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Parametric Study Of Delamination In Glass Fiber Reinforced Polymer (GFRP) Through Drilling

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***Abstract**:*
Machining processes play a crucial role in shaping, drilling, and contouring composite laminates for various product applications. Among these processes, drilling stands out as a fundamental method for attaching fasteners and assembling composite laminates. The inherent material anisotropy, arising from the fiber reinforcement, significantly impacts the machinability of these materials.
Even though most fibre-reinforced plastic (FRP) structures can be manufactured close to their desired shape, secondary machining processes like drilling are often necessary. It becomes essential to execute precise machining to ensure dimensional stability and enhance overall productivity.
In this study, we focused on drilling parameters and specimen-related factors, including cutting speed, feed rate, drill size, and specimen thickness. We conducted experiments using a TRIAC VMC CNC machining centre to machine composite laminate specimens, varying these parameters alongside material properties.
We employed a signal-to-noise ratio to assess the impact of different parameters on both peel-up and push-down delamination factors in drilling glass fibre-reinforced plastic (GFRP) composite laminates. Our primary objective was to identify the key factors and combinations thereof affecting delamination. To achieve this, we utilized Taguchi and response surface methodology to optimize machining conditions, minimizing delamination.
The analysis demonstrated that among all significant parameters, specimen thickness and cutting speed primarily influenced peel-up delamination, while specimen thickness and feed rate had a more pronounced effect on push-down delamination. To validate our predicted optimal parameters, confirmation experiments were conducted, showing a high level of agreement between predicted and experimental results, with an accuracy level of approximately 99%.
***Background**: In the realm of composite materials, such as Glass Fiber Reinforced Polymer (GFRP), understanding and mitigating delamination is crucial. Delamination, the separation of layers, can significantly impact the structural integrity of composites. This study delves into the intricate details of delamination in GFRP, employing drilling as a method of exploration. The research incorporates both experimental techniques and statistical analyses to comprehensively examine and comprehend the factors influencing delamination in GFRP composites.*
***Materials and Methods**: Composite specimens of this work were fabricated by applying hand lay-up method. The specimens were manufactured using ML 506 epoxy resin and unidirectional E-glass fibers.*
By employing the hand lay-up method, utilizing ML 506 epoxy resin, and integrating unidirectional E-glass fibers, the fabrication process aimed to produce composite specimens with tailored properties suitable for the subsequent drilling experiments. This detailed approach ensures the reliability and relevance of the materials used in the study.
***Results:** The interaction of speed, feed, and the number of fiber layers plays a crucial role in determining the delamination factor and thrust during drilling.*
Optimal combinations of these parameters are essential to minimize delamination and control thrust, contributing to the overall efficiency and quality of the drilling process in composite materials.
***Conclusion**: This research not only advances our understanding of the drilling process in composite materials but also provides valuable insights for practical applications. The findings emphasize the importance of tailored parameter selection to minimize delamination, optimize thrust, and enhance the overall quality and integrity of drilled composite structures. As we move forward, these insights will serve as a foundation for refining drilling practices and advancing the field of composite material fabrication.*
***Key Word**: Glass fiber reinforced epoxy(GFRP); Thrust; Delamination; Design of experiments; ANOVA.*

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I. Introduction

In the realm of composite material fabrication, the drilling process plays a pivotal role in shaping structural integrity and performance. This study delves into the nuanced interplay between key input parameters—speed, feed, and the number of fiber layers—and their consequential impact on two critical aspects: the delamination factor and thrust during drilling.

Composite materials, such as fiber-reinforced polymers, are renowned for their lightweight and high-strength properties. However, the drilling of these materials presents challenges, particularly concerning delamination—the separation of layers within the composite. The parameters of speed and feed, representing the rotational speed of the drill bit and the rate of advancement into the material, respectively, have been identified as influential factors in the drilling process. Additionally, the number of fiber layers within the composite structure adds a layer of complexity, requiring a comprehensive exploration of its impact on drilling dynamics.

The delamination factor, a quantitative measure of layer separation within the material, serves as a crucial indicator of the drilling process's success. Understanding how variations in speed, feed, and the number of fiber layers contribute to the delamination factor is essential for refining drilling practices and optimizing the fabrication of composite structures.

Simultaneously, the study addresses thrust, the axial force experienced by the drill bit during drilling. The relationship between speed, feed, the number of fiber layers, and thrust provides insights into the overall forces acting on the drilling apparatus, offering a comprehensive perspective on the efficiency and control of the drilling process.

As we embark on this exploration, the findings are poised to not only advance our understanding of drilling in composite materials but also contribute practical insights for optimizing parameters to minimize delamination and enhance thrust. Through this comprehensive analysis, we aim to pave the way for improved drilling practices, ensuring the continued progress and reliability of composite material fabrication.

II. Material And Methods

Composite Specimen Fabrication:

The process initiates with a meticulous selection of materials. For this study, the chosen composite specimens are fabricated using the hand lay-up method.Two primary materials are carefully chosen:ML 506 Epoxy Resin: Selected for its documented performance and compatibility . Unidirectional E-Glass Fibers: Chosen for their reinforcing properties.

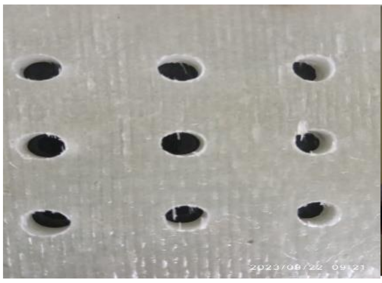

Figure:1. Glass fiber epoxy specimen   Figure2&3Vertical CNC Drilling machine

Drilling of GFRP materials:

The machine of GFRP is quite different from that of metals and results in many undesirable effects such as rapid tool wear, rough surface finish and defective subsurface layers caused by cracks and delaminations. At the beginning of the drilling operation, the thickness of the laminated composite materials can withstand the cutting force and as the tool approaches the exit plane, the stiffness provided by the remaining plies may not be enough to bear the cutting force, causing the lamina to separate result in delamination. The delaminations that occur during drilling severely influence the mechanical characteristics of the material around the hole. In order to avoid these problems, it is necessary to determine the optimum conditions for a particular machine operation. Drilling is a particularly critical operation for fiber-reinforced plastics (FRP) laminates because the great concentrated forces generated can lead to widespread damage. The major damage is certainly the delamination that can occur both on the entrance and exit sides of the work piece [4]. The delamination on the exit surface, generally referred to as push down delamination, is more extensive, and is considered more severe. Hocheng and Tsao have beautifully explained the causes and mechanisms of the formation of these push-down delaminations and they have also reasoned out the dependence of extent of delamination on the feed rate [5]. In earlier studies it has been observed that the extent of delamination is related to the thrust force feed, material properties and speed, etc. and that there is a critical value of the thrust force (dependent on the type of material drilled) below which the delamination is negligible [6]. Attempts have been made to model these delaminations considering the axial thrust and that causes in many early investigations and an analytic model proposed to evaluate the critical thrust force is available.

In the existing literature [7], a theory proposed by Jain and Yang has been presented, which considers the material's anisotropy and suggests that cracks take on an elliptical shape [8]. Their research also highlighted that the load on the drill point is primarily attributed to the chisel edge, while the contribution of the cutting lips in the axial thrust direction is minimal.

Similar models have been developed for carbon-fiber composites [9,10], demonstrating a relationship between the size of the delamination zone and the thrust force generated during drilling. These studies introduced the concept of a 'critical thrust force' below which no damage occurs [11,12]. However, there was a need for a comprehensive study that simultaneously considers multiple variables, which prompted the current research.

Recognizing that the critical force responsible for delamination is influenced by factors such as feed rate, spindle speed, tool diameter, and material thickness, our study aimed to investigate the combined effects of these parameters. The present work outlines a methodology for optimizing process parameters during the drilling of glass fiber-reinforced polyester to minimize delamination damage. To achieve this, we employed experimental design techniques following the Taguchi method and conducted an analysis of results using ANOVA.

Configuration of Experimental Setup and Machining Parameters:

To create the GFRP specimens, a high-strength E-glass chopped fiber mat was employed as the reinforcement material in combination with polyester resin. The resulting laminate slabs were designed to have dimensions of 100 mm × 100 mmX3. The E-glass used in the fiber mat had a modulus of 72.5 GPa and a density of 2590 kg/m3. The polyester resin chosen for this process possessed a modulus of 3.25 GPa and a density of 1350 kg/m3. The specimens were prepared using a contact molding process, where the required numbers of fiber mats were stacked to achieve the desired thickness and fiber volume fraction. The final fiber volume fraction was determined to be 0.60 using the weight loss method.

Drilling set-up:

The carbide-coated drills bits used in the experiments was 6mm diameter. Dry drilling tests were conducted on CNC TRIAC VMC machining center supplied by Denford, UK. The instrumentation consisted of a force–torque strain gauge drilling dynamometer, fixture, and an amplifier, connecting cables, and an A/D converter a PC for data acquisition. The laminate composite specimen was held in a rigid fixture attached to the dynamometer, which is mounted on the machine table. The experimental set-up is as shown by the schematic in Fig. 2&3.

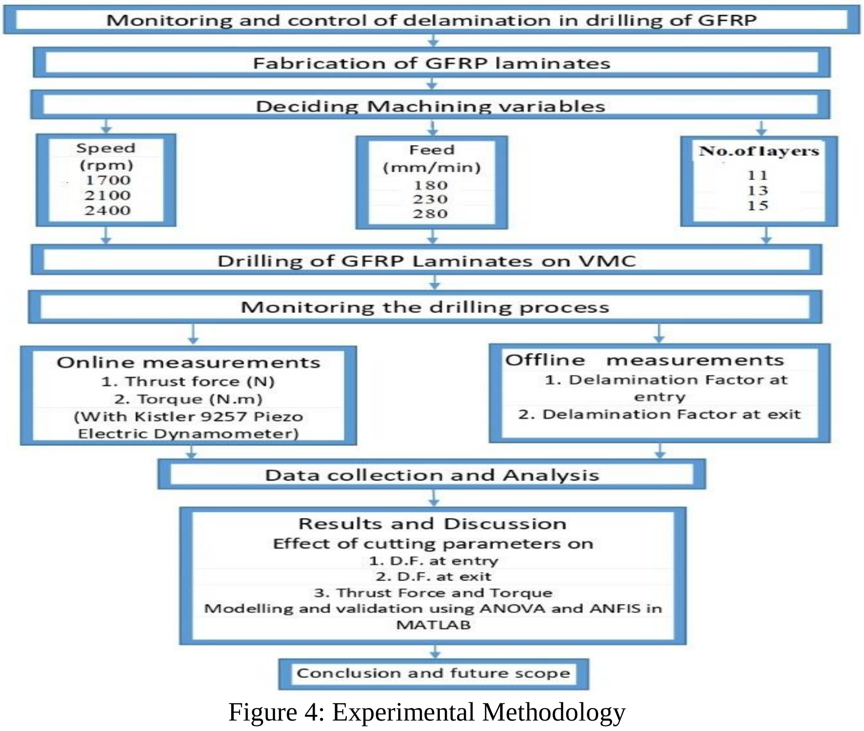

Figure 4: Experimental Methodology

Table 1 Levels of the variables used in the experiment.

Sr no	Level1	Level2	Level3
	Cutting Speed in rpm	No.of layers	Feed rate in mm/min
1	1700	11	180
2	2100	13	230
3	2400	15	280

Experimental Design

The design of experiments is a powerful analytical tool used to model and understand the impact of process variables on a specific outcome, which is often an unknown function of these variables. A crucial step in the design of experiments is the selection of control factors. It is advisable to include as many process variables as possible to identify the most significant ones early in the analysis. In this experiment, we employed a full factorial design with four factors, each having four levels. Table 1 provides detailed information about the variables utilized in the experiment. It's important to note that the primary focus of this work is not an in-depth analysis of the variability associated with these parameters.

The Taguchi Method

Robust design is an engineering approach aimed at obtaining product and process conditions that are minimally sensitive to various sources of variation. The goal is to produce high-quality products while minimizing development and manufacturing costs [13]. Taguchi's parameter design is a crucial tool within robust design, offering a systematic approach to optimizing design for performance, quality, and cost. It combines experimental design theory with the concept of the quality loss function, providing solutions to complex manufacturing problems.

To assess the degree of influence of control factors (feed rate, spindle speed, drill diameter, and workpiece thickness) in drilling, we considered four factors, each with four levels, using a full factorial design. Taguchi defines product quality in terms of the loss incurred by society from the time the product is shipped to the customer. Some of these losses result from deviations in the product's functional characteristics from their desired values, termed losses due to functional variation. Noise factors, which are uncontrollable factors causing functional characteristic deviations, can include external factors like temperature and human factors. Quality engineering aims to create products robust to all noise factors.

The Taguchi method utilizes special orthogonal arrays to explore the entire parameter space with a minimal number of experiments. The results are then transformed into a signal-to-noise (S/N) ratio. Taguchi recommends using the S/N ratio to measure the deviation of quality characteristics from desired values. A higher S/N ratio indicates better quality characteristics [14]. Therefore, the optimal process parameter levels correspond to the highest S/N ratio. Additionally, statistical analysis of variance (ANOVA) is conducted to identify statistically significant process parameters. The optimal combination of process parameters is predicted using S/N and ANOVA analyses. Finally, a confirmation experiment is conducted to validate the optimal process parameters obtained from the parametric design.

The Taguchi method provides a systematic and efficient approach for optimizing process parameters, emphasizing the use of the S/N ratio and ANOVA analyses. The final confirmation experiment ensures the practical applicability and reliability of the identified optimal process parameters.

Table 2 Observation table

Sr no.	Cutting Speed in rpm	Feed rate in mm/min	Glass Fiber : Epoxy	Average Thrust force in N	Average Delamination factor Fd at entry	Average Delamination factor Fd at exit
1	1700	180	11	48.01	1.22	1.26
2	1700	180	13	48.41	1.38	1.33
3	1700	180	15	50.62	1.46	1.38
4	1700	230	11	66.53	1.83	1.31
5	1700	230	13	66.81	1.89	1.36
6	1700	230	15	88.23	1.92	1.39
7	1700	280	11	69.82	1.68	1.15
8	1700	280	13	76.95	1.73	1.28
9	1700	280	15	89.23	1.79	1.31
10	2100	180	11	53.42	1.32	1.27
11	2100	180	13	54.23	1.39	1.31
12	2100	180	15	58.00	1.41	1.36
13	2100	230	11	68.58	1.30	1.38
14	2100	230	13	71.31	1.34	1.39
15	2100	230	15	73.26	1.39	1.42
16	2100	280	11	66.31	1.71	1.69
17	2100	280	13	65.68	1.75	1.70
18	2100	280	15	71.8	1.80	1.73
19	2400	180	11	56.23	1.21	1.23
20	2400	180	13	58.26	1.25	1.26
21	2400	180	15	60.52	1.36	1.30
22	2400	230	11	69.24	1.70	1.42
23	2400	230	13	72.67	1.72	1.41
24	2400	230	15	78.31	1.74	1.48
25	2400	280	11	87.11	1.68	1.54
26	2400	280	13	91.63	1.72	1.59
27	2400	280	15	98.25	1.81	1.62

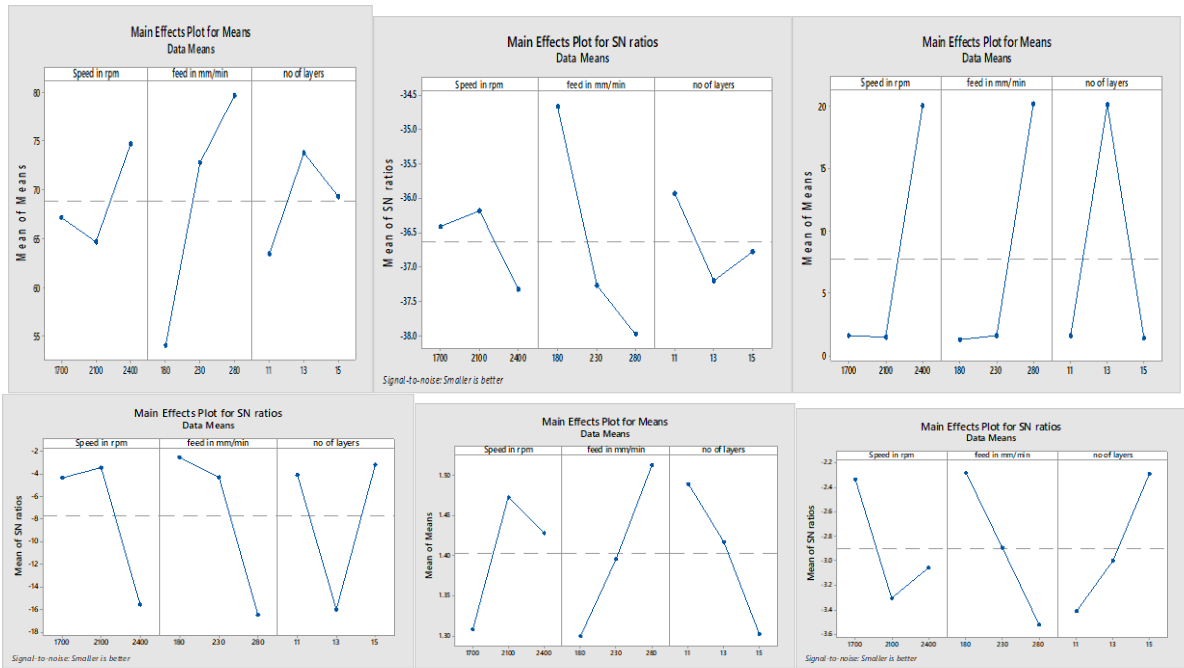

Figure 5: Main effects plots for minimizing Thrust, delamination at entry and exit.

Figure 5 explain as Main effects plots for minimizing Thrust, delamination at entry and exit" is a visual tool that provides a comprehensive overview of how variations in speed, feed, and the number of fiber layers influence the critical factors of thrust and delamination at entry and exit points in the drilling process.

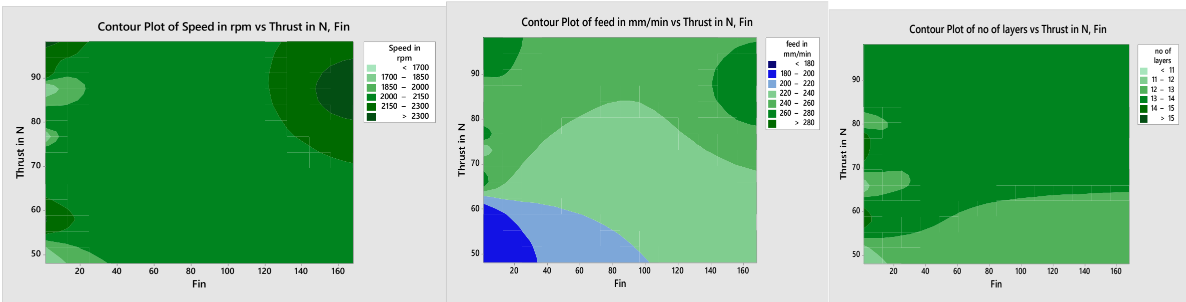

Figure 6: Contour plots for minimizing Thrust, delamination at entry and exit.

Figure 6 explain as Contour plots for minimizing Thrust, delamination at entry and exit" offers a visual tool for understanding the complex interactions between multiple factors and their combined influence on thrust and delamination during the drilling process. Researchers and practitioners can use these plots to make informed decisions about the optimal settings for various parameters in order to achieve the desired outcomes in composite material drilling.

III. Result

Optimal Settings for Optimization:
Speed: 1700 rpm
Feed: 180 mm/min
Number of Layers: 14
Objective: Minimizing thrust and delamination at entry and exit points.

Interpretation: The provided values represent the optimal settings identified through the optimization plot for achieving the desired outcomes in the drilling process. These settings indicate that, according to the experimental or analytical findings, the most favourable conditions for minimizing thrust and delamination involve the following:
Speed (Rotational Speed): Set to 1700 rpm.
Feed (Rate of Advancement): Set to 180 mm/min.
Number of Layers: 14 layers in the composite structure.

Implications:

These optimal settings are the result of a comprehensive analysis that considers the interplay of speed, feed, and the number of layers.The selected values aim to strike a balance between minimizing thrust on the drill bit and reducing the occurrence of delamination at both entry and exit points during the drilling process.

Implementation of these settings is expected to enhance the efficiency and quality of the drilling process in the context of composite material fabrication. Further Considerations:It's important to note that these optimal settings are specific to the study or experiment from which they were derived.

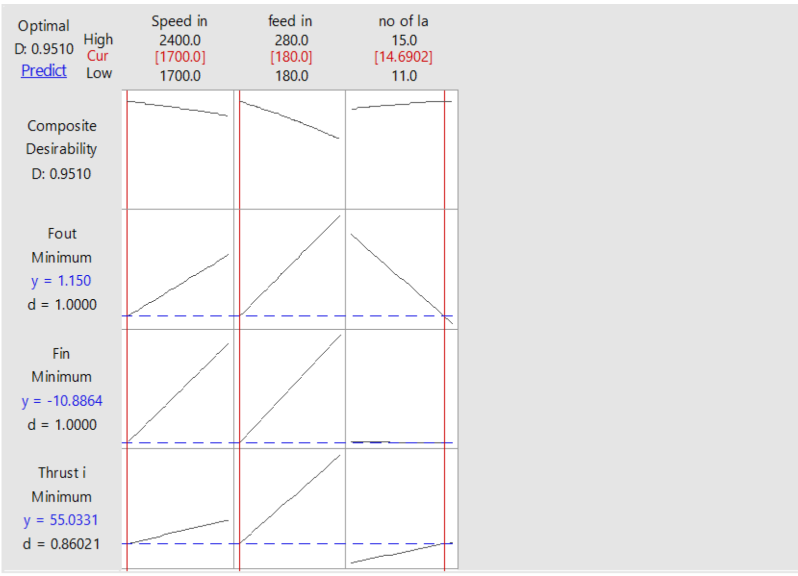

Figure 7. Optimization plot

Figure 7 explains that the optimization plot is often generated using mathematical algorithms that explore the design space and identify the optimal point. Optimization algorithms aim to efficiently navigate the parameter space to find the combination that maximizes or minimizes the response variable.

An optimization plot is a visual tool that aids researchers in understanding how different combinations of input parameters influence the desired outcome, allowing for the identification of optimal conditions within the experimental design space.

IV. Discussion

1. Speed (1700 rpm):

Implications: The choice of 1700 rpm for the rotational speed suggests that, within the given experimental context, this speed is optimal for achieving the desired outcomes.

2. Feed (180 mm/min):

Implications: A feed rate of 180 mm/min is identified as the optimal setting. This value indicates the rate at which the drill advances into the material, and it is chosen to minimize thrust and delamination.

3. Number of Layers (14):

Implications: The optimal number of layers for the composite structure is identified as 14. This suggests that, under these experimental conditions, this specific layering configuration contributes to minimizing thrust and delamination.

Overall Optimization:

The combination of the specified speed, feed, and number of layers represents an optimized set of parameters that aims to achieve a balance between minimizing thrust on the drill bit and reducing delamination at entry and exit points during drilling.The optimization results provide valuable guidance for practical applications, offering insights into how drilling conditions can be tailored to enhance efficiency and quality in composite material fabrication.

V. Conclusion

The discussion highlights the significance of the identified optimal settings and emphasizes the need for a thoughtful and practical application of these values. Ongoing research and experimentation will further refine and expand our understanding of optimal drilling conditions in the context of composite materials.

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