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Research paper

Analysis of factors affecting delamination in drilling GFRP composite

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Abstract

Composite materials have proven their applicability for various structural components. Excellent properties of glass fiber reinforced plastic (GFRP) composite materials have presented GFRP composites for potential applications in aerospace and automobile-related industries. Drilling is an important operation for composite structures during final assembly. This paper investigates the factors affecting delamination in GFRP composite during the drilling process. Drill speed and feed rate are selected two parameters affecting delamination during the drilling process. The response surface methodology approach has been used for experimental design and analysis of variance. Delamination was evaluated at the entry, middle, and exit positions of the hole. An attempt has been made to optimize the speed and feed rate for minimization of delamination at the three positions using grey relational analysis. The results of this work will help in selecting an optimum level of speed and feed rate to minimize delamination at the entry, middle, and exit positions of the hole to improve quality of the drilled hole.

1. Introduction

Among the fiber-reinforced composites, glass fiber reinforced plastic (GFRP) composite is one of the most used composite materials, consisting of two distinct materials: a polymer resin as matrix and glass as reinforcement providing good strength to weight ratio. GFRP composites are widely used in various industrial applications like aerospace, aircraft, automobile, and various sports good, etc. Among various machining processes associated with GFRP, drilling is a frequently used operation for hole making for structural assemblies of the component in aerospace and automobile industries [1-3]. Major failure mechanisms associated during the drilling of composite materials are fiber pull-out, surface damage by delamination, burning of cracks, fuzziness, and accuracy affected by debonding [4-6]. This is because of the anisotropy of the material, as it contains a soft epoxy matrix and hard fibers. Achieving good quality of drilled holes along with accuracy is a difficult task in the drilling of GFRP. Delamination is a major problem encountered in the drilling of GFRP, and it affects assembly tolerance and reducing the overall performance of the composite. About 60% rejection in the assembly of aircraft is because of delamination [7, 8]. Delamination occurs at the entry and exit surface of the composite plate, so it is a major concern in drilling holes when the top and bottom surfaces are exposed to assembly [9]. A number of researchers studied the drilling of composite materials and presented that quality of the drilled hole is related to the machining parameters, tool geometry, machining process, and workpiece material [10-12]. Mohan et al. [13] evaluated the effect of cutting parameters on delamination in the drilling of GFRP composites. They reported that peel-up delamination is significantly affected by the cutting speed and specimen thickness while pushing down delamination significantly affected by the specimen thickness and feed rate. Abrao et al. [14] investigated the effect of tool geometry and material on delamination and thrust force during drilling GFRP. Palanikumara and Paulo Davim [15] studied the effect of fiber orientation angle, depth of cut, cutting speed, and feed rate on tool flank wear, and reported that the tool flank wear is significantly affected by cutting speed followed by feed rate. Paulo Davim and Reis [16] implemented the design of experiments (DoE) to study the effect drill tool flute on drilling-induced damage in carbon fiber reinforced plastics (CFRP). They observed that a helical flute K10 carbide drill creates less damage than a four-flute K10 drill.

The objective of the present study is to analyze the effect of drilling variables such as feed rate and spindle speed on delamination of GFRP at the entry, exit, and middle positions of the hole. Response surface methodology based regression model is proposed, and Analysis of variance (ANOVA) is performed to find the significant parameter affecting delamination.

2. Drilling-induced delamination

2.1. Mechanism of drilling induced delamination

GFRP composite laminates are used in landing gear doors, storage room doors, fairings, and passenger compartments [17]. Drilling is a more frequently used operation and, during this drilling, delamination is unavoidable damage to composite laminates, which occurs due to inter-ply failure. Two significant delamination mechanisms associated with drilling-induced delamination are ‘Peel-up’ and ‘Push-out’ [18-21]. Fig. 1 shows the mechanism of peel-up and push–out delamination around the drilled hole at entry and exit periphery, respectively. Most of the studies in the past have concentrated on push-out delamination as it is more severe than peel-up delamination [22, 23].

2.2. Assessment of delamination

In the drilling of the composite laminate, the quality of the hole is the main priority. A hole quality depends upon surface finish, roundness, hole diameter, etc. Along with these quality measures, the delamination factor (F_d), Eq. (1), is also an important parameter for analyzing the quality of the hole. F_d is a quantitative measure for delamination around the hole. F_d is determined as the ratio of the maximum diameter (D_{max}) at the delamination area to the nominal diameter (D_{nor}) [24]. Fig. 2 illustrates the maximum and nominal diameter at the delamination area.

$$F_d = \frac{D_{max}}{D_{nor}} \tag{1}$$

3. Experimental procedure

In this study, the experiments were conducted on a computer numerical control (CNC) vertical machining center. Drilling trials were conducted on 15 mm and 10 mm thick bi-directional GFRP composite laminate specimens. An 8 mm diameter high-speed steel twist drill was used for all drilling operations.

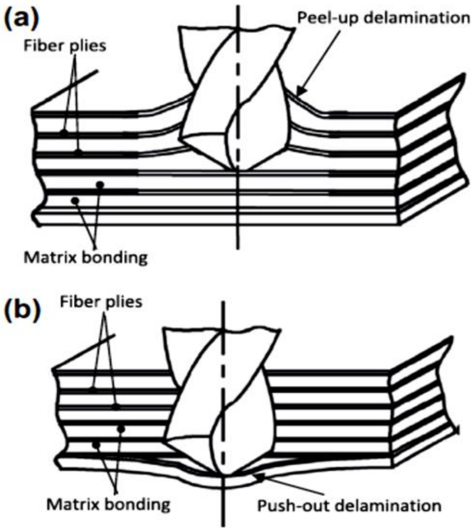

Fig. 1. Mechanism of drilling-induced delamination in FRP composite laminate.

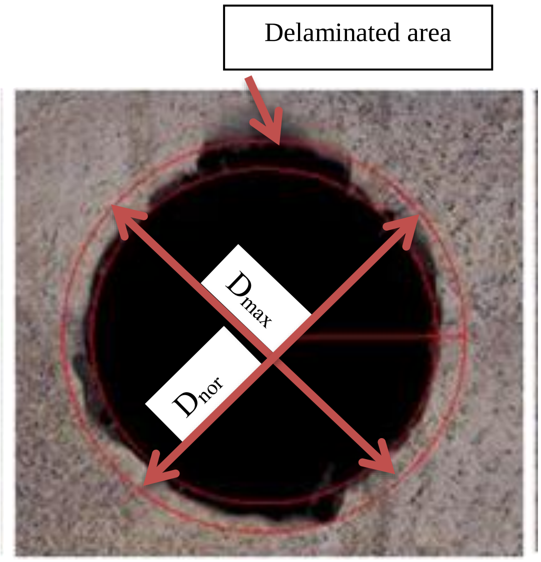

Fig. 2. Delamination zone diameters.

All operations performed without coolant. Spindle speed and feed were two parameters selected for study to obtain the optimized levels for minimization of delamination. The experiments were conducted according to RSM-central composite design. The parameters and corresponding levels are shown in Table 1. After conducting the drilling operation, the quality of the hole was measured in terms of circularity error with the help of a coordinate measuring machine (CMM). The maximum and the normal diameters were measured with CMM for determination of delamination factor at entry, middle, and exit positions of the hole. The delamination factor was evaluated for both 15 mm and 10 mm plates using Eq. (1). Fig. 3 shows a cross-sectional SEM image of GFRP plate representing the distribution of glass fiber in the plastic matrix. Fig. 4 shows optical microscopic photographs of delamination observed in the composite laminate plate during drilling. Table 2 shows corresponding values of delamination factor evaluated at the entry, middle, and exit of the hole.

4. Results and discussion

4.1. Multi-objective optimization using GRA

The aim of every manufacturing or machining process is to obtain a quality output. In order to achieve quality output from any process, it is essential to maintain an optimal combination of process parameters. But, when it is being worked with a number of outputs/responses, in that case, the optimal combination of process parameter for one response may not be an optimal combination for another response.

So, a multi-objective optimization is essential to obtain the optimal combination of process parameters for achieving quality responses in all cases. In this study, it is tried to minimize delamination at the entry, middle, and exit levels during drilling of GFRP composite laminate. An attempt is made to obtain the optimal combination of spindle speed and feed for minimization of delamination at the three positions so as to achieve a delamination factor of 1 at all positions. To solve these kinds of multi-objective problems, GRA is a suitable technique. This GRA is based on Grey system theory proposed by Deng in 1982 to study the uncertainties in system models, establish models, analyze relations between systems, and make a prediction [25-27]. The GRA involves the following steps:

Table 1. Control parameters and levels.

No.	Parameter	Unit	Levels				
			-β	-1	0	+1	+β
1	Spindle speed	rpm	600	800	1000	1200	1400
2	Feed rate	mm/ min	20	60	70	80	90

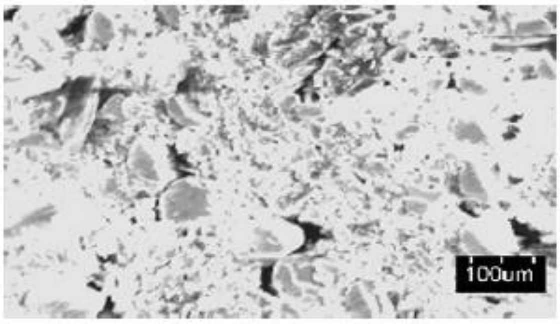

Fig. 3. Cross-sectional SEM image of the composite laminate plate.

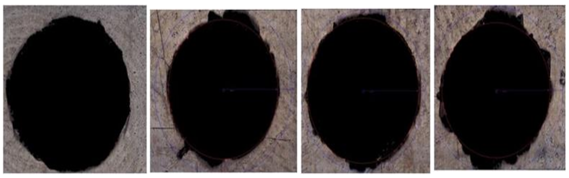

Fig. 4. Typical photographs of delaminated hole.

Table 2. Experimental results.

Plate thickness	No.	Spindle speed (rpm)	Feed (mm/min)	Delamination factor at the		
				Entry (F_{de})	**Middle (F_{dm})**	**Exit (F_{dex})**
15 mm thick GFRP plate	1	600	70	0.99606	1.00078	1.00084
	2	1200	80	1.00028	1.00091	0.99949
	3	800	80	0.99915	1.00001	0.99962
	4	1000	50	0.99625	1.00100	1.00013
	5	1000	70	0.99999	1.00074	0.99937
	6	1000	70	0.99964	1.00090	0.99979
	7	1000	70	0.99984	1.00021	0.99967
	8	1000	70	0.99977	0.99961	0.99988
	9	800	60	0.99949	1.00078	0.99868
	10	1200	60	0.99984	0.99984	0.99872
	11	1400	70	0.99974	1.00016	0.99962
	12	1000	90	1.00049	1.00094	0.99941
	13	1000	70	1.00017	0.99977	0.99953
10 mm thick GFRP plate	1	600	70	0.99568	1.00188	0.99577
	2	1200	80	1.00097	1.00056	0.99646
	3	800	80	1.00026	0.9998	0.99814
	4	1000	50	1.00045	1.00048	0.99739
	5	1000	70	1.00001	1.00012	0.99928
	6	1000	70	1.00011	1.00020	0.99872
	7	1000	70	1.00012	1.00066	0.99949
	8	1000	70	1.00020	0.99991	0.99977
	9	800	60	1.00089	0.99992	0.99927
	10	1200	60	1.00044	0.99998	0.99664
	11	1400	70	1.00116	1.00022	0.99951
	12	1000	90	1.00089	0.99921	0.99978
	13	1000	70	1.00001	1.00011	0.99982

- **Normalization of experimental data**

In this step, the data collected from experiments is normalized in the range of 0-1, called 'Grey relational generation'. If the objective is to minimize the response, then lower-the- better (LB) criteria are used, and when the objective is to maximize the response, then higher-the- better (HB) criteria are used for normalizing data.

- **Evaluation of grey relational coefficient (GRC)**

GRC (ζ) is computed to establish a correlation between the finest data and the definite normalized data. The GRC is calculated as:

$$\zeta_i(k) = \frac{\Delta_{min} + \psi\Delta_{max}}{\Delta_{0i}(k) + \psi\Delta_{max}} \tag{2}$$

$$\Delta_{0i}(k) = \|x_0(k) - x_i(k)\| \tag{3}$$

where Δ_{0i} is the absolute difference value. Δ_{min} and Δ_{max} are the minimum and maximum values of the absolute differences of all compared sequences. The purpose of distinguishing coefficient ψ (0 ≤ ψ ≤ 1) is to weaken the effect where i is the number of the experiment, $x_i(k)$ is obtained 'grey relational generation', y_0 is the nominal value of delamination factor =1, and max $y_i(k)$ is the highest value for the kth response, where k = 1,2,3, …n for the various output responses considered in a sequence.
data is normalized using criteria nominal-the-best (NB) using the following equation:

$$x_i(k) = \frac{|y_i(k) - y_o|}{\max y_i(k) - y_0} \tag{4}$$

In this study, the delamination factor is a response and needs to be normally 1 for good quality of the drilled hole. So, the experimental of Δ_{max} when it is excessive. In the present study, the value of ψ is set to 0.5.

- **Evaluation of grey relational grade (GRG)**

The average of the grey relational coefficient is used to calculate GRG (γ) as follow:

$$\gamma_i = \frac{1}{n}\sum_1^n(\beta * \zeta_i(k)) \tag{5}$$

where, n is the number of responses and β is the weighing factor.

Minimum delamination is expected at the entry and exit levels. So, high weightage is assigned to delamination at the entry and exit levels. Following weightage, factors were assigned to different responses: at the entry and exit levels=0.45, and at the middle level=0.1. The higher value of GRG signifies the optimal combination of input parameters for all quality responses. Tables 3 and 4 show GRC and GRG values evaluated for 15 mm thick and 10 mm thick GFRP plates during the drilling operation.

Figs. 5 and 6 show surface plot and contour of GRG with respect to spindle speed and feed rate for 15 mm thick GFRP plate, respectively.

Figs. 7 and 8 show surface plot and contour of GRG with respect to spindle speed and feed rate for 10 mm thick GFRP plate, respectively.

GRG presents multiple characteristics in terms of a single characteristic. Irrespective of quality characteristic, a higher value of GRG are preferred for quality output characteristic [28]. Experiments 8 and 13 give an optimal combination of drilling process parameters for minimization of delamination at three positions in 15 mm thick and 10 mm thick GFRP composite laminate plates.

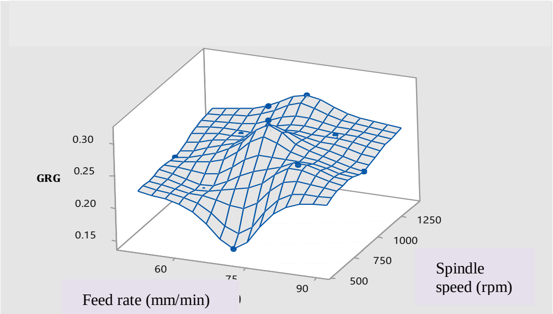

Fig. 5. Surface plot of GRG Vs spindle speed and feed rate.

Table 3. Grey relational coefficients and grades for 15 mm thick plate.

Sr.	**Input parameters**		**GRC**			**GRG**	
No.	**Spindle speed (rpm)**	**Feed (mm/min)**	**At entry**	**At middle**	**At exit**	**Value**	**Rank**
1	600	70	0.360	0.399	0.526	0.146	13
2	1200	80	0.947	0.362	0.676	0.256	8
3	800	80	0.755	1.000	0.760	0.261	7
4	1000	50	0.372	0.340	1.000	0.217	11
5	1000	70	1.076	0.412	0.614	0.267	6
6	1000	70	0.914	0.365	0.909	0.286	3
7	1000	70	1.000	0.719	0.798	0.294	2
8	1000	70	0.968	0.574	1.013	0.316	1
9	800	60	0.860	0.399	0.399	0.202	12
10	1200	60	1.000	0.774	0.408	0.237	9
11	1400	70	0.954	0.774	0.760	0.283	4
12	1000	90	0.864	0.355	0.633	0.236	10
13	600	70	0.996	0.700	0.700	0.278	5

Table 4. Grey relational coefficients and grades for 10 mm thick plate.

No.	**Input parameters**		**GRC**			**GRG**	
	Spindle speed (rpm)	**Feed (mm/min)**	**At entry**	**At middle**	**At exit**	**Value**	**Rank**
1	600	70	0.122	0.341	0.363	0.084	13
2	1200	80	0.381	0.640	0.408	0.140	12
3	800	80	0.707	0.843	0.580	0.221	7
4	1000	50	0.576	0.677	0.487	0.182	11
5	1000	70	1.000	0.906	0.812	0.302	2
6	1000	70	0.858	0.843	0.678	0.259	5
7	1000	70	0.844	0.601	0.876	0.278	4
8	1000	70	0.761	0.933	0.981	0.292	3
9	800	60	0.403	0.943	0.809	0.213	8
10	1200	60	0.582	1.000	0.421	0.184	10
11	1400	70	0.34	0.828	0.884	0.211	9
12	1000	90	0.403	0.556	0.986	0.227	6
13	1000	70	1.000	0.915	1.000	0.331	1

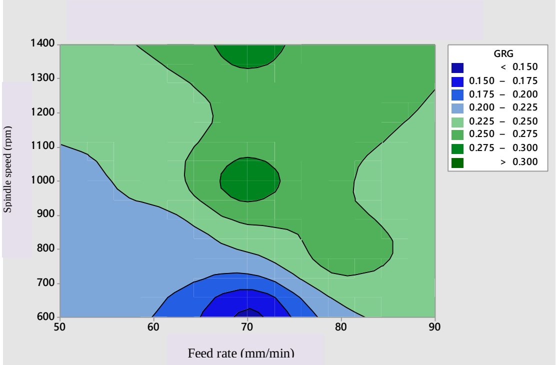

Fig. 6. Contour plot of GRG Vs spindle speed and feed rate.

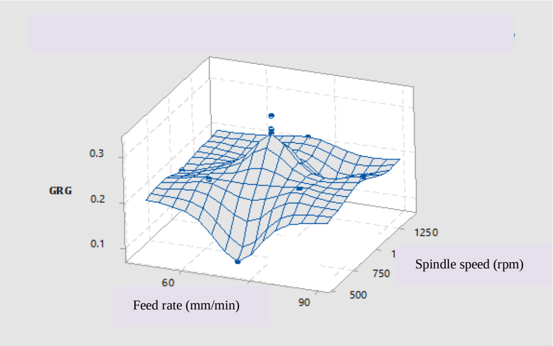

Fig. 7. Surface plot of GRG Vs spindle speed and feed rate.

Fig. 8. Contour plot of GRG Vs spindle speed and feed rate.

4.2. *Mathematical model*

Experiments were planned according to the RSM –central composite design, which offers the advantage of reducing the number of experiments for studying individual and interacting effect of process parameters on the response. RSM creates a model using the interaction between the statistical techniques and mathematical procedures. A second-order quadratic model developed using RSM for GRG in terms of spindle speed and feed rate. The mathematical model in uncoded coefficient is presented below for 15 mm thick and 10 mm thick plates, respectively.

$$GRG_{15mm} = -1.496 + 0.001411\ Speed + 0.02793\ Feed\ rate - 0.000001\ Speed * Speed - 0.000157\ Feed\ rate*Feed\ rate - 0.000005\ Speed*Feed\ rate \qquad (6)$$

$$GRG_{10mm} = -\ 2.31 + 0.00236\ Speed + 0.0388\ Feed - 0.000001\ Speed*Speed - 0.000227 Feed*Feed - 0.000006\ Speed*Feed \qquad (7)$$

4.3. ANOVA

ANOVA is a statistical technique, helps to investigate which design parameters significantly affect the output parameter. In this study, ANOVA performed to investigate the significance of coefficients in establishing the relationship between drilling parameters and GRG. ANOVA presents the individual and combined contribution of each factor on the output parameter [29, 30].

The analysis is carried out for the level of significance of 5% (the level of confidence is 95%).

In the ANOVA table:

- The degree of freedom (DF) is a measure of the amount of independent information available from the given set of data. DF for the concerning factor is one less than the number of levels.
- Percentage contribution is a measure of the individual contribution of a factor on the mean response.
- Variance ratio (F-value): commonly called F statistics, is the ratio of variance due to individual factors and variance due to error terms.

Tables 5 and 6, present ANOVA of GRG evaluated for minimization of delamination during drilling of 15 mm and 10 mm thick GFRP plates.

Table 5. ANOVA for response surface model of GRG for 15 mm thick plate.

Source	DF	Seq SS	% Contribution	F-value	P-value
Model	5	0.019930	81.56	6.19	0.017
Spindle Speed	1	0.007701	31.54	11.97	0.011
Feed Rate	1	0.001121	4.59	1.74	0.228
Spindle Speed * Spindle Speed	1	0.005050	20.68	12.44	0.010
Feed Rate * Feed Rate	1	0.005641	23.10	8.77	0.021
Spindle Speed * Feed Rate	1	0.00040	1.64	0.62	0.456
Error	7	0.004503	18.44		

Table 6. ANOVA for response surface model of GRG for 10 mm thick plate.

Source	DF	Seq SS	% Contribution	F- value	P-value
Model	5	0.037743	66.67	2.80	0.106
Spindle Speed	1	0.001728	3.05	0.64	0.450
Feed Rate	1	0.000243	0.43	0.09	0.773
Spindle Speed * Spindle Speed	1	0.023241	41.05	11.63	0.011
Feed Rate* Feed rate	1	0.011855	20.94	4.40	0.074
Spindle Speed * Feed rate	1	0.000676	1.19	0.25	0.632
Error	7	0.018872	33.33		

ANOVA had revealed the % contribution of various terms on GRG for 15 mm thick plates as follow:

- Spindle speed has an individual contribution of 31.54% compared to only 4.59% contribution of Feed rate.
- Squared terms spindle speed*spindle speed and feed rate* feed rate has a contribution of 20.68% and 23.10%, respectively.
- Interaction term spindle speed*feed rate has a negligible contribution to GRG.

ANOVA had revealed the % contribution of various terms on GRG for 10 mm thick plate as follow:

- Spindle speed has an individual contribution of 3.04% compared to only 0.43% contribution of feed rate.
- Squared terms spindle speed*spindle speed and feed rate* feed rate has a contribution of 41.05% and 20.94%, respectively.
- Interaction term spindle speed*feed rate has a negligible contribution of 1.19% to GRG.

5. Conclusions

Drilling operation performed on 10 mm and 15 mm GFRP plates. Further Grey relational analysis was performed for minimization of delamination at the entry, middle, and exit positions of the hole. Based on analysis following conclusions are drawn:

1. 1000 rpm speed and 70 mm/min feed rate are found to be optimum in both plates for minimization of delamination at all three positions of the hole. Squared terms of speed and feed rate are a major contributing factor on delamination rather than individual speed and feed rate. It also proves the applicability of GRA for obtaining optimum machining / operating conditions for minimization/ maximization of various characteristics simultaneously.
2. 1000 rpm speed and 70 mm/min feed rate are found to be optimum in both plates for minimization of delamination at all three positions of the hole.
3. Squared terms of speed and feed rate are a major contributing factor to delamination rather than individual speed and feed rate. It also proves the applicability of GRA for obtaining optimum machining / operating conditions for minimization/ maximization of various characteristics simultaneously.

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