International Journal of Engineering, Management and Humanities (IJEMH)
Volume 2, Issue 1, pp: 19-32 www.ijemh.com

Optimization of Drilling Parameters in GFRP Using Grey Relational Analysis with End Mill.

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Date of Submission: 29-01-2021 Date of Acceptance: 14-02-2021

ABSTRACT
Drilling has been acknowledged to be one of the key machining operations done on composite laminates. During drilling many defects such as delamination, splintering, swelling, burrs, fiber pullout etc. arise. Among these delamination stands out. This paper promulgates an experimental investigation on drilling-induced delamination of GFRP laminates using End mill. Taguchi grey relation approach based on multiple parameters has been used to optimize the results. Delamination has been quantified with the help of two dimensional delamination factor, similarly thrust force and torque are measured and its impact on delamination has been reviewed.

KEYWORDS: GFRP laminates; Drilling; Delamination; Grey relation analysis.

I. INTRODUCTION

Fiber reinforced composite laminates commonly used in industries mainly include CFRP (Carbon Fiber Reinforced Polymer) composite laminates, GFRP (Glass Fiber Reinforced Polymer) composite laminates and fiber metal composite laminates (FMLs). Currently composites are being used to replace conventional metallic materials in a wide range of industries including aerospace, aircraft and defense which require structural materials with high strength-to-weight and stiffness-to-weight ratios. GFRP (Glass fiber-reinforced polymer) are used in fairings, passenger compartments, storage room doors due to their high mechanical properties.

Drilling is the most commonly employed operation of secondary machining for fiber-reinforced materials owing to the need for structure joining. However, composite laminates are regarded as hard-to-machine materials, which results in low drilling efficiency and undesirable drilling-induced delamination. For rivets and bolted joints, damaged free and precise holes must be drilled in the components to ensure high joint strength and precision. However, some special characteristics of composite laminates such as non-homogeneous, anisotropic, and highly abrasive and hard reinforced fibers, result in them difficult to machine.

Among the problems caused by drilling, delamination is considered the major damage. It was reported that, in aircraft industry, the rejection of parts consist of composite laminates due to drilling-induced delamination damages during final assembly was as high as 60%. To increase drilling efficiency of composite laminates with the least waste and damages, it is essential to understand the drilling behavior by conducting a large number of drilling experiments and by establishing of drilling models of composite laminates.

This thesis paper presents delamination study of composite materials by conducting drilling experiments using Taguchi's L_{16}, 4-level orthogonal array and Analysis of variance (ANOVA) was used to analyze the data obtained from the experiments and finally determine the optimal drilling parameters in drilling GFRP composite materials by using special tools. Experiments were also conducted to determine whether varying feed & spindle speed during drilling could reduce the delamination.

Introduction to Delamination.

Drilling-induced damage, such as delamination, burrs, swelling, splintering and fiber pullout is the characteristic in machining composites. Delamination is considered the major concerns of applying the fiber reinforced composite materials in various industries. The size of the delamination zone has been show into be related to the thrust force developed during the drill process and it is believed that there is a "critical thrust force" below which no damage occurs.

Delamination destruction was the most critical defect which could be created because of machining operation in the composites since it could

severely damage the performance of the finished part.

Mechanisms of Delamination

(a) Peel-up delamination at entrance and (b) Push-out delamination at exit

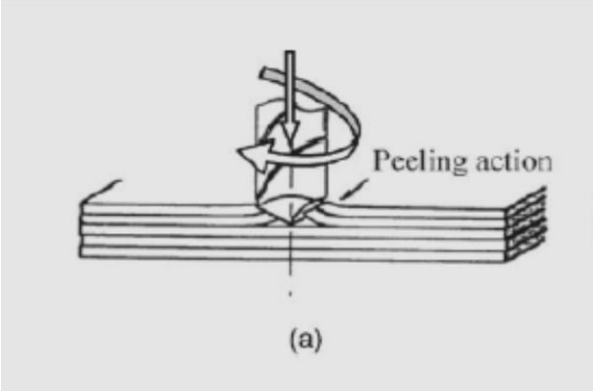


Figure: Peel-Up Delamination

Peel-up at entrance

The cutting edge of the drill will first abrade the laminate initially. It then, by moving forward, tends to pull the abraded material away along the flute. The material spirals up before it is machined completely. This action introduces a peeling force upwards to separate the upper laminas from the uncut portion held by the downward acting thrust force as described by Capello E (2004).

Push-out at exit

In drilling, the drill always exerts a compressive thrust force on the work piece. The laminar under the drill thus tend to be drawn away from the inter-laminar bond around the hole. As the drill approaches the end, the uncut thickness becomes smaller and the resistance to deformation decreases. At some point, the loading exceeds the inter-laminar bond strength and delamination occurs.

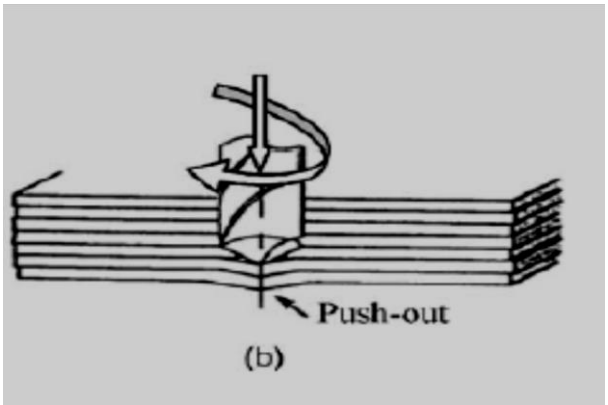


Figure: Push-Out Delamination

Two Dimensional Delamination Factor (F_A)

An index or factor called delamination factor (F_A) is used to determinate the extent of delamination given by Danim et.al, (2004[a], 2004[b]) by using equation, $F_A = ((A_{DEL} - A_{NOM})/(A_{NOM}))\%$

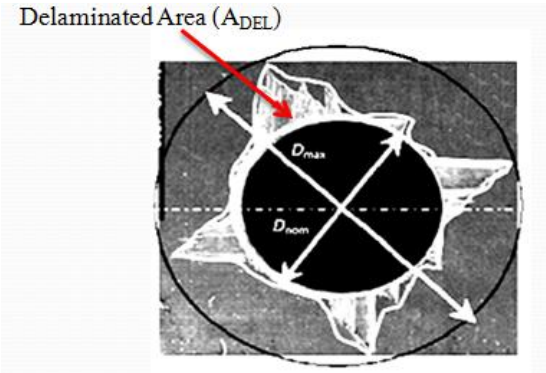


Figure: Diagram of the Damage

D_{max} is the maximum diameter created due to delamination around the hole and D is the hole or drill diameter. At a critical thickness, the bending stress becomes greater than the inter-laminar strength between the plies and an inter-laminar crack is initiated around the hole. Further pushing down by the drill point causes the crack to propagate and the flexural rigidity of the supporting plies becomes weaker. This leads to fracturing the material below the drill point as the chisel edge proceeds to exit the laminate. The damage at exit plies is shown as Spalling that extends beyond the hole diameter.

II. LITERATURE REVIEW

Introduction

Literature review briefly describes about literatures on mechanical drilling for composite laminates. Literature survey was carried out to find out methods to increase drilling efficiency of

composite laminates with the least waste and damages. Detailed study was conducted to find out the most suitable drilling parameters to reduce delamination using special drilling tools & finalize the optimal parameters.

Amongst all machining operations, drilling using twist drill is the most commonly applied method for generating holes [2]. A large number of experiments were conducted by many researchers to research the influence of input variables (spindle speed, feed rate, and drill bit geometry) on output variables (delamination & thrust force). Park KY, Choi JH & Lee DG firstly introduces grinding drilling to reduce delamination by improving drilling performance (1995). Tsao CC & Hocheng H investigate that delamination is generally regarded as resulting from excessive thrust force & smaller delamination holes can be obtained when grinding drilling composite laminates (2004). A low (<1000 Hz) or high (>1000 Hz) frequency and low amplitude vibration is superimposed on a twist drill bit along the feed direction during drilling. Ramkumar J, Malhothra SK, Krishnamurthy R found that the thrust by (vibration-assisted twist drill) VATD are reduced by 20–30%, compared with conventional drilling (2004). Therefore, VATD is used to reduce the delamination damage during drilling of composite laminates. Unlike conventional drilling operation, high speed drilling operation of composite laminates has to be conducted in a high speed drilling machine system which is very expensive**.** Investigators revealed that the delamination tendency decrease with increase in cutting speed and the combination of low feed rate and point angle is also essential in minimizing delamination during high speed drilling of composite laminates.

H. Hochenga, C.C. Tsao(2006) studied about effects of special drill bits on delamination of composite materials and find out that core drill was able to with stand the highest feed rate with reduced delamination. From literature it is clear that twist drill bits made of HSS or carbides are the primary attraction in drilling of composite laminates among various drill bits. However, the applications of other drill bits in drilling of composite laminates are also very extensive to improve machine ability of composite laminates. Most of investigators found that using drill bits with different geometry and materials in drilling of composite laminates find more advantages & beneficiaries.

III. FINDINGS FROM THE REVIEW

For practical machining of GFRP, it is necessary to determine the optimal machining parameters to achieve less delamination etc. Optimization of process parameters is the important criterion in the machining process to achieve high quality. Most of the studies on GFRP shows eliminating delamination is very difficult and is to be controlled. K. Palanikumar (2011) conducted experiments on GFRP composites using Brad & Spur drill and optimized drilling parameters by using two input variables with four levels and concluded that low feed rate and high spindle speeds are beneficial to reduce delamination. E. Kilickap (2010) conducted similar experiments to optimize the input parameters in drilling GFRP composites by using twist drill with different point angles and concluded that low feed rate and low spindle speeds are beneficial to reduce delamination. Previous researcher optimized the parameters by using only three or four levels.

The main aim this paper is to analyze the influence of spindle speed and feed rate on delamination by considering more levels (five) that are very low, low, medium, high and very high in order to find the optimum parameters. Experiments are carried out using End Mill (Carbide). Taguchi method with Analysis of variance (ANOVA) is used to optimize the input parameters. After obtaining the optimum parameters experiments are also conducted with varying speed and feed during drilling in order to obtain delamination free holes.

IV. OBJECTIVES OF THE WORK

As structural materials, joining composite laminates to other metal materials structures could not be avoided, and bolt joining efficiency and quality depend critically on the quality of machined holes. Various drilling processes are extensively used for producing riveted and bolted joints during assembly operation of composite laminates with other components. For rivets and bolted joints, damaged-free and precise holes must be drilled in the components to ensure high joint strength and precision.

Among the problems caused by drilling, delamination is considered the major damage. It was reported that, in aircraft industry, the rejection of parts consist of composite laminates due to drilling-induced delamination damages during final assembly was as high as 60%. Therefore the main aim is to reduce delamination during drilling by conducting experiments with End mill.

The objectives of the work are

- To analyze the influence of spindle speed and feed rate on delamination by considering more levels (five) that are very low, low, medium, high

and very high in order to find the optimum parameters.

- ❖ Experiments are carried out using End Mill (Carbide).
- ❖ Taguchi method with Analysis of variance (ANOVA) was performed to find out input drilling parameters significance.
- ❖ By both S/N and ANOVA analysis, the optimal combination of process parameters was predicted.
- ❖ After obtaining the optimum parameters experiments are also conducted with varying speed and feed during drilling in order to obtain delamination free holes.

V. MATERIALS AND EXPERIMENTAL PROCEDURES

The laminates were composed of 26 layers, laid-up in the symmetrical form [0, 90]. The fibers were unidirectional (UD) E-Glass. The applied resin was of grade L-12 with K-5 hardener. The thickness of the laminate was 6mm. The GFRP composite was provided in the size of 250 X 40X6 mm. Drilling experiments are carried out on a MAKINO S 56 CNC vertical milling machine.

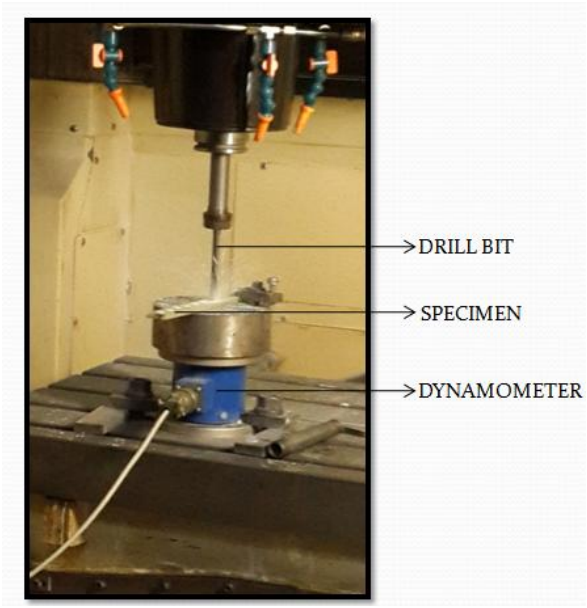


Figure: Experimental Setup

The tool used is End mill. AutoCAD 2010 software was used to measure the delaminated area around the hole.

Figure: Four Fluted End Mill

Traditional experimental design methods are too complicate and difficult to use. Experimental design procedures like simple factorial design or central composite design are very complex and are also difficult to handle. Additionally, these methods require a large number of experiments, when the number of process parameters increases. In order to minimize the number of tests required, Taguchi experimental design method a powerful tool for designing high quality system, was developed by Taguchi. Taguchi developed certain standard orthogonal arrays by which the simultaneous and independent evaluation of two or more parameters could be done in the entire space. The arrays were so designed that the number of experiments were very low compared to classical design approach.

A loss function was then defined to calculate the deviation between the experimental values and the desired values. This loss function was further transferred into a signal-to-noise (S/N) ratio. Usually there were three categories of the performance characteristics in the analysis of the S/N ratio, i.e. the lower-the-better (LB), the higher-the-better (HB) and the nominal-the-better (NB). The signal-to-noise ratios were calculated using the condition smaller is better.

In this study, two machining parameters were used as control factors and each parameter was designed to have five levels, denoted 1, 2, 3, and 4. Each experiment was repeated twice for getting reliable data. The averages of two tests were taken for determining delamination factor. The experimental design was according to an L_{16} array based on Taguchi method, while using the Taguchi orthogonal array would markedly reduce the number of experiments. Grey relational analysis based on Taguchi method is used to converts a multiple response process optimization problem into a single response.

Minitab software was used for Taguchi analysis. Using Analysis of Variance (ANOVA), the effect of input parameters on delamination factor is studied.

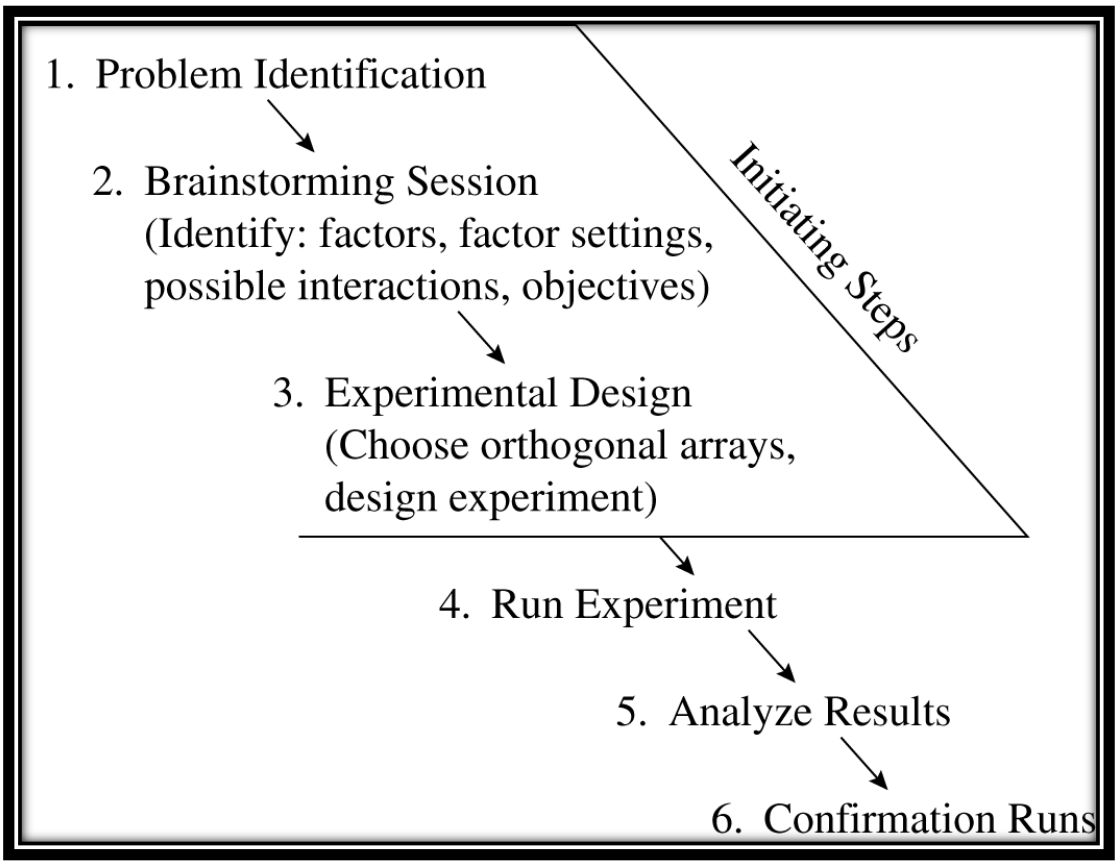


Figure: Taguchi Method Used for Optimization.

TABLE: DRILLING PARAMETERS AND LEVELS

Parameters		Very low (Level 1)	Low (Level 2)	Medium (Level 3)	High (Level 4)
Feed Rates (mm/rev)		0.05	0.1	0.15	0.2
Spindle Speed(rpm)		1750	2000	2250	2500

TABLE: ORTHOGONAL ARRAY OF TAGUCHI L_{16}

Experiment No.	Feed Rate	Spindle Speed
1	1	1
2	1	2
3	1	3
4	1	4
5	2	1
6	2	2
7	2	3

8	2	4
9	3	1
10	3	2
11	3	3
12	3	4
13	4	1
14	4	2
15	4	3
16	4	4

GREY RELATIONAL ANALYSIS

The optimization of process parameters are carried out using Taguchi method with grey relational analysis. The grey relational theory provides an efficient management upon the uncertainty, multi-input and discrete data. Grey relational analysis is actually a measurement of the absolute value of the data difference between sequences, and it could be used to measure the approximate correlation between sequences. For optimization of process parameters, the following steps are followed:

(1) Calculation of S/N ratio for the responses thrust force, surface roughness and delamination factor.
(2) Normalize the experimental results of thrust force, surface roughness and delamination factor (data pre-processing).
(3) Calculate the deviation sequence.
(4) Calculate the grey relational coefficient.
(5) Calculate the grey relational grade by averaging the grey relational coefficient.
(6) Analyze the experimental results using grey relational grade and statistical analysis of variance.
(7) Select the optimal levels of process parameters.
(8) Verify the optimal parameters through the confirmation experiment.

Calculation of S/N ratio for the responses studied:

It is proposed for the purpose to improve the quality of products based on the concepts of statistics and engineering. If smaller values are preferred, i.e., minimization of the quality characteristic, smaller-the-better is preferred. The equation for calculating S/N ratio for smaller-the-better characteristic (in decibels) is;

Data pre-processing

In grey relational analysis, the experimental data of the thrust force and surface roughness are first normalized to be in the range of zero to one and is known as data preprocessing. Data pre-processing is normally required since the range and the unit in one data may differ from the others. Data pre-processing is a means of transferring the original sequence to a comparable sequence. Depending on the characteristics of a data sequence, various methodologies of data pre processing are available for the grey relational analysis

$$x_i^*(k) = \frac{\max x_i^o(k) - x_i^o(k)}{\max x_i^o(k) - \min x_i^o(k)}$$

Grey relational coefficient

In grey relational analysis, the measure of the relevancy between two systems or the sequences is defined as the grey relational grade. The xo (k) is the ideal sequence for thrust force, surface roughness and delamination factor. The definition of the grey relational grade in the grey relational analysis is to show the relational degree between the sequences of xo (k) and xi (k), (i = 1,2 , _ _ _ ,m; k = 1,2 , _ _ _ ,n), where m is the total number of experiment to be considered, and n is the total number of observation data. The grey relational coefficient n(k) can be calculated as follows

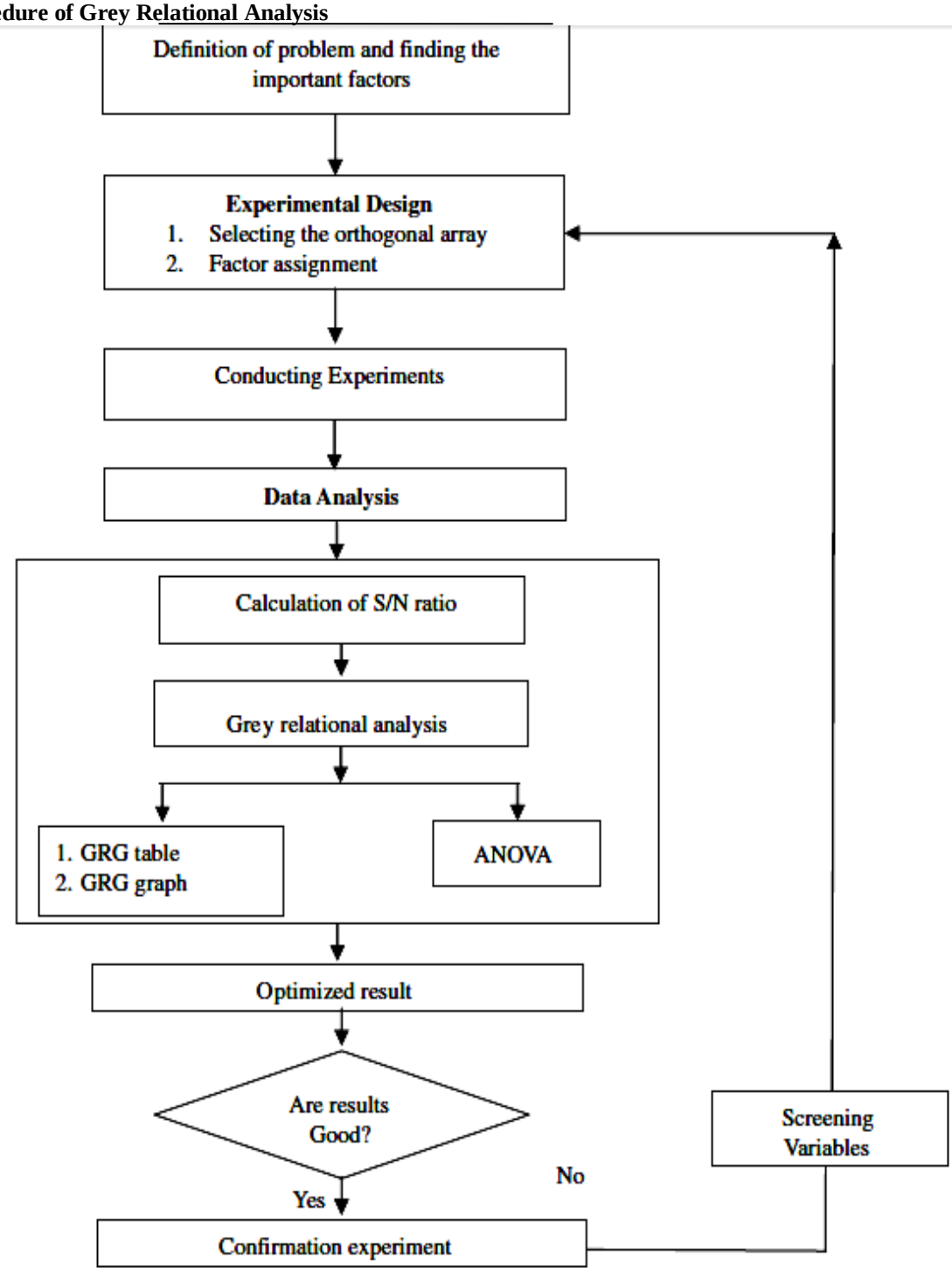
$$\xi(k) = \frac{\Delta_{\min} + \zeta\Delta_{\max}}{\Delta_{oi}(k) + \zeta\Delta\max}$$

where Δ_{oi} denotes the absolute value of the difference between xo (k) and xi (k) and is also known as the deviation sequence. ε is the distinguishing coefficient. A value of the f is the smaller and the distinguished ability is the larger ε = 0.5 is generally used.

6.4. Grey relational grade

After the grey relational coefficient is derived, it is usual to take the average value of the grey relational coefficient as the grey relational grade. The grey relational grade is defined as follows:

Procedure of Grey Relational Analysis



ANALYSIS OF RESULTS & DISCUSSION

Drilling tests were conducted with special tools to evaluate the effect of cutting parameters on the damage at work piece. The damage around the work piece was measured using AutoCAD software 2010 as shown in figure 9. After measuring the nominal area and delaminated area of each hole, the delamination factor is determined by utilizing equation as mentioned in the section

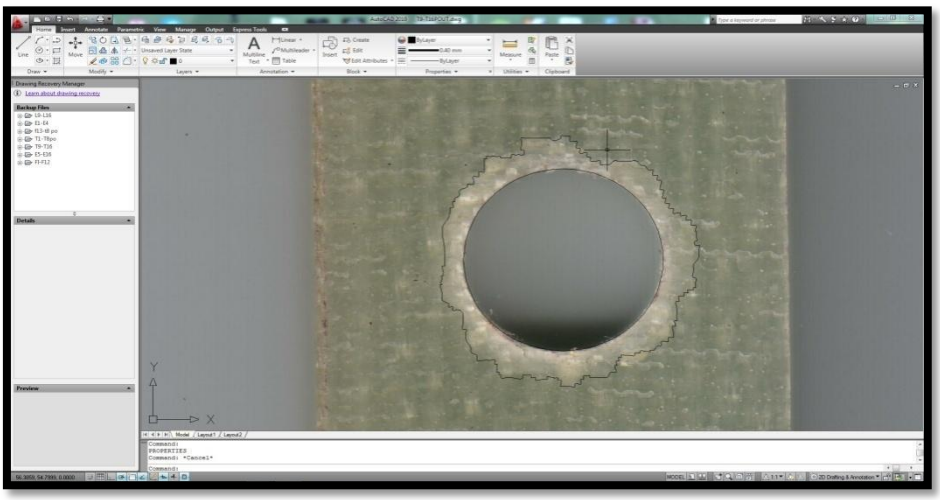


Figure: Analysis of Drilled Hole by AutoCAD 2010

Analysis of end mill (Push Out)

The table given below illustrates the influence of cutting parameters on the delamination factor of End mill.

TABLE: EXPERIMENTAL DESIGN USING L_{16} ORTHOGONAL ARRAY AND EXPERIMENTAL RESULTS OF END MILL DRILL

Exp. no.	Spindle speed (rpm)	Feed rate (mm/rev)	Thrust force (N)	Torque (Nm)	2D- delamination factor
1	1750	0.05	145	0.24	0.268
2	2000	0.05	145	0.24	0.259
3	2250	0.05	145	0.24	0.278
4	2500	0.05	142	0.22	0.309
5	1750	0.1	223	0.42	0.444
6	2000	0.1	223	0.42	0.454
7	2250	0.1	223	0.42	0.422
8	2500	0.1	221	0.41	0.412
9	1750	0.15	221	0.41	0.501
10	2000	0.15	221	0.41	0.511
11	2250	0.15	299	0.64	0.496
12	2500	0.15	299	0.64	0.559
13	1750	0.2	405	0.8	0.530

14	2000	0.2	313	0.56	0.566
15	2250	0.2	384	0.66	0.503
16	2500	0.2	384	0.66	0.512

S/N ratio

Trial no.		S/N ratio (dB)	
	2D-Delamination factor	Thrust	Torque
1	11.448	-43.227	12.396
2	11.735	-43.227	12.396
3	11.124	-43.227	12.396
4	10.192	-43.046	13.152
5	7.054	-46.966	7.535
6	6.855	-46.966	7.535
7	7.491	-46.966	7.535
8	7.708	-46.888	7.744
9	5.996	-46.888	7.744
10	5.830	-46.888	7.744
11	6.095	-49.513	3.876
12	5.044	-49.513	3.876
13	5.523	-52.149	1.938
14	4.945	-49.911	5.036
15	5.960	-51.687	3.609
16	5.822	-51.687	3.609

Normalization

Table: THE RESULT OF NORMALISATION OF THREE RESPONSE VARIABLES

Trial no	Normalized values of S/N ratio		
	2D-Delamination factor	Thrust force	Torque
1	0.042	0.020	0.067
2	0.000	0.020	0.067
3	0.090	0.020	0.067
4	0.227	0.000	0.000
5	0.690	0.431	0.501
6	0.719	0.431	0.501
7	0.625	0.431	0.501
8	0.593	0.422	0.482
9	0.845	0.422	0.482
10	0.870	0.422	0.482
11	0.831	0.710	0.827
12	0.985	0.710	0.827
13	0.915	1.000	1.000
14	1.000	0.754	0.724
15	0.851	0.949	0.851

16	0.871	0.949	0.851

Deviation sequence

Table:THE DEVIATION SEQUENCE.

Trial no	Deviation values of S/N ratio		
	2D-Delamination factor	Thrust force	Torque
1	0.915	1.000	1.000
2	1.000	1.000	1.000
3	0.808	0.996	1.000
4	0.968	0.996	1.000
5	0.549	0.476	0.628
6	0.758	0.476	0.628
7	0.382	0.536	0.614
8	0.559	0.599	0.738
9	0.456	0.206	0.324
10	0.257	0.206	0.324
11	0.683	0.206	0.324
12	0.629	0.206	0.324
13	0.431	0.023	0.000
14	0.234	0.000	0.057
15	0.000	0.000	0.057
16	0.300	0.048	0.065

Grey relational coefficient and grade

Table: THE CALCULATED GREY RELATIONAL COEFFICIENT AND GREY RELATIONAL GRADE.

Exp. no.	Spindle speed (rpm)	Feed rate (mm/rev)	Grey relational coefficient			Grey relational grade	Order
			2D-Delamination factor	Thrust force	Torque		
1	1750	0.05	0.922	0.962	0.881	0.922	2
2	2000	0.05	1.000	0.962	0.881	0.948	1
3	2250	0.05	0.847	0.962	0.881	0.897	3
4	2500	0.05	0.687	1.000	1.000	0.896	4
5	1750	0.1	0.420	0.537	0.500	0.486	7
6	2000	0.1	0.410	0.537	0.500	0.482	8
7	2250	0.1	0.444	0.537	0.500	0.494	6
8	2500	0.1	0.457	0.542	0.509	0.503	5
9	1750	0.15	0.372	0.542	0.509	0.474	9
10	2000	0.15	0.365	0.542	0.509	0.472	10
11	2250	0.15	0.376	0.413	0.377	0.389	11
12	2500	0.15	0.337	0.413	0.377	0.375	13
13	1750	0.2	0.353	0.333	0.333	0.340	16
14	2000	0.2	0.333	0.399	0.409	0.380	12
15	2250	0.2	0.370	0.345	0.370	0.362	14
16	2500	0.2	0.365	0.345	0.370	0.360	15

Grey relational grade graph

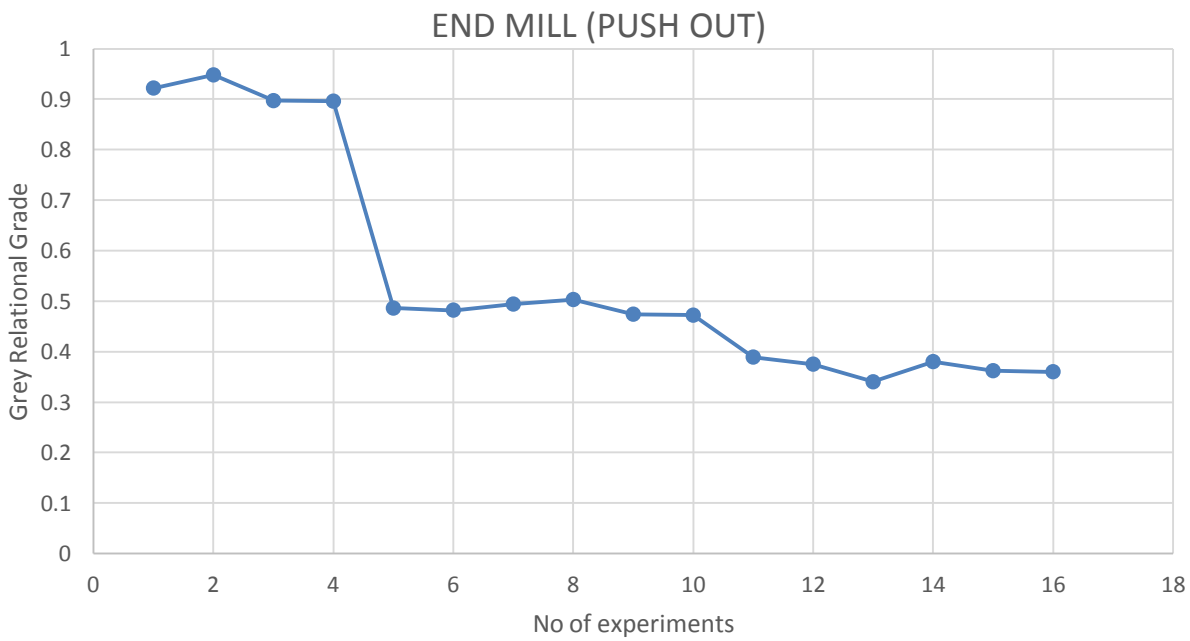


Fig: Grey Relational Grade Graph

ANOVA analysis

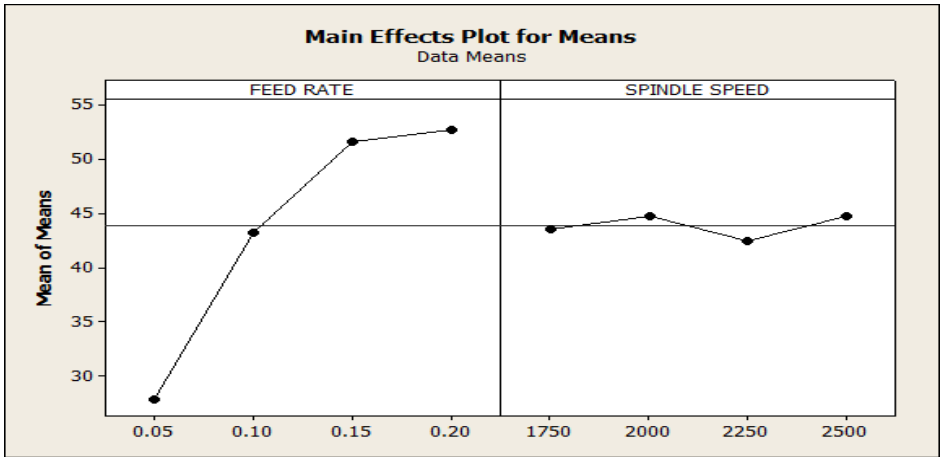


Figure: Main Effects for Means (End Mill)

Analysis of Variance for Means

Table-ANALYSIS OF VARIANCE FOR GREY RELATIONAL

Source	DF	Seq SS	Adj SS	Adj MS	F	P
FEED RATE	3	1589.54	1589.54	529.848	79.94	0.000
SPINDLE SPEED	3	14.70	14.70	4.901	0.74	0.555
Residual Error	9	59.65	59.65	6.628		
Total	15	1663.90				

Response Table for Means

Level	FEED RATE	SPINDLE SPEED
1	27.85	43.56
2	43.30	44.75
3	51.69	42.48
4	52.76	44.80
Delta	24.92	2.32
Rank	1	2

Table :RESPONSE TABLE FOR MEANS

The importance of process parameters is obtained from ANOVA analysis and the optimized values of process parameters are obtained from grey relational analysis.

From the table it can be observed that the delamination value varies drastically with increase in the feed rate. As the feed rate increases the delaminated area increases. The dependence on spindle speed is very less compared to feed rate. By varying spindle speed and speed rate.

The importance of main effects plot for means is that when the line is horizontal there is no main effect. Each level of factor affects the response in the same way, and the response mean is same across all factor levels. When the line is not horizontal then there is a main effect. Different levels of the factor affect the response differently. The steeper the slope of the line, the greater the magnitude of the main effect. From the figure it has been observed that the plot for feed rate increases steeply. But the plot for spindle speed is in a zigzag manner. Thus it shows that feed rate is the most important parameter affecting the delaminated area. As the feed rate increases the delaminated area also increases.

From the Table the delta values for feed rate are more compared to that of spindle speed. The rank for feed rate is 1 and that of spindle speed is 2.Thus from the Table (F value larger) it's clear that feed rate is mainly affecting the delamination factor compared to spindle speed.

From the grey relational analysis the optimum feed rate is 0.05 mm/rev and spindle speed is 2000 rpm. It has been observed that by varying speed and feed rate the delamination can be reduced to a certain limit. Varying the spindle speed and feed rate during drilling will be more beneficial while drilling higher thickness plates as the savings drilling time.

Optimized Process Parameters
PUSH OUT

DRILL BIT USED	FEED RATE	SPINDLE SPEED	DELAMINATION FACTOR
END MILL	0.05	2000	25.9

VI. RESULTS

1. The experiments are carried out using taguchi orthogonal array.
2. Grey relational analysis is used to convert multiple performance characteristics into a single performance characteristics.
3. ANOVA is carried out to study which machining parameter significantly affects the machining parameters.
4. Grey relational grade reveals that feed rate of 0.05mm/rev is the most optimized value for drilling using End mill.
5. The response table and main effective plots for means shows that feed rate is the most influential parameter affecting the quality of drilled holes
6. The order of importance for the controllable factors based on grey relational grade is feed rate followed by spindle speed.
7. The geometry of the drill bits has a very high effect on the nature of delamination.
8. Delamination increases as the thrust force on the material increases.
9. Chisel edge in the tool is the main cause for increasing the thrust force applied by it.
10. Peel up delamination is negligible in case of end mill.
11. Push out delamination is also very low in end mill because the geometry of end mill such that the force is distributed in a circular way and not on a single point.

VII. CONCLUSIONS & FUTURE WORK

This report has presented an application of the Taguchi based grey relational analysis method for the delamination study of drilling of GFRP composites by using special tools. The conclusions of this present study were drawn as follow:

1. The analysis of experimental results is carried out using Taguchi's orthogonal array and analysis of variance. The level of the best of the cutting parameters on the drilling induced delamination is determined by using ANOVA.
2. The drilling induced delamination increases with feed rate (0.05mm/rev to 2mm/rev).
3. The reason for higher delamination at spindle speed 2500 rpm may be, when the drill speed increases, the thrust force increases because severe heat generation in the drilling area leads to softening of the fiber and matrix. As a result, fiber cutting becomes harder for the cutting edges of the

drill and drilling thrust force increases a small amount causing more delamination.

4. The reason for higher delamination at the higher feed rate is due to more heat is generated and transferred to the laminate in the drilling area. This may be created local thermal destruction of the work piece and made undesirable results on delamination.

5. The results of ANOVA revealed that feed rate is the main cutting parameter, which has greater influence on the delamination factor

6. By varying the spindle speed and feed rate during drilling with the optimized values can reduce delamination.

7. Delamination occurred even at minimum feed. Therefore, the variable feed technique that depends on using CNC drilling machine is recommended to drilling of composite laminates to prevent the delamination around the drilled holes and to improve drilling efficiency at the same time.

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