

The lower value of step angle causes a decrease in thrust force because of easy piercing of cutting edge into the work piece material. Decrease in surface roughness was observed with decrease in step angle from 135^0 to 90^0. The SEM image of step drill bits in Fig. 5 indicates effect of step angle on drill bits. Fig. 5 (a) reveals that drill bit with higher step angle suffered with flank wear, smearing of material, and roundness of corners and built up edges. Fig. 5 (b) shows less effect as compared to drill with higher step angle. The last factor i.e. cutting environment has little effect on grey relational grade. This is shown in Fig. 3 (d).

IV. Optimization of Process Parameters for Grey Relational Grade

The confirmation experiments were conducted at the selected optimum levels ($A_3B_1C_1D_2$) to verify the quality characteristics for drilling of Al6063/15%SiC composite using step drill bits. After selecting the optimal levels, the optimum grey relational grade is predicted using the following equation [15]:

$$\mu_{predicted} = \mu_m + \sum_{i=1}^{n}(\mu_o - \mu_m) \quad (8)$$

where, μ_m is the mean response, μ_o is the mean response at optimal level. Here, n is the number of factors affecting the GRG. The confirmation experiment is used to verify the improvement in the quality characteristics.

$$\mu_{\text{predicted mean grade}} = A_3+B_1+C_1-2T$$

where T = overall mean of grade = 0.5649; A3, B_1 and C_1 are taken from the Table III.

Substituting the values of various terms in the above equation,

$$\mu_{\text{predicted mean grade}} = 0.8865$$

The 95% confidence interval of confirmation experiment (Cl_{CE}) was calculated by the following equation [15]:

$$Cl_{CE} = \sqrt{F_{\propto}(1, f_e)V_e\left[\frac{1}{n_{eff}} + \frac{1}{R}\right]} \quad (9)$$

where, V_e is the error variance, F_α (1, f_e) is the F-ratio at a confidence level of (1-α) against DOF of mean (which is always one) and error degree of freedom f_e . α is confidence level.

$$n_{eff} = \frac{N}{1 + [Total\ DOF\ associated\ in\ the\ estimate\ of\ mean]}$$

where, N is the total number of results = 27X3=81 and R is the sample size for confirmation experiment = 3.

$$n_{eff} = 11.571$$

Error variance V_e = 0.00104 (From Table IV)
f_e= error DOF= 6 (From Table IV)
F (1, 6) = 5.14 (Tabulated F-ratio).
So, CL_{CE} = ± 0.047
Predicted optimum range for confirmation experiment is:

Predicted GRG + CI_{CE}> GRG > Predicted GRG - CI_{CE}
0.8865+0.047 > GRG > 0.8865-0.047
0.9335 > GRG > 0.8395

A. Verification of Optimal Parameters through Confirmation Test

The confirmation experiments were conducted at optimum level (A_3, B_1, C_1, D_2). The confirmation experimental results at optimal levels are shown in Table V. The grey relational grade at optimal levels is 0.9316. The obtained result is within the 95% confidence interval of the predicted optimum condition. Table V indicates that grey relational grade value of confirmation experiment is improved by 28.01% from the initial value. This shows that the grey relational analysis of multi response problems is an important technique for optimizing the responses in the drilling of Al6063/15%SiC composites.

TABLE V
Comparison between Initial and Optimum Machining Parameters

Machining parameter	Initial machining parameter	Optimum machining parameters	
		Predicted	Experimental
Level	$A_1\ B_1\ C_1\ D_1$	$A_3B_1C_1D_2$	$A_3B_1C_1D_2$
Grey relational grade	0.7069	0.8865	0.9316

V. Conclusions

Grey relational analysis, based on the Taguchi's L_{27} orthogonal array was used for optimization of drilling process parameters. Drilling was conducted on Al6063/15%SiC composites using high speed steel step drill bits. The following conclusions were drawn from this study:

1. Grey relational analysis in the Taguchi method for the optimization of the multi response characteristics is used for predicting the surface roughness, burr height and hole diameter error.
2. The optimal level of process parameters for optimum multi response quality targets was obtained as $A_3B_1C_1D_2$: cutting speed of 150.72 m/min, feed rate of 0.05 mm/rev, step angle of 90^0 and cutting environment of water soluble oil.
3. Analysis of variance reveals that feed rate has maximum influence (60.59%) followed by step angle (19.07%) and cutting speed (11.48%) in affecting the drilling of composites.
4. The interaction of cutting speed and feed is found be significant (4.98%).

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