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Optimization of Drilling Parameters for Composite Materials using Taguchi Method

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Abstract: *Composite materials' heterogeneous and anisotropic nature renders drilling them very challenging and may lead to defects such as delamination, pull-out of fibers, and non-uniform surface finish. To improve hole quality and process performance, the present work addresses how drilling parameters for composite laminates can be optimized using the Taguchi approach. Spindle speed, feed rate, drill diameter, and percentage of fiber reinforcement are the key process parameters considered. An L9 orthogonal array is employed to evaluate each of these parameters at three levels. The "smaller-the-better" signal-to-noise (S/N) ratio criterion is applied to evaluate the performance metrics like thrust force, torque, surface roughness, and delamination factor.*

Results indicate that although drill diameter and reinforcing content contribute a secondary effect on thrust force and delamination, feed rate and spindle speed have a prominent effect.The predominance of feed rate in minimizing drilling-induced damage is substantiated through ANOVA analysis. Under ideal conditions, the confirmation experiment exhibits a perceptible improvement in surface finish and hole quality. This paper demonstrates that the Taguchi approach gives a direct, efficient, and statistically valid way of optimizing drilling parameters in the machining of composite materials..

Keywords: *Composite materials'*

I. INTRODUCTION

Due to their high mechanical, thermal, and chemical properties, composite materials are among the most significant engineering materials of today's era. Composite materials consist of two or more distinct phases, including a reinforcement and a matrix, that are combined in a manner that maintains each phase's specific properties while enhancing overall functionality[8]. Advantages of high specific strength, stiffness, and corrosion resistance of popular composites such as glass fiber reinforced polymer (GFRP), carbon fiber reinforced polymer (CFRP), and hybrid composites render them ideal for application in the automotive, aerospace, marine, and defense industries.The most widely used secondary process amongst all the various machining operations performed on composite parts is drilling, which is primarily used for joining, fastening, and assembling. But due to their anisotropic and non-homogeneous nature, composite laminates are very hard to drill[9]. Delamination, matrix cracking, fiber pull-out, spalling, and thermal degradation are often induced by the cutting process and significantly affect the mechanical integrity and the dimensional accuracy of the hole[7]. In addition, since composites respond differently to mechanical and thermal stresses compared to metals, the selection of appropriate drilling parameters is problematic.High thrust force and torque to drill are the primary issues due to their tendency to cause interlaminar separation, or delamination, especially around the hole entrance and exit[10]. These imperfections reduce the component's load capacity and fatigue strength. For improved surface quality, minimum delamination, and process stability, it is highly essential to maximize machining parameters like spindle speed, feed rate, drill diameter, and reinforcement content.

The correct process parameters through conventional trial-and-error approaches are not effective, costly, and take a lot of time. Conversely, statistical optimization methods provide a systematic and scientific approach to obtaining optimum conditions with minimal trial and error. Among these, perhaps the most well-known and effective optimization approach in manufacturing has proven to be the Taguchi approach to Design of Experiments (DOE). This

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method, developed by Dr. Genichi Taguchi, employs orthogonal arrays (OAs) to equilibrate multiple levels and factors in tests, ensuring efficient analysis with minimal trials[6]. The signal-to-noise (S/N) ratio is yet another performance stability and quality measure employed by the Taguchi method[5].

The method identifies parameter combinations that make the process robust against external disturbances or noise sources by selecting an appropriate S/N criterion, for example, "smaller-the-better" to minimize thrust force, torque, and surface roughness. Furthermore, the statistical significance and percentage contribution of each parameter are determined through Analysis of Variance (ANOVA), which provides a quantitative understanding of its effect on the output answers. The Taguchi optimization method is applied here to investigate drilling composite laminates.

The main objectives are:

- To study the effect of significant drilling parameters, including spindle speed, feed rate, drill diameter, and fiber content, on drilling performance;
- To Evaluate Quality Parameters Such as Delamination Factor, Surface Roughness, Thrust Force, And Torque;
- To Apply the Taguchi "Smaller-The-Better" Approach to Obtain the Optimum Combination of Parameters; And
- Ought to Employ Statistical Inference and Confirmation Tests to Confirm the Results.

Through providing an effective and inexpensive methodology for improving drilling performance of composite materials, this research intends to assist industries in boosting productivity, reducing material loss, and enhancing hole quality[1].

II. METHODOLOGY

Materials and Equipment: -

The Taguchi Design of Experiments (DOE) technique was employed in the experimental research to find out the optimum drilling parameters for composite materials[4]. Important process parameters are defined, appropriate values are selected, experiments are planned with an orthogonal array, drilling trials are conducted, output responses are gauged, and results are analyzed based on the Signal-to-Noise (S/N) ratio and Analysis of Variance (ANOVA). This approach ensures maximum precision and reliability of outcomes at the least experimental effort.

A Glass Fiber Reinforced Polymer (GFRP) composite laminate that was created by hand lay-up was the workpiece material utilized in the experiment[2]. The composite was made up of epoxy resin (LY556) with hardener (HY951) as the matrix and E-glass fiber mats as reinforcement. The laminates were allowed to cure at room temperature before being cut with a diamond saw into samples that measured 120 mm by 120 mm by 6 mm.
A vertical drilling machine with a dynamometer to record thrust force and torque was used for the drilling trials. Variable diameter High-Speed Steel (HSS) twist drills (3 mm, 6 mm, and 9 mm) were employed. A stereo microscope and image analysis software were used to analyze surface roughness and a surface profilometer to measure delamination[3].

Selection of Process Parameters and Levels: -

Based on preliminary experiments and literature review, four controllable process parameters were chosen:

Spindle Speed (A) – the rotational speed of the drill (rpm)
Feed Rate (B) – the rate of tool advancement (mm/rev)
Drill Diameter (C) – tool size (mm)
Fiber Reinforcement (%) (D) – weight percentage of fiber in the composite

Each parameter was varied at **three levels**, as shown in Table 1.

Parameter	Symbol	Level 1	Level 2	Level 3	Unit
Spindle Speed	A	1000	2000	3000	rpm
Feed Rate	B	0.05	0.10	0.15	mm/rev
Drill Diameter	C	3	6	9	mm
Fiber Reinforcement	D	0	5	10	wt.%

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Design of Experiments using Taguchi Method: -

The Taguchi method employs a special set of orthogonal arrays (OAs) to examine the entire parameter space in the minimum number of tests. For four factors at three levels, the L9 orthogonal array (3^4) with nine experimental runs was used. Without sacrificing statistical independence, this arrangement ensures balanced representation of each factor level.

Table 2: Taguchi L9 Orthogonal Array Design

Run	**A**	**B**	**C**	**D**
1	1	1	1	1
2	1	2	2	2
Run	**A**	**B**	**C**	**D**
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Each combination was executed once under identical conditions. The measured responses included **thrust force (N)**, **torque (N·mm)**, **surface roughness (µm)**, and **delamination factor (Fd)**.

Signal-to-Noise (S/N) Ratio Analysis:-

Signal-to-Noise (S/N) ratio, which measures a process's robustness against uncertainty or external environment disturbances, is applied in the Taguchi method to determine the suitability of process parameters. The optimal drilling parameters for reducing the measured responses such as thrust force, torque, surface roughness, and delamination factor were determined in this research based on the S/N ratio. The "smaller-the-better" criterion was applied to the computation of the S/N ratio since the purpose of this study was to reduce these reactions. By providing lower response values with higher S/N ratios, this criterion ensures higher performance and less variation. The mean S/N values for each level of each factor were next calculated after the S/N ratio for each test run in the L9 orthogonal array was determined from the measured data. The most desirable state for that parameter was determined by the level for the largest S/N ratio. The best combination of spindle speed, feed rate, drill diameter, and reinforcement percentage for reducing drilling-induced defects with the minimum amount of experimental effort was determined using this statistical approach.

Analysis of Variance (ANOVA):-

An Analysis of Variance (ANOVA) was performed on experimental data to explore in detail the statistical significance and relative importance of individual drilling parameters. By partitioning the total variation indicated by findings into parts attributed to each factor, ANOVA provides a quantitative measure of how varying input parameters influence output responses. To determine the contribution ratio and F-value of each factor, the sum of squares and mean squares were calculated using this research. The higher percentage contribution indicates the parameter effect on the response is more significant. The ANOVA results from this study revealed that the significant parameters that affected thrust force and delamination were feed rate and spindle speed, followed by drill diameter and fiber reinforcement quantity. Another advantage of the study was determining the factors that were statistically significant in a 95% confidence interval.

Lastly, a confirmation experiment was performed to determine the optimal parameter values based on S/N analysis. The outcome was a notable reduction in drilling forces and surface flaws, validating the effectiveness of the Taguchi optimization method.

III. RESULT & DISCUSSION

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The optimum drilling conditions and their corresponding influences on hole quality were conclusively identified by the analysis of Signal-to-Noise (S/N) ratios and analysis of Variance (ANOVA). To reduce the thrust force, torque, surface roughness, and delamination factor, the "smaller-the-better" S/N ratio analysis indicated that a combination of high spindle speed (3000 rpm), low feed rate (0.05 mm/rev), large drill diameter (9 mm), and high fiber content (10 wt.%) yielded the best results. ANOVA also confirmed that the feed rate was the most significant factor, having the largest statistical significance and contribution. Spindle speed ranked second, with drill diameter and percentage of fiber reinforcement having minimal effects.These are because greater spindle speed facilitates cleaner shear cutting, while the lower feed rate reduces interlaminar tensions and damage by reducing the uncut chip thickness and cutting pressures. The robustness and performance of the Taguchi optimization method were confirmed by the verification experiment conducted using this optimal parameter setting, which demonstrated significant improvement in surface finish as well as a substantial decrease in drilling-induced defects.

Table 3: Summary of Optimal Parameters and Factor Influence

Factor	Symbol	Optimal Level	Value	Rank of Influence
Spindle Speed	A	3	3000 rpm	2
Feed Rate	B	1	0.05 mm/rev	**1**
Drill Diameter	C	3	9 mm	3
Fiber Reinforcement	D	3	10 wt.%	4

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