MULTI OBJECTIVE OPTIMIZATION IN DRILLING OF GLASS FIBER/EPE FOAM SANDWICH COMPOSITE BASED ON GREY RELATIONAL ANALYSIS

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Abstract

A grey relational analysis is a novel decision-making technique for forecast, developing relational analysis in numerous areas of manufacturing or production processes in industry. In this research paper, the objective is to optimize the drilling process input parameters considering assigned weight fraction of output quality characteristics using grey relational analysis in drilling of Glass fiber/ EPE foam sandwich composite. The output quality characteristics considered are thrust force, torque and delamination under the experimental domain of spindle speed, feed and drill diameter. The drilling experiments were designed as per Taguchi design of experiments using L_{25} orthogonal array. The best possible input process parameters which give minimum thrust force, torque and delamination factor have been established by the combined methodology of orthogonal array design of experiments ANOVA and grey relational analysis. The results indicate that most significant factor is drill diameter followed by feed and spindle speed respectively. The experimental results have shown that with the help of grey relational analysis, output quality characteristics can be enhanced efficiently.

Keywords: Glass fiber, thrust force, delamination, ANOVA, grey relational analysis (GRA)

I. Introduction

This Sandwich composite materials are made of two high strength external skins bonded on a low strength core. The sandwich composite of glass and carbon fiber reinforced polymers have gradually invaded in many daily applications, automotive parts, aircraft components, marine industries and sports [1] They have some outstanding property to resist corrosion, easy ability for making intricate shapes, better maximum strength to weight ratio, etc. [2]. The skins withstand the bending stresses and give the structure hardwearing surface whereas light core material carries the shear stresses generated by loads, distributing them over a larger area [3]. Any engineering application of these sandwich composite materials may involve the various manufacturing methods [4]. Failure of laminated composites during drilling is a complex phenomenon that involves matrix cracking, delamination and fiber breaking, fiber pull-out, hole shrinkage, spalling, fuzzing and thermal degradation as they exhibit anisotropic and inhomogeneous structure, thus drilling of a composite material is a difficult task [5].

In drilling of composites, increase of feed rate and cutting speed have effects of reduction in cutting force and torque examined by Pramendra et al [6]. Davim et al used Taguchi's orthogonal array and ANOVA to investigate the effect of input drilling parameters in drilling of GFRP composite on delamination and surface roughness. Their investigation shows that spindle speed is the most significant input parameters followed by others [7]. By experiments on HSS twist drill bit, Palanikumar et al have developed an approach combining ANOVA and the regression equations [8]. The complicated multi output response problem can be effectively solved using grey relational analysis (GRA) based upon grey theory [9]. Pawade and Joshi used Taguchi grey relational analysis (TGRA) to optimize SR and cutting forces in highspeed turning of Inconel 718 [10]. Palanikumar applied GRA for drilling of MMCs to obtain the optimized input process parameters for optimized multi response output quality characteristics [11].

The main objective of the present work is to optimize the process parameters in the drilling of glass fiber/EPE (Expanded polyethylene) foam sandwich composite. The optimization can be stated as minimize thrust force, torque and delamination with reference to independent input process parameters, spindle speed, feed, drill diameter. This multi objective problem can be converted into a single objective function using GRA, and a grey relational grade has been identified. Maximizing this grey relation grade, subjected to independent process parameter, is in experimental range. Taguchi method design is used to find the significance of each process parameter using ANOVA.

II. Materials and Methods

The glass fiber/EPE foam sandwich composite laminates were developed in house with hand lay-up method. The glass fiber is used as skin material, EPE foam as core material and epoxy resin as adhesive. The glass fiber sheets were supplied by Liyo Sign Composites SD private Ltd, Ahmedabad, Gujarat and EPE foam sheets were supplied by LATA Foam, Vapi, Gujarat. Epoxy resin and hardener were procured from Atul Industries Ltd, Gujarat under the trade name of Lapox L-12 and K-6 respectively. The epoxy to hardener ratio was taken as 10:1 as per the supplier's prescribed standard.

The glass fiber sheets and EPE foam sheets are cuts into required size. The glass fiber/EPE foam sandwich composite laminate was fabricated with 12 layers of glass fibers sheets (20 vol. % of reinforcement) having 6 layers on each side of laminates as a skin and 4 layers (each layer of 3mm) of EPE foam (32.2 vol. %) are used as core. The laminates were then cured in a compression moulding press at 60° C temperature for 20 minutes at pressure of 1 MPa. After removing the laminates, they were dried in an oven at 50° C for 3 hrs. to remove moisture and other volatile entities. Samples were cut as per the required dimensions of 120 × 120 × 5 mm^3. Samples were then post cured in an oven at 145°C for 5 hrs.

The drilling experiments were performed on radial drilling machine (Batliboi and company Pvt. Ltd, Surat, Gujarat, India.) powered by 15 kW main spindle motor. High speed steel Twist drill geometry of various diameters were used for experimentation as shown in Figure 1. The mechanism of the experiment setup is such that the specimen of fabricated laminate is fitted on the fixture of the radial drilling machine as shown in Figure 2. The process parameters under investigation were categorized as machine tool parameters and cutting tool parameters with their different levels as presented in Table 1.

Figure 1: *High speed steel Twist drill geometry of various diameters.*

Table 1: *Factors and factor levels for experiment.*

Experimental level	Spindle Speed (rpm)	Feed (mm/rev.)	Drill Diameter (mm)
1	500	0.05	4
2	710	0.12	6
3	1000	0.19	8
4	1420	0.26	10
5	2000	0.33	12

The thrust forces (N), torque (Nm) and delamination factor were considered as output quality characteristics. Drilling force along the axis of drill (thrust force: Fz) and moment (Torque: T) along the axis of rotation were recorded using drill dynamometers (make: KISTLER, type: 9257B, Winterthur, Switzerland), as shown in Figure 2. The experimental results with L_{25} orthogonal array (OA) for thrust forces (N), torque (Nm) and delamination factor are presented in Table 2.

III. Methodology for GRA

In GRA, black represent to have null information and white represents to have all information. A grey structural system has a level of information between black and white. In other words, in a grey structural system, some information is known and some information is unknown. The stepwise procedure for GRA is explained in the subsequent sections [9].

A. Data Pre-Processing.

In GRA, to normalize the original sequence pre-processing of data is performed to process within the range of zero to one for comparable sequence. when the sequence range is too large or when the goal and directions of parameters are disparate, data preprocessing is performed. The approach of pre-processing is to transfer the original sequence data by normalizing into a comparable sequence. Let the original reference and comparability sequence be presented as $x_0^0(k)$ and $x_i^0(k)$, i = 1, 2,….m; k = 1, 2, …..n, respectively, where m and n are the total number of experiment to be after sequence and the total number of initial data respectively. For this purpose, the experimental results are normalized in the range between zero and one. The various pre-processing methods for data sequence in GRA depending on the characteristics of distinguishing coefficient denoted by ζ. In the present investigation, the target for the output quality characteristics, thrust force, torque and delamination factor is 'lower-the-better', and the original sequence can be normalized as follows

$$x_i^*(k) = \frac{max\ x_i^0(k) - x_j^*(k)}{max\ x_i^0(k) - min\ x_i^0(k)} \tag{1}$$

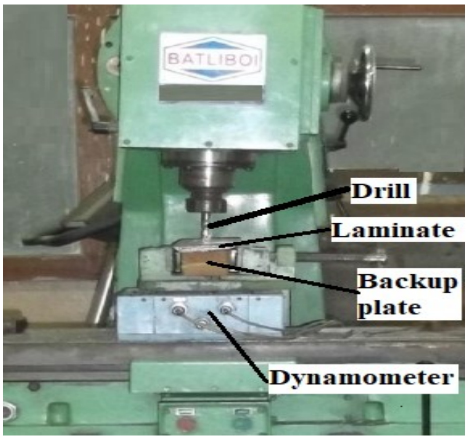

Figure 2: *Drilling process setup with drill dynamometer.*

Table 2: *Reference sequence and comparability sequence for delamination factor, thrust force and torque with experimental factor levels.*

Experimental runs	Comparability sequence			Reference sequence		
	Spindle Speed (rpm)	Feed (mm/rev.)	Drill diameter (mm)	Delamination Factor	Thrust force (N)	Torque (Nm)
1	500	0.05	4	1.23	81.99	29.93
2	500	0.12	6	1.27	106.05	41.47
3	500	0.19	8	1.32	132.82	55.53
4	500	0.26	10	1.37	159.74	70.16
5	500	0.33	12	1.41	173.92	83.02
6	710	0.05	6	1.26	85.63	33.43
7	710	0.12	8	1.3	112.46	49.56
8	710	0.19	10	1.36	139.82	64.43
9	710	0.26	12	1.41	166.22	74.93
10	710	0.33	4	1.32	118.8	42.93
11	1000	0.05	8	1.27	97.16	38.28
12	1000	0.12	10	1.32	123.72	52.66
13	1000	0.19	12	1.37	150.72	68.93
14	1000	0.26	4	1.3	102.62	37.24
15	1000	0.33	6	1.36	129.48	48.43

16	1420	0.05	10	1.29	107.99	47.2
17	1420	0.12	12	1.35	134.52	56.96
18	1420	0.19	4	1.28	76.36	34.2
19	1420	0.26	6	1.35	113.82	38.88
20	1420	0.33	8	1.39	137.42	55.21
21	2000	0.05	12	1.3	118.42	50.67
22	2000	0.12	4	1.23	85.56	26.16
23	2000	0.19	6	1.3	113.12	35.57
24	2000	0.26	8	1.35	139.19	50.3
25	2000	0.33	10	1.4	176.84	65.71

The alternate simple method,

$$x_i^*(k) = \frac{x_i^0(k)}{x_i^0(1)} \tag{2}$$

Where $x_i^0(k)$:the initial sequence, $x_i^*(k)$:for the i[th] experiment the sequence after the data processing, $max\ x_i^0(k)$:the maximum value of $x_i^0(k)$, and $min\ x_i^0(k)$: the minimum value of $x_i^0(k)$.

B. Grey relational coefficient (GRC)and grey relational grade (GRG)

After data preprocessing, grey relational coefficient (GRC) can be calculated using preprocessed sequence of quality characteristics. The GRC is defined as follows

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

Where $\Delta_{oi}(k)$ is deviation sequence of reference sequence $x_0^*(k)$ and comparability sequence $x_i^*(k)$ respectively.

$$\Delta_{oi}(k) = \|x_0^*(k) - x_i^*(k)\| \tag{4}$$

$$\Delta_{min} = min_{\forall j \in i} min_{\forall k} \left| x_0^*(k) - x_j^*(k) \right|$$

$$\Delta_{max} = max_{\forall j \in i} max_{\forall k} \left| x_0^*(k) - x_j^*(k) \right|$$

Where $x_0^*(k)$ symbolizes reference sequencing and $x_i^*(k)$ symbolizes comparability sequence. is distinguishing or identification coefficient: . In the present study the value of is assumed as 0.5.
The grey relational grade is determined by the average of grey relational coefficients and it is given

$$\gamma_i = \frac{1}{n} \sum_{k=1}^{n} w_k\ \xi_i(k) \tag{5}$$

The association among reference and comparability sequences is designated by grey relational grade. For indistinguishable sequence, value of grey relational grade is equal to 1. The level of influence exercised by comparability sequence on reference sequence is also pointed out by grey relational grade. Subsequently, The Grey relational grade sequences the degree of significance by the comparability sequence over the reference sequence. if a specific comparability sequence is more significant to reference sequence than other comparability sequences, the grey relational grade for that comparability sequence and reference sequence will exceed that for other grey relational grades [9]. In reality, The GRA is a measurement of absolute value of data variance among sequences and can be used to estimate the association between sequences.

IV. Result and Discussion

Table 3: *Sequence after data processing.*

Reference sequence/ comparability sequence	Delamination factor	Thrust force	Torque
Reference sequence/ comparability sequence	1	1	1
Experiment 01	1	0.943	0.934
Experiment 02	0.778	0.705	0.731
Experiment 03	0.5	0.438	0.483
Experiment 04	0.222	0.170	0.226
Experiment 05	0	0.029	0
Experiment 06	0.833	0.908	0.872
Experiment 07	0.611	0.641	0.588
Experiment 08	0.278	0.368	0.327
Experiment 09	0	0.106	0.142
Experiment 10	0.5	0.578	0.705
Experiment 11	0.778	0.793	0.787
Experiment 12	0.5	0.529	0.534
Experiment 13	0.222	0.260	0.248
Experiment 14	0.611	0.739	0.805
Experiment 15	0.278	0.471	0.608
Experiment 16	0.667	0.685	0.630
Experiment 17	0.333	0.421	0.458
Experiment 18	0.722	1	0.859
Experiment 19	0.333	0.627	0.776
Experiment 20	0.111	0.392	0.489
Experiment 21	0.611	0.581	0.569
Experiment 22	1	0.908	1
Experiment 23	0.611	0.634	0.835
Experiment 24	0.333	0.375	0.575
Experiment 25	0.056	0	0.304

The desirability criterion for optimum drilling performance is minimum thrust force, minimum torque and minimum delamination factor. When sandwich composite laminates are in consideration, cutting forces are considerably higher because of skin act as abrasive reinforcement at the entry to the object, which causes deterioration in the performance of the process. The experimental results for delamination factor, thrust force and torque are presented in Table 2. For data preprocessing in GRA, thrust force, torque and delamination factors were based upon 'lower-the-better' principle; thus, Equation 1 was employed for data preprocessing. The result of experimental runs for comparability sequence and reference sequence was calculated and presented in Table 3. The distinguished coefficient ζ (0.5) was substituted in Equation 5 to generate GRC. The weight (w) assigned to output quality characteristics depends upon the requirement of process or its application. In the present investigation, equal weights (0.333) were assigned to thrust force, torque and delamination factor, and their summation is equal to 1.

The grey relational coefficients and grey relational grades for each experimental r un were calculated as per Equation 3 and Equation 5 and are presented in Table 4.From the calculated values of grey relational grade, it was observed that experimental run 22(A_5, B_1,and C_1) spindle speed 2000 rpm, feed 0.05 mm/rev. and drill diameter 4 mm has highest grey relational grade. Therefore, experimental run setting at experiment 22 of input process parameters gives minimum thrust force, torque and delamination factor (i.e. best multi performance experimental run) among all

Table 4: *Calculated grey relational coefficient and grey relational grade.*

Experimental runs (comparability sequence	Orthogonal array			Grey relational coefficient			Grey relational grade	Rank
	A	B	C	Delamination Factor	Thrust force	Torque		
1	1	1	1	1	0.899	0.882	0.927	2
2	1	2	2	0.692	0.629	0.650	0.657	6
3	1	3	3	0.5	0.471	0.491	0.488	15
4	1	4	4	0.391	0.376	0.392	0.387	22
5	1	5	5	0.333	0.340	0.333	0.336	25
6	2	1	2	0.75	0.844	0.796	0.797	4
7	2	2	3	0.562	0.582	0.549	0.564	10
8	2	3	4	0.409	0.442	0.426	0.426	20
9	2	4	5	0.333	0.359	0.368	0.353	24
10	2	5	1	0.5	0.542	0.629	0.557	12
11	3	1	3	0.692	0.707	0.701	0.700	5
12	3	2	4	0.5	0.515	0.518	0.511	14
13	3	3	5	0.391	0.403	0.399	0.398	21
14	3	4	1	0.562	0.657	0.720	0.646	7
15	3	5	2	0.409	0.486	0.561	0.485	16
16	4	1	4	0.6	0.614	0.575	0.596	9
17	4	2	5	0.429	0.463	0.480	0.457	18
18	4	3	1	0.643	1	0.780	0.807	3
19	4	4	2	0.429	0.573	0.691	0.564	11
20	4	5	3	0.36	0.451	0.495	0.435	19
21	5	1	5	0.563	0.544	0.537	0.549	13
22	5	2	1	1	0.845	1	0.948	1
23	5	3	2	0.563	0.577	0.751	0.630	8
24	5	4	3	0.429	0.444	0.541	0.471	17
25	5	5	4	0.346	0.333	0.418	0.367	23

experimental runs. But it does not give an idea about optimal setting of input process parameters for optimum output quality characteristics. A GRA technique was applied on generated grey relational grade to obtain optimal setting of input process parameters for optimal multi response performance. For all input process parameters with all factor levels average grey relational grades were determined as shown in Table 4.

The method is, group grey relational grade by factor level at each column in orthogonal array and then takes average of them. For example, in the first column of orthogonal array (Table 4), experimental runs 1–5 are at first level of factor cutting speed. The calculated grey relational grade for cutting speed at levels 1–5 is given as

$$A_1 = \frac{1}{5}(0.927 + 0.657 + 0.488 + 0.387 + 0.336) = 0.559$$
$$A_2 = \frac{1}{5}(0.797 + 0.564 + 0.426 + 0.353 + 0.557) = 0.539$$
$$A_3 = \frac{1}{5}(0.700 + 0.511 + 0.398 + 0.646 + 0.485) = 0.548$$
$$A_4 = \frac{1}{5}(0.596 + 0.457 + 0.807 + 0.564 + 0.435) = 0.572$$
$$A_5 = \frac{1}{5}(0.549 + 0.948 + 0.630 + 0.471 + 0.367) = 0.592$$

Using the same approach, average grey relational grade for each factor was calculated and is presented in Table 5. The grey relational grade value always gives tremendous performance to characterizes the amount of correlation among reference sequence and comparability sequence. The factor level with the highest value of grey relational grade is the most optimal level [9]. In other words, regardless of type of performance characteristics, highest grey relational value indicates to enhanced optimal performance [10]. Based upon this criterion, one can select the level of input process parameters that provides large average grey relational grade. The highest value of average grey relational grades from table 5 are identified as spindle speed at highest factor level 5, feed and drill diameter at lowest factor level 1 respectively. Hence, in drilling of sandwich composite laminates, by optimization of multi response through grey relational analysis cutting speed of 2000 rev./min, feed of 0.05 mm/rev and drill diameter of 4mm is the most optimum combination of drilling process parameters. For each drilling process input factor, the difference between maximum and minimum average grey relational grades are as follows: for spindle speed of 0.053, for feed of 0.278, and for drill diameter of 0.359. These numerical values give an idea about most important controllable factor that influences output quality characteristics of process. The most important controllable factor corresponds to the maximum of these values, that is, drill diameter of 0.359, followed by feed of 0.278 and spindle speed of 0.053.

It is observed from figure 3 and value of Table 5, that the drill diameter is the most significant input parameter when considering the multiple responses, which is followed by Feed Rate and at last the spindle speed. The mean GRG values for each drilling parameters is shown in Figure 3. In grey relational technique, the highest value of GRG corresponds to the optimal process output. Therefore, Spindle Speed of 2,000 rpm, Feed of 0.05 mm/ rev. and drill diameter of 4 mm gives the desired optimized output. It was observed that the increase of diameter of drill, increases in total surface area of contact of the drill bit with work piece. This leads to increase in thermal influence in region which in return increases the torque and thrust force generated in process.

Table 5: *Response table for Average grey relational grade by factor level*

Parameters	Level 1	Level 2	Level 3	Level 4	Level 5	(Maximum) –(Minimum)	Rank
Spindle speed	0.559	0.539	0.548	0.572	0.592	0.053	3
Feed	0.713	0.628	0.550	0.484	0.436	0.278	2
Drill diameter	0.777	0.627	0.532	0.457	0.418	0.359	1

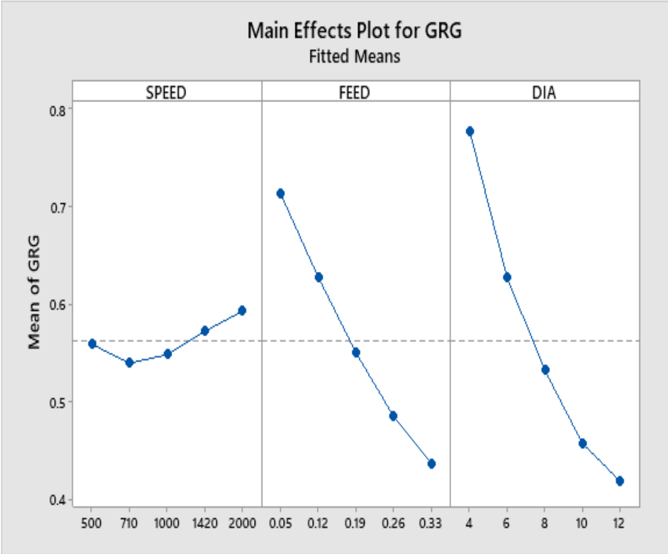

Figure 3: *Main effects plot for Grey relational grades.*

The thermal influence causes surface flaws and discontinuities get wiped out that leads to delamination. Furthermore, thermal heating in cutting region causes decrease in shear strength of workpiece and allows easy shearing of material during drilling process. The delamination is corresponded to variations in the torque and thrust force. The delamination has an effect on the hole quality. Similarly, the hole quality is tolerated by the increase in Feed Rate. It has also been observed that cutting speed with respect to feed and drill diameter have least effect during the drilling process. Thus, overall drilling performance is higher at higher grey relational grade for input process parameter cutting speed, as shown in Figure 3 It was observed from Figure 3 that there is a sharp decrease in grey relational grade with increase in feed. It is observed that at least feed of 0.05 mm/rev the cutting forces were lowest and with increase in feed of 0.33 mm/rev its swifts to increased values. At least value of feed, smallest value of output parameters was observed. Therefore, overall drilling performance is optimal at lower feed of 0.05, which was reflected by higher grey relational grade in Figure 3.

A. Most influential factor

The purpose of conducting ANOVA is to investigate the relative magnitude of the effect of each factor on the objective function. The ANOVA investigate which drilling parameters significantly affected the performance characteristics and to estimate the error variance. In the ANOVA table the F-value column is also called as Fisher's F-test value. The higher value of F represents the highest effect on the output whereas the lower value represents the least effect on the output characteristics. The ANOVA Table 6 clearly represent the percentage contribution of each input drilling process parameters. From the ANOVA table it is observed that the drill diameter has the highest influences on the output characteristics of about 59.60% followed by the Feed Rate.

Table 6: *Result of analysis of variance (ANOVA)*

Factor	Degree of Freedom	Sum of Squares	Mean Square	F-Value	Percentage Contribution
Spindle speed	4	0.008801	0.002200	0.98	1.26
Feed	4	0.247075	0.061769	27.49	35.38
Drill diameter	4	0.415478	0.103870	46.23	59.50
Error	12	0.026960	0.002247		3.86
Total	24	0.698314			100.00

The feed rate has about 35.38% significance with respect to the output characteristics. The spindle speed has very minimum significance on the output characteristics of lesser than 1.3%.

B. Confirmation test

After identifying the most influential parameters, the final phase is to verify the output by conducting the confirmation experiments. The $A_5B_1C_1$ is an optimal parameter combination during drilling process via the grey relational analysis. Therefore, the condition $A_5B_1C_1$ of the optimal parameter combination was treated as a confirmation test. The result of the confirmation test gives the thrust force, torque and delamination factor similar to those given in Table 2.

V. Conclusion

Multi response optimization using GRA was performed to study the drilling behaviour of glass fiber/EPE foam sandwich composite. Thrust force, torque and delamination were considered as quality targets of the drilling process. A L_{25} orthogonal array as per Taguchi design of experimentations was used to perform the experiments. The following conclusions can be drawn on the basis of GRA:

- The grey relational analysis for optimum multi response optimization of drilling parameters for quality drilling holes were obtained as: spindle speed of 2000 rpm, feed of 0.05 mm/rev, and drill diameter of 4 mm which leads to the minimization of thrust force, torque and delamination and ensures a good quality hole.
- Among the input process parameters under consideration, drill diameter exhibits strongest correlation with the thrust force, torque and delamination, which followed by feed and cutting speed.
- The ANOVA shows that drill diameter is the most significant machining parameter with percentage contribution of 59.50, followed by feed and spindle speed with percentage contribution of 35.38 and 1.26 respectively.
- GRA is a very useful technique to optimize the thrust force, torque and delamination during drilling of glass fiber/EPE foam sandwich composite under experimental domain. It does not involve any complicated mathematical theory, computation or simulation. Therefore, GRA concept can be utilized without any statistical background in industry.

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