MULTIPLE-PERFORMANCE OPTIMIZATION OF DRILLING PARAMETERS AND TOOL GEOMETRIES IN DRILLING GFRP COMPOSITE STACKS USING TAGUCHI AND GREY RELATIONAL ANALYSIS (GRA) METHOD

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ABSTRACT

Composite materials are used in many applications and are mainly used for structural components. Glass fiber reinforced polymer (GFRP) composite is an economic alternative for engineering materials due to its advantageous properties. Drilling is the one of important operations for composite structure which is quite often used as a final operation before assembly. The objective of this paper is to optimize drilling parameters such as cutting feed and cutting speed, tool geometries such as drill point geometry and drill point angle on the thrust force, hole roundness and hole surface roughness in drilling GFRP stacks. In this research, experiments are carried out as per Taguchi design of experiments and an L_{18} orthogonal array was used to study the influence of various combinations of drilling parameters and tool geometries on quality of the hole. The optimum drilling parameter is determined by using grey relational grade obtained from grey relational analysis for multiple-performance characteristics. The drilling experiments were carried out by using twist drill and CNC machining center. This work is useful for optimum values selection of various drilling parameters and tool geometries that would not only minimize the thrust force but also reduce the hole roundness error and hole surface roughness, so it can improve the quality of the drilled hole.

Keywords: optimization, drilling, GFRP, tguchi, GRA.

INTRODUCTION

Applications of glass fiber reinforced polymer (GFRP) have increased significantly in many fields of science and engineering because of the superior properties such as high stiffness, light weight, good corrosive resistance, low thermal expansion, high strength and excellent fatigue resistance. There is a difference in machining of this material from the traditional materials because of its non homogeneous and anisotropic properties. Among all the operations in machining for composite, drilling is the most common operation, and poor hole quality accounts for an estimated 60% of all part rejection [1]. Drilling composite is quite different from other metal materials. While drilling composite materials, the two phases namely filler and matrix behave differently than when they are separate, because composite contain of soft epoxy matrix and hard fibers. In composite drilling, drill point geometry, drill point angle, cutting feed and spindle speed are the most influential factor that influence the quality characteristics of the hole. The hole quality on drilling composite can be evaluated by using quality characteristics such as roundness and surface roughness. Thrust force on drilling can also be used as a measure of machinability of composite material. The structural integrity of composite materials will decrease because of quality of the drilled hole which cause poor assembly tolerance and has potential for long term performance deterioration. In order to mitigate this problem, developing procedure to select appropriate drilling parameters and tool geometries is necessary. Optimizing drilling parameters and tool geometries which affect the hole surface such as drill point geometry, drill point angle, cutting feed and spindle speed is needed for improving the quality of drilled surface.

Orthogonal array from design of experiment theory in Taguchi method is used to study a large number of variables with a small number of experiments [2]. The orthogonal arrays reduce the number of experimental configurations to be studied. Furthermore, the conclusions taken from small number of experiments are valid over the entire experimental region spanned by the control factors and their setting [3]. The results of experiment are then transformed into a signal to noise (S/N) ratio to measure the quality characteristic deviating from or near to the desired values. There are three quality characteristics in Taguchi method, they are smaller is better, nominal is the best and larger is better. Taguchi method is only used for individual performance. However, usually the most common problem are multiple-performance, hence many researchers combine Taguchi method and grey relational analysis (GRA). In the grey system theory, the grey relational analysis is used to analyze the relationship between sequences, using less data and multifactor [4]. This is considered as more advantageous than the statistical regression analysis. This method is proposed for drilling GFRP composite.

Different investigators have studied the optimization of drilling parameters on GFRP composite using Taguchi and GRA method. Palanikumar [5] carried out experiment and reported that the drilling parameters which affect the total variance of thrust force, surface roughness and delamination are feed rate followed by spindle speed. Ranganathan *et al.* [6] in their study on drilling parameters optimization namely feed rate and spindle speed in drilling GRFP composite reported that the drilling parameters which affect the total variance of delamination, thrust force and torque are feed rate followed by spindle speed. Palanikumar *et al.* [7] in their study on optimization of machining parameters in drilling composite reported that feed is the most influential factor which affect the total variance of responses optimized followed by drill diameter and spindle speed.

Drill type and geometry have effect in drilling composite materials. Feito *et a*l. [8] in their experimental analysis of drill point angle influence and wear in drilling of carbon fiber-reinforced polymer reported that drill point angle influence the thrust force when it is combined with the effect of wear progression. The delamination factor at entry and exit hole increase with the increase of drill point angle. Parameters which have the most influence on thrust force and delamination are tool geometry (wear and drill point angle) and feed rate, while cutting speed has negligible influence. Kashaba *et al.* [9] in their research study in drilling of polymer matrix composite reported that types and geometries of the drill bit have influence on the quality of the drilled hole. The chisel edge contribution to the thrust force is often up to 40-60% of the total thrust force. Kilickap [10] in his research reported that drill point angle has influence in the damage resulted from drilling composite GFRP. The drill point angle of 118° drill has less damage than the drill point angle of 135°, hence the quality of the drilled hole is better when using smaller drill point angle.

Drilling of composite stacks is quite different from its individual plate. In mechanical structure the holes are produced in large number and have high precision on distance between the holes. The purpose of stacking and drilling the composite stacks is increasing productivity by reducing machining time. Machining composite stacks requires a good understanding on cutting processes to achieve better accuracy and efficiency. In this work, drilling parameters (cutting feed and spindle speed), tool geometries (drill point geometry and drill point angle) are optimized in drilling of GFRP composite using Taguchi experimental design technique and grey relational analysis (GRA). The main objectives of this work are to find the significance of drilling parameters and tool geometries to reduce the total variance of the multiple-performance characteristics simultaneously and to find the proper setting of the drilling parameters and tool geometries to minimize the thrust force, hole roundness and hole surface roughness simultaneously.

EXPERIMENTAL DESIGN

Material and Equipments

The work piece material used in this experiment is glass fiber reinforced polymer (GFRP) composite. Epoxy resin is used as a matrix material due to its high mechanical and thermal properties. The fiber used is E-glass. It has tensile strength of 390 Mpa, tensile modulus of 19 Gpa, density of 1.86 g/cm^3 and shear modulus of 20.5 Mpa. The dimension of GFRP composite sheet having length of 200 mm, width of 30 mm, thickness of 3 mm and thickness per ply of 0.25 mm. Two sheets are stacked together to create a 6 mm thick of composite to be drilled.

The drill bits used in this experiment are two flute straight twist drill made up of high speed steel (HSS) and HSS-Cobalt having diameter of 10 mm and helical angle of 30˚. The drilling experiments are carried out on CNC vertical machining center and all tests were conducted without coolant. The parameters selected are drill point geometry which has two levels, drill point angle, cutting feed and spindle speed and each of them has three levels. Table-1 shows the parameters and levels used in this experiment.

Table-1. Parameters and their levels.

Parameters	Unit	Level		
		1	2	3
Drill point geometry	-	HSS (type S)	HSS-*Cobalt* (type X)	-
Drill Point angle	(°)	90	118	135
Cutting feed	mm/min	50	100	150
Spindle speed	rpm	2000	2500	3000

Thrust force (FZ) was measured by using KISTLER dynamometer type 9272. Roundness of the holes (R) resulted from drilling process were measured by using round test roncorder EC-3D. Mitutoyo Surftest SJ-310 was used to measure the hole surface roughness (SR) resulted from drilling process.

Design of Experiments

The drilling operations are carried out as per Taguchi's design of experiment. The orthogonal array used for the experiment is L_{18}, which can handle 4 factors and 3 levels. L_{18} orthogonal array needs minimum of 18 runs and has 7 degrees of freedom (DOF). In the Taguchi experimental design, the total DOF of selected orthogonal array should be higher than or equal to the total DOF required for the experiment and hence L_{18} orthogonal array has been selected. Table-2 shows the experimental design.

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Table-2. Experimental design used for experiment.

No	Parameters			
	Drill Point Geometry (PG)	**Drill Point angle** (PA)	**Cutting feed** (VF)	**Spindle speed** (N)
1	1	1	1	1
2	1	1	2	2
3	1	1	3	3
4	1	2	1	1
5	1	2	2	2
6	1	2	3	3
7	1	3	1	2
8	1	3	2	3
9	1	3	3	1
10	2	1	1	3
11	2	1	2	1
12	2	1	3	2
13	2	2	1	2
14	2	2	2	3
15	2	2	3	1
16	2	3	1	3
17	2	3	2	1
18	2	3	3	2

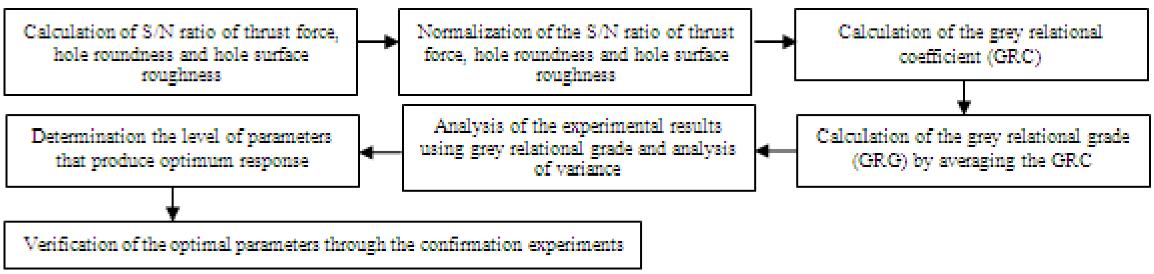

Figure-1. Steps for optimization using Taguchi-GRA.

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Table-3. Results of experiment and S/N ratio of the responses.

NO	PG	PA	VF	N	FZ	R	SR	SNRA-FZ	SNRA-R	SNRA-SR
1	1	1	1	1	39.12	160	2.005	-31.84797692	-44.08239965	-6.0422875
2	1	1	2	2	42.17	150	1.017	-32.50007202	-43.52182518	-0.1464191
3	1	1	3	3	42.17	150	0.873	-32.50007202	-43.52182518	1.1797151
4	1	2	1	1	66.03	150	2.573	-36.39482595	-43.52182518	-8.2087957
5	1	2	2	2	66.18	145	1.024	-36.41453526	-43.22736004	-0.2059991
6	1	2	3	3	66.95	145	0.878	-36.51501163	-43.22736004	1.1301097
7	1	3	1	2	100.2	135	2.585	-40.01735443	-42.60667537	-8.2492109
8	1	3	2	3	113.2	125	1.151	-41.07692854	-41.93820026	-1.2215065
9	1	3	3	1	91.5	120	0.889	-39.22842188	-41.58362492	1.0219648
10	2	1	1	3	29.86	115	1.256	-29.50179607	-41.21395681	-1.9797928
11	2	1	2	1	23.16	110	0.968	-27.2947711	-40.8278537	0.2824929
12	2	1	3	2	25.65	110	0.85	-28.18174739	-40.8278537	1.4116215
13	2	2	1	2	46.85	110	1.934	-33.4141919	-40.8278537	-5.7291294
14	2	2	2	3	58.1	105	0.986	-35.28352265	-40.42378598	0.1224617
15	2	2	3	1	42.32	100	0.774	-32.53091318	-40	2.2251808
16	2	3	1	3	83.8	100	1.968	-38.46488037	-40	-5.8805019
17	2	3	2	1	73.99	80	0.999	-37.38346055	-38.06179974	0.0086902
18	2	3	3	2	83.58	80	0.844	-38.44204734	-38.06179974	1.4731511

Table-4. Normalization of S/N ratio, Grey relational coefficient (GRC) and Grey relational grade (GRG).

No	xi_FZ	xi_R	xi_SR	GRC_FZ	GRC_R	GRC_SR	GRG
1	**0.6696**	**0.0000**	**0.2107**	**0.6021**	**0.3333**	**0.3878**	**0.4411**
2	0.6223	0.0931	0.7736	0.5697	0.3554	0.6883	0.5378
3	0.6223	0.0931	0.9002	0.5697	0.3554	0.8336	0.5862
4	0.3397	0.0931	0.0039	0.4309	0.3554	0.3342	0.3735
5	0.3383	0.1420	0.7679	0.4304	0.3682	0.6830	0.4939
6	0.3310	0.1420	0.8955	0.4277	0.3682	0.8271	0.5410
7	0.0769	0.2451	0.0000	0.3513	0.3984	0.3333	0.3610
8	0.0000	0.3561	0.6709	0.3333	0.4371	0.6031	0.4578
9	0.1341	0.4150	0.8851	0.3661	0.4608	0.8132	0.5467
10	0.8399	0.4764	0.5985	0.7574	0.4885	0.5547	0.6002
11	1.0000	0.5406	0.8145	1.0000	0.5211	0.7294	0.7502
12	0.9356	0.5406	0.9223	0.8860	0.5211	0.8655	0.7576
13	0.5560	0.5406	0.2406	0.5297	0.5211	0.3970	0.4826
14	0.4204	0.6077	0.7993	0.4631	0.5603	0.7135	0.5790
15	0.6201	0.6781	1.0000	0.5682	0.6083	1.0000	0.7255
16	0.1895	0.6781	0.2261	0.3815	0.6083	0.3925	0.4608
17	0.2680	1.0000	0.7884	0.4058	1.0000	0.7026	0.7028
18	0.1912	1.0000	0.9282	0.3820	1.0000	0.8744	0.7522

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Table-5. ANOVA of GRG and percentage of contribution.

Source	DF	Adj SS	Adj MS	F	P	% contribution
PG	**1**	**0.120339**	**0.120339**	**126.42**	**0**	**42.26%**
PA	2	0.021604	0.010802	11.35	0.003	6.97%
VF	2	0.122766	0.061383	64.48	0	42.78%
N	2	0.008259	0.004129	4.34	0.044	2.25%
Error	10	0.009519	0.000952			5.73%
Total	17	0.282488				100%

MULTIPLE-PERFORMANCE OPTIMIZATION USING TAGUCHI-GRA

Taguchi's technique from Taguchi method has been carried out for analyzing the experimental results. Taguchi method uses the design of orthogonal arrays to study the variables and its interactions using small number of experiments. The steps used to perform an optimization using Taguchi-GRA are shown on Figure-1.

S/N Ratio Calculation

Signal to noise ratio (S/N) in the Taguchi method is the measure of quality characteristics and deviation from the desirable value. There are three types of quality characteristics in the S/N ratio analysis. The S/N ratio of all responses in this experiment were calculated using the smaller is better characteristic and tabulated in Table-3. Equation 1 shows the formula for smaller is better [11].

$$(\eta) = -10\, log_{10} \frac{1}{n} \sum_{i=1}^{n} y_i^2 \qquad (1)$$

where n is the number of measurements and y_i is the characteristic value which is measured.

Normalization of S/N Ratio

In the Grey relational analysis, data preprocessing is used to normalize the initial data. The experimental results of thrust force, hole roundness and hole surface roughness have been performed in the range between 0 and 1 by using linear normalization. The normalization of S/N ratio of the responses were calculated using equation 2 [11] and shown in the Table-4.

$$X_i^*(k) = \frac{X_i(k) - \min_{\forall k} X_i(k)}{\max_{\forall k} X_i(k) - \min\limits_{\forall k} X_i(k)} \qquad (2)$$

where $X_i^*(k)$ is the normalization value, min $X_i(k)$ is the smallest value of $X_i(k)$for the k^{th} response and max $X_i(k)$ is the largest value of $X_i(k)$ for the k^{th} response.

Grey Relational Coefficient and Grey Relational Grade

The Grey relational analysis is used for measuring the two systems relevancy. The sequences used in the grey relational analysis are called grey relational coefficient (GRC). The calculation of GRC $\xi_i(k)$ uses equation 3 [11].

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

where $\Delta_{0,i}(k)$ is the deviation sequence of the reference sequence, ζ the distinguishing coefficient, $\Delta_{min}$is the smallest value of $\Delta_{0,i}$ and Δ_{max} is the largest value of $\Delta_{0,i}$. After the calculation of GRC, the average value of the GRC is taken as the grey relational grade (GRG). The GRC which is calculated from all responses and GRG are shown in the Table-4.

RESULTS AND DISCUSSIONS

Experimental Results

The results of the thrust force, hole roundness and hole surface roughness are shown in the Table-3.

ANOVA and Percentage Contribution

The influence of drilling parameters and tool geometries can be evaluated by the value of GRG. However, the relative importance analysis among the drilling parameters and tool geometries for multiple-performance characteristics still needed so that the optimum condition of the parameter levels can be determined clearly. The purpose of ANOVA is to analyze which parameters affect the performance characteristics significantly. The result of the ANOVA of GRG of three responses (thrust force, hole roundness and hole surface roughness), is shown in Table-5. For analyzing the significant parameters and their contribution to the drilling process of GFRP, percentage of contribution also calculated. The percentage of contribution of each response and the error is shown in Table-5. The result indicates that the most significant parameters which have influence to reduce the total variance of thrust force, hole roundness and hole surface roughness simultaneously is

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the cutting feed followed by drill point geometry, drill point angle and spindle speed. The results of the ANOVA of thrust force, hole roundness and hole surface roughness are shown in the Table-6, Table-7 and Table-8.

Table-6. ANOVA of thrust force.

Source	DF	SS	MS	% contribution
PG	1	1426	1426	11.87%
PA	2	9955	4977.5	83.57%
VF	2	50.8	25.4	0.15%
N	2	280	140	2.09%
Error	10	162	16.2	2.32%
Total	17	11873.8		100%

Table-7. ANOVA of hole roundness.

Source	DF	SS	MS	% contribution
PG	1	7605.6	7605.6	73.75%
PA	2	2158.3	1079.2	20.77%
VF	2	408.3	204.2	3.78%
N	2	33.3	16.7	0.14%
Error	10	94.4	9.4	1.56%
Total	17	10300		100%

Table-8. ANOVA of hole surface roughness.

Source	DF	SS	MS	% contribution
PG	1	0.32428	0.32428	4.23%
PA	2	0.20352	0.10176	1.40%
VF	2	5.06921	2.5346	78.49%
N	2	0.13931	0.06965	0.38%
Error	10	0.57523	0.05752	15.49%
Total	17	6.31155		100%

Based on Table-6, drill point angle is the most influential parameter which affect the thrust force followed by drill point geometry, spindle speed and cutting feed. The bigger drill point angle the bigger thrust force needed during drilling GFRP composite.

From Table-7, it is known that drill point geometry is the most influential parameter which affect the hole roundness followed by drill point angle, cutting feed and spindle speed. Different drill point geometry has different influence on the hole roundness. HSS-Cobalt drill has point geometry with X type and HSS drill has point geometry with S type. The hole resulted by using X type drill has smaller roundness error than hole resulted by using S type drill.

Cutting feed is the most influential parameter which affect the surface roughness followed by drill point geometry, drill point angle and spindle speed like shown on Table-8. The higher the cutting feed will cause higher hole surface roughness.

Optimum Level of Drilling Parameters

The optimum condition of the parameter levels can be clearly determined by using average analysis from response table. The procedure of response table is to group GRG by parameter levels and then to calculate the average. The response table is shown in Table-9. The average GRG for each factor levels then plotted in Figure-2 to attain the optimum parameter setting that would reduce the total variance of the responses simultaneously.

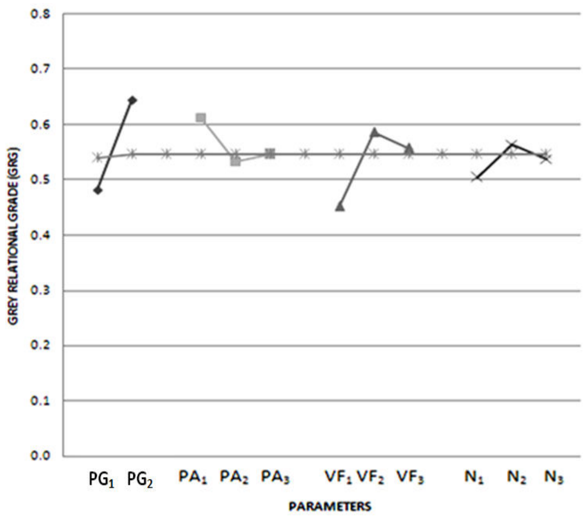

Figure-2. Average GRG for each factor levels.

Based on Figure-2, for minimizing the thrust force, hole roundness and hole surface roughness in drilling composite material (GFRP), the drill point geometry, drill point angle, cutting feed and spindle speed are set at level 2 (HSS-Cobalt), level 1 (90°), level 2 (100 mm/min) and level 2 (2500 rpm) respectively. This setting is selected from the drilling parameters which have the greatest GRG.

Table-9. Response table.

Parameters	level 1	level 2	level 3
Drill point geometry	0.4821	0.6456	
Drill point angle	0.6122	0.5326	0.5469
Cutting feed	0.4532	0.5869	0.5584
Cutting speed	0.5057	0.5642	0.5375
Average	0.5478		

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Prediction of Optimal Multiple-performance

The prediction of multiple-performance is aimed for calculating the predicted GRG which is resulted from optimum condition of drilling process. Equation 4 is used for the calculation of predicted grey relational grade [12].

$$\hat{\gamma} = \gamma_m + \sum_{i=1}^{o}(\bar{\gamma}_i - \gamma_m) \quad (4)$$

where γ_m is the total mean of GRG, $\bar{\gamma}_i$ is the mean of the GRG at the optimum level, and i is the number of the machining parameters that significantly affect the multiple-performance characteristics.

$$\hat{\gamma} = 0.5478 + (0.6456 - 0.5478) + (0.6122 - 0.5478) + (0.5869 - 0.5478) + (0.5642 - 0.5478)$$
$$\hat{\gamma} = 0.7656$$

Hence, the predicted grey relational grade for optimum parameter is 0.7656.

Confirmation Experiment

The validation of experimental results is carried out by confirmation experiment. Table-10 shows the results of confirmation experiments. The confirmation experiments were replicated 3 times and the average of this experiments then used to validate the prediction.

Table-10. Results of confirmation experiments.

No	Parameters				FZ (N)	R (μm)	SR (μm)
	TM	PA	N	VF			
1	2	1	2	2	25.75	115	0.973
2	2	1	2	2	26.41	105	0.972
3	2	1	2	2	24.34	110	0.98
Average					25.5	110	0.975

The GRG which is calculated from confirmation experiments is 0.7691. The interval plots of GRG prediction and confirmation experiments using 95% confidence of interval are shown in Figure-3.

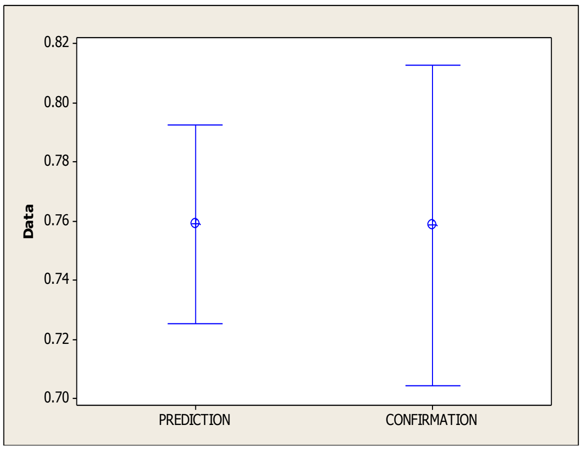

Figure-3. Interval plots of GRG of prediction and confirmation experiments.

Based on the interval plots of GRG prediction and GRG confirmation, the value of GRG confirmation is in the range of GRG prediction. It can be concluded that the setting parameters for optimum condition is valid.

The comparison between optimum combination and initial combination experiment is used to obtain the improvement of quality resulted from optimization process. Initial combination experiment is an experiment which is conducted by using level 2 for all parameters which has 3 levels. For experiment which has 2 levels, the level is selected from the optimum condition. The results of the initial combination experiments are shown in Table-11.

Table-11. Results of the initial combination experiments.

No	Parameters				FZ (N)	R (μm)	SR (μm)
	TM	PA	N	VF			
1	2	2	2	2	55.42	115	0.982
2	2	2	2	2	54.85	110	0.97
3	2	2	2	2	56.23	120	0.988
Average					55.5	115	0.98

The comparison of individual responses of initial combination experiments and optimum combination experiments are calculated and tabulated in Table-12. The comparison betwen multiple-performance characterictics which is represented by GRG for both experiments also shown in Table-12.

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Table-12. Result of the initial combination experiments and optimum combination experiments.

	Initial	Optimum	Improvement	
FZ	**55.5**	**25.50**	**54%**	**decrease**
R	115	110	4%	decrease
SR	0.980	0.975	1%	decrease
GRG	0.5164	0.7691	48.9%	increase

From Table-12, the GRG which represents the multiple-performance characteristics increase up to 48.9% from 0.5164 to 0.7691. Thrust force decrease up to 54% from 55.5 N to 25.50 N, hole roundness decrease up to 4% from 115 μm to 110 μm and hole surface roughness decrease up to 1% from 0.980 μm to 0.975 μm. It is suitable with the smaller is better characteristic which is used as the target for measuring the hole quality resulted from drilling process in this experiment.

CONCLUSIONS

This research present the multiple-performance optimization in drilling GFRP composite stacks with drilling parameters such as cutting feed and spindle speed and tool geometries such as drill point geometry and drill point angle as the experiment parameters. Taguchi method combined with grey relational analysis is used for optimization. The conclusions of this research are as follows:

- The percentage contribution of cutting feed, drill point geometry, drill point angle and spindle speed for reducing the total variance of multiple-performance characteristics are 42.78%, 42.26%, 6.97% and 2.25% respectively.
- For minimizing the thrust force, hole roundness and hole surface roughness in drilling composite material (GFRP), the drill point geometry, drill point angle, cutting feed and spindle speed are set at level 2 (HSS-Cobalt), level 1 (90°), level 2 (100 mm/min) and level 2 (2500 rpm) respectively.
- The results of experiment have shown that machining performance in the drilling process of GFRP composite can be improved effectively through this method.
- Taguchi-GRA method can simplify the optimization of drilling parameters and tool geometries with multiple-performance.

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