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Experimental Investigation on Drilling of Fiber Metal Laminates using grey based Taguchi Approach

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Abstract

The drilling of multi-material stacks is a complex task for engineers due to their heterogeneous nature. Delamination is the main surface damage involved during multi-material composites drilling leads to workpiece rejection. In this work, the influence of three distinct drill geometries with different diameters and cutting parameters in the drilling have been assessed through the delamination factor. Machining trials involved drilling of holes on CFRP/Al/CFRP composites according to L27 Taguchi's orthogonal array (OA) approach using the solid carbide drill tools. Analysis of variance has been used to find the effect, percentage contribution, and significance of the process parameters, namely, cutting speed, feed rate, drill bit type and diameter. The focus of this article is to convey multi-objective optimization of CNC drilling parameters using the Grey-Taguchi method to achieve the minimum response in the machining of multi-material composites used in aircraft industries. The hybrid technique's effective execution aids in the production of high-quality, defect-free holes.

Keywords: *FML, delamination, drill geometry, drilling, cutting parameters, ANOVA.*

Nomenclature:

CFRP	Carbon fiber reinforced polymer
Al	Aluminium
Ti	Titanium
CNC	Computer numerical control
OA	Orthogonal Array
FML	Fiber metal laminates
CARALL	Carbon fibre reinforced aluminium laminates
GLARE	Glass reinforced aluminium
ARALL	Aramid reinforced aluminium laminates
GRG	Grey relation grade
ANOVA	Analysis of variance

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1.0 Introduction

The layer by layer stacking of fibres and metals or metal alloys with adhesives or epoxy resins and hardeners is entitled Fiber Metal Laminates (FML). These FMLs have collective properties of metal (aluminium, titanium or both) and fibres as they are formed by the stacking layers of fibre and metals. Typically fibre reinforced aluminium laminates are of different types such as carbon fibre reinforced aluminium laminates (CARALL), glass reinforced aluminium (GLARE) and aramid reinforced aluminium laminates (ARALL). This type of hybrid composite laminates also possesses high fire resistance in combination with the good damping nature. So they can bear a load in the hazardous zone in an aircraft engine (Mohammed et al., 2018). With such excellent properties, these materials are adequately used in aerospace, automotive applications. These hybrid composite laminates are fabricated using compression moulding methods, forming, 3D printing (Yelamanchi et al., 2020). Especially in the aerospace sector for assembling or bolting or rivetting of aircraft components, thousands of holes have to be produced on these FMLs.

However, drilling FMLs with damage-free holes is a highly challenging task for the engineers as they exhibit heterogeneous nature because of fiber and metals possession. The accuracy of holes will be determined by some parameters like drill diameter, material, machining parameters. Thereby selecting the right parameters of the drill, the quality of holes can be enhanced. Few researchers investigated the quality of holes with different optimization techniques by using different drills (such as twist, brad point, step, core etc.,), with different drill geometries and parameters (Jamwal et al., 2019). The stacking sequence and resin also influence the fastening ability of fibers to analyse the mechanical properties. This is reported by some researchers with the ANOVA analysis. In recognising the damage free hole drilling, specially designed drills are employed for better machining (Koyyagura & Karanam, 2021; Xu et al., 2019).

The Back propagation neural network-particle swarm optimization (BPNN-PSO) approach is used for optimizing the responses such as thrust force, torque and delaminations in the drilling of CFRPs (Soepangkat et al., 2020). According to Sobri et al. (Sobri et al., 2020) previous research ignored the inside of the hole, and a proper method for quantifying the interior surface of a hole including the entry and exit hole should be incorporated. In attempt to define the influence of input variables on critical output measures, such as delamination as well as other damages, researchers proposed a unique approach for measuring holes by employing the augmentation of the adjusted delamination factor for drilling carbon fibre reinforced polymer (CFRP) composites. The results of the trial revealed a substantial variation in how the damage was interpreted during the study. Better perspectives for recognising hole faults were provided, which improved the situation. As per the report of Shunmugesh and Pannerselvan (Shunmugesh & Kavan, 2017), the most influencing factors for minimizing the delamination are feed rate and speed found by applying the optimization techniques.

Based on the literature survey, it was observed that more experimentation on drilling of multi- materials stacks is needed. According to many sources, the composites used in the aviation industry are usually carbon fibre reinforced plastic propped with Al or Ti metals, with composite applied on top. This study investigated the effects of drilling CFRP/Al/CFRP composite laminates using three different drill types (twist, broad point and step drills), drill diameter, spindle speed and feed rate on responses such as thrust force, torque, hole entrance, and exit delamination. Using the Grey-Taguchi approach, the best parameters to match the drilling criterion were discovered.

2.0 Experimentation

2.1. Workpiece Details

Twenty four UD Carbon fibres having 0.24 mm thickness each, LY556 epoxy resin, HY951 hardener and AA 2024-T3 alloy sheets of 2.25 mm thick materials were used for the fabrication of carbon fiber

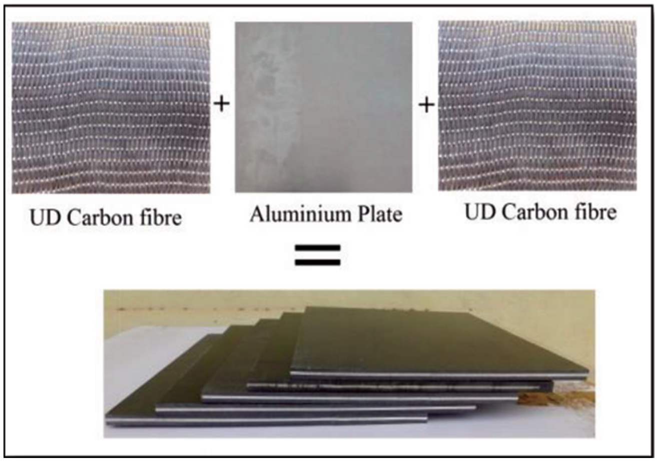

Figure 1: Fabricated CFRP/Al/CFRP stacks

reinforced aluminium sandwich composite material. The hand layup method was adopted for the fabrication in a traditional way. The 12 fibres in a sequence of 0/45/90/- 45/0/452/0/-45/90/45/0 were employed first on which the roughened Al alloy sheet was placed followed by again the same sequence of 12 carbon fibres. Then it was cured for a sufficient time in ambient conditions. Finally, the processed fabricated material composite is shown in Figure.1 with dimensions. The properties like tensile strength, impact strength and flexural strength were assessed for the fabricated material (Lakshmi Kala & Prahlada Rao, 2022).

2.2. Machine Configuration

Figure 2 exemplifies the experimental set up for the machining. The job with the dynamometer fixation (to note the thrust force) is fixed on the table of a CNC drilling machine, and the solid carbide drill is fed to the workpiece.

According to the necessity of drilled holes for the assembling of components used in the aircraft industry, drilling experiments were performed on the fabricated material. The drill parameters and cutting parameters for the experimentation were detailed in Table 1. The thrust force and torque are noted using SYSCON dynamometer.

2.3 Delamination Measurement

The detriment surrounding the holes for delamination factor calculation was assessed through a Dino-lite AM7013MZT microscope and image processing software shown in Figure 3.

The delamination factor (Fd) around each and every hole is calculated by measuring the maximum diameter (dmax) in the damage zone.

The damaged zone's maximum diameter (dmax) and hole diameter ratio determines the delamination factor, Fd, expressed in Eq. (1).

$$F_d = \frac{d_{max}}{d} \qquad \text{... (1)}$$

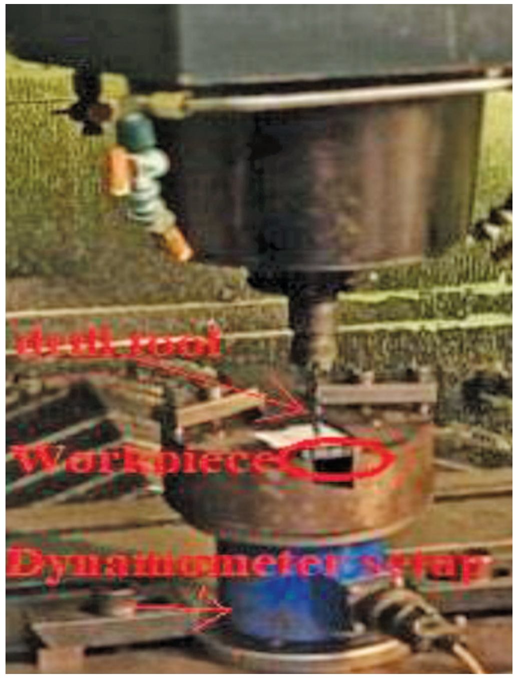

Figure 2: Experimental set up

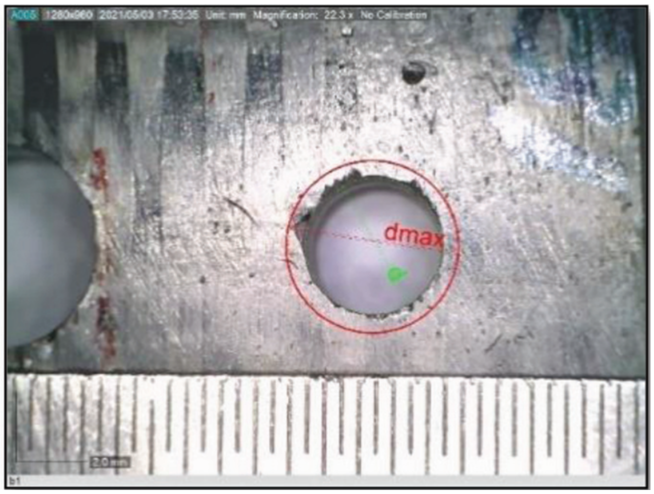

Figure 3: Maximum diameter measurement using image processing software

Table 1: Drill parameters and levels

			Levels		
Drilling parameters	Units	Symbol	1	2	3
Drill type	-	A	Twist drill	Broad point drill	Step drill
Drill diameter	(mm)	B	4	6	8
Spindle Speed	(rpm)	C	1250	2000	2750
Feed rate	(mm per rev)	D	0.05	0.1	0.15

Table 2: Experimental table derived from L_{27} orthogonal array (OA) for test trials

Input parameters				
Exp No	Drill Type	Drill Diameter (mm)	Speed(rpm)	Feed(mm per rev)
1	Twist Drill	4	1250	0.05
2	Twist Drill	4	2000	0.10
3	Twist Drill	4	2750	0.15
4	Twist Drill	6	1250	0.10
5	Twist Drill	6	2000	0.15
6	Twist Drill	6	2750	0.05
7	Twist Drill	8	1250	0.15
8	Twist Drill	8	2000	0.05
9	Twist Drill	8	2750	0.10
10	Broad Point Drill	4	1250	0.05
11	Broad Point Drill	4	2000	0.10
12	Broad Point Drill	4	2750	0.15
13	Broad Point Drill	6	1250	0.10
14	Broad Point Drill	6	2000	0.15
15	Broad Point Drill	6	2750	0.05
16	Broad Point Drill	8	1250	0.15
17	Broad Point Drill	8	2000	0.05
18	Broad Point Drill	8	2750	0.10
19	Step Drill	4	1250	0.05
20	Step Drill	4	2000	0.10
21	Step Drill	4	2750	0.15
22	Step Drill	6	1250	0.10
23	Step Drill	6	2000	0.15
24	Step Drill	6	2750	0.05
25	Step Drill	8	1250	0.15
26	Step Drill	8	2000	0.05
27	Step Drill	8	2750	0.10

2.4 Optimization and Modelling Using Grey Based Taguchi's Approach

The designing of any gathering data experiments where variation exists in the process under examination is referred to as design of experiments (DOE). A set of organised tests is created in which the input variables of a process or system are changed in a methodical manner. The impact of these modifications on a predetermined output is then assessed.

Before optimising design to meet the target values for output responses, the Taguchi approach optimises design parameters to reduce variation. The Taguchi approach employs specific orthogonal arrays to investigate all design aspects with the fewest number of experiments possible. Depending on the signal to noise ratio (S/N ratio), the optimum parameter levels are determined. There are three equations for the response characteristic analysis based on the equations i.e., Eq. (2) for smaller the better, Eq. (3) for nominal the better and Eq. (4) for larger the better (Karazi et al., 2019).

$$\frac{S}{N} = 10\ log\frac{y}{s^2 y} \quad \text{... (2)}$$

$$\frac{S}{N} = log\frac{1}{n}\sum_{i=1}^{n} y_i^2 \quad \text{... (3)}$$

$$\frac{S}{N} = log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \quad ... (4)$$

Where y, the observed data,
n, the number of observations.

In this study the responses deliberated are thrust force, torque and delamination. In order to analyze the best input process parameters, these responses should be minimum and thus the corresponding equation is used to evaluate the characteristics. Table 2 shows the input parameters following Taguchi technique - L_{27} orthogonal array (OA) and the corresponding values of output responses measured.

By using Grey Taguchi approach, optimization of the process parameters can be done. The steps tangled for the optimization process are as follows:

Step 1: The corresponding responses will be evaluated by considering S/N ratio formulae based on the goal of experiments i.e., larger the better (Eq.(5)), smaller the better equations (Eq.(6)).

$$\frac{S}{N} = -10\ log_{10}\frac{1}{n}\sum\frac{1}{y^2} \quad ... (5)$$

$$\frac{S}{N} = -10\ log_{10}\frac{1}{n}\sum y^2 \quad ... (6)$$

Step 2: Normalization to be done for the definite target value i.e., for the lower the better values, the normalized data can be expressed in the form using Eq. (7) (Naresh et al., 2014):

$$x_i(k) = 1 - \frac{\max(y_i(k)) - y_i(k)}{\max(y_i(k)) - \min(y_i(k))} \quad ... (7)$$

Step 3: After the data normalization, the Grey relational coefficient values are calculated by using Eq.8

Grey relational coefficient,

$$\varepsilon_1 k = \frac{\Delta_{min} + \varphi\Delta_{max}}{\Delta_{oi}(k) + \varphi\Delta_{max}} \quad ... (8)$$

The obtained values are used to find the Grey relation grade (GRG) by using Eq. (9) for all the corresponding experimental trials.

$$y_i = \frac{1}{n}\sum_{i=1}^{n}\varepsilon_i\ (k) \quad ... (9)$$

Where n, the number of responses

Step 4: Optimum levels and factors determination Based on the rank decision, the optimum levels and factors can be determined.

3.0 Results and Discussions

To identify the most appropriate process parameters for multiple responses, the integrated Grey based Taguchi approach is used which integrates the Taguchi method's algorithm with Grey relational analysis. Using this method, the multi-response optimisation problem has now been reduced to a single corresponding objective function optimisation problem. In general, higher the GRG, better the performance. But, knowing the relative relevance of the machining parameters for the various performance characteristics is indeed necessary in order to establish the best combinations of machining parameter levels. The Grey relational coefficient of responses and corresponding GRG is calculated and graphical representation is shown in Figure 4. By the higher values of GRGs, the optimised parameters are perceived from Table 3 as A2 (Brad point drill), B1 (4mm diameter), C1 (1250 rpm) and D1 (0.05 mm/rev) for multiple performance characteristics.

The relevance of each input parameter on the measurements of process performance, was determined using ANOVA. ANOVA is used to find the important factors using the Grey relational grade

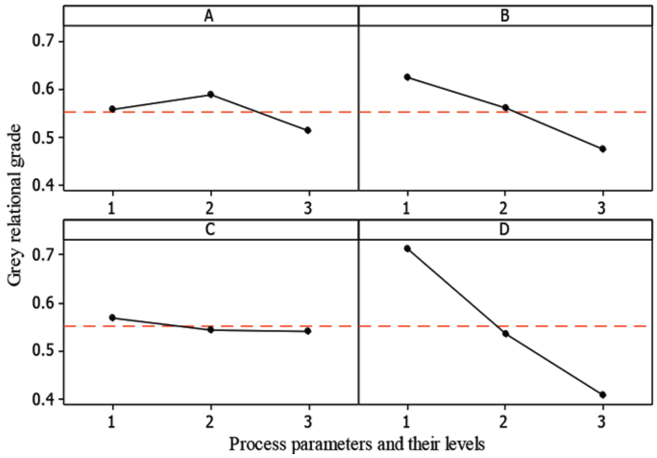

Figure 4: Process parameters and levels

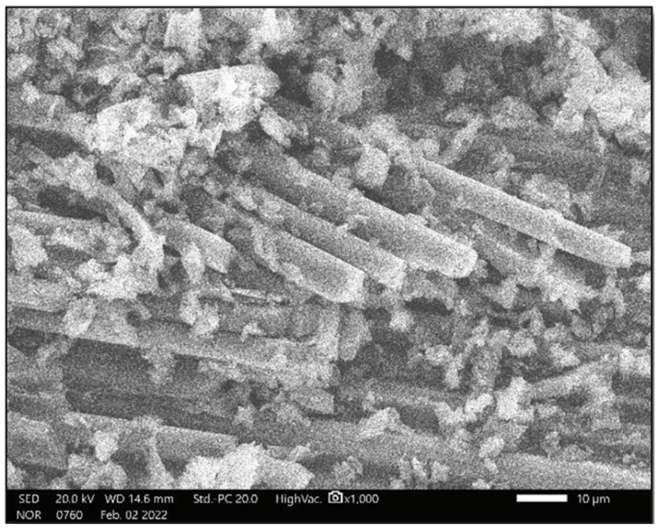

Figure 5: SEM image of the drilled specimen

Table 3: Response table for grey relational grade

Parameter	Level-1	Level-2	Level-3	Delta=Max-Min	Rank	Optimum levels
A	0.5560	0.5871	0.5127	0.0744	3	A2
B	0.6243	0.5590	0.4724	0.1519	2	B1
C	0.5702	0.5452	0.5403	0.0299	4	C1
D	0.7126	0.5360	0.4072	0.3053	1	D1

Table 4: Results of the ANOVA for GRG

Parameter	Sum of square (SS)	Degree of freedom	Mean square (MS)	F-test	% Contribution, P
A	0.025163	2	0.012581	3.65	4.06
B	0.104492	2	0.052246	15.17	16.87
C	0.004627	2	0.002313	0.67	0.75
D	0.422952	2	0.211476	61.38	68.30
Error	0.062012	18	0.003445	10.01	
Total	0.619246	26	100.00		

R-Sq = 89.99% R-Sq(adj) = 85.54%

value. The results of ANOVA are tabulated in Table 4. From the ANOVA table, it is concluded that the parameter feed rate (68.30 per cent) influences more on drilling of CFRP/Al/CFRP composites followed by drill diameter (16.87 per cent), drill type (4.06 per cent) and spindle speed (0.75 per cent) parameters. The feed rate influences more on the drilling conditions as per the ANOVA analysis matched the results with the Shunmugesh report. The SEM image of the drilled specimen is shown in Figure 5.

4.0 Conclusions

The current study demonstrates that contributing variables such as drill type, drill diameter, speed, and feed have an impact not only on productivity but also on delamination of machined components. Using an L27 orthogonal array. Experiments are planned and carried out on a CNC machine with solid carbide drills of various sizes, types including the speed and feed parameters on CFRP/Al/CFRP composite material to optimise the drilling parameters considering the thrust force, torque and delamination are the responses:

- The proposed Grey based Taguchi method is constructive in optimising the multi-responses. It is identified that the order of the machining parameters which contribute towards machining performance are feed, drill type, drill diameter and speed.
- Based on Grey relational analysis, the optimal process parameters obtained are drill type - Brad point drill, diameter - 4mm, speed-1250 rpm and feed - 0.05 mm/rev for drilling of CFRP/Al/CFRP composites.

The scope of future work is to fabricate the new composite materials with a new sequence of fiber materials along with metals and machining parameters for better applications in various areas such as the aviation sector. Using other hybrid optimization tools like Grey_ANFIS etc., for comparison of experimental and predicted values can be explored.

Conflicts of interest

The authors have no conflicts of interest to declare.

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