Eng. Sci., 2022, **19**, 312–318

Engineered Science

DOI: https://dx.doi.org/10.30919/es8d733

Experimental and Statistical Evaluation of Drilling induced Damages in Glass Fiber Reinforced Polymer Composites – Taguchi integrated Supervised Machine Learning Approach

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Abstract

Glass-reinforced polymer (GFRP) composites are gaining on its usage in various sectors. The drilling of GFRP composite is an inevitable machining operation. The anisotropy feature of the polymer composite makes it little difficult-to-machine material. The drilling of GFRP composite is accompanied by delamination damage. Moreover, the quality of the drill, characterized by the hole's surface roughness is also an important response variable to consider. The effect of Feed and drilling speed has been always focused on by several researchers, to minimize the damages caused during the drilling of GFRP composites but very few have considered the drill tool geometry as an affecting parameter. The present study, thus, investigates the effect of drill tool geometry along with drilling speed and feeds on the delamination damage and surface roughness of the drilled hole. The study indicates that drill geometry has the highest significance on the damages considered in the study and contributes more than 75% towards the variance. The supervised learning approach, in terms of linear regression, is used in the present work to determine the predicting models for the obtained data. The mathematical models developed using the machine learning approach possess a high degree of fitness with all three R^2 values being more than 90%.

Keywords: Drilling; Polymer composites; Regression; Supervised Learning.

Received: 13 April 2022; Revised: 29 May 2022; Accepted: 02 June 2022.

Article type: Research article.

1. Introduction

Due to their high strength and stiffness, fiber-reinforced polymer (FRP) composites are used in the automotive, aerospace, railway, marine, and construction industries.[1,2] Due to the inhomogeneity, anisotropy, and laminated structure of FRP composite materials, their machining becomes extremely complex. As the application spectrum broadens, the requirement for various machining operations, particularly drilling, to assemble various FRP components into a product has increased significantly.[3,4] The laminate thickness is sufficient to withstand the cutting forces at the start of the drilling operation. However, as the operation progresses toward the exit plane of the laminate, the thickness decreases to the point where the laminate is no longer able to withstand the cutting force, resulting in the separation of lower layers from upper layers (delamination phenomenon).[5] The delamination phenomenon is a significant issue when drilling holes in composite materials.[6,7] It occurs on both the entry and exit planes of the workpiece and weakens the complete assembly.[8] Delamination can be attributed to various drilling operation parameters, including feed rate, spindle speed, and cutting tool geometry. It can thus be minimized, if not eliminated, through parametric optimization and rigorous experimentation.[9] The surface roughness of the drilled hole is another critical factor to consider when drilling FRP composites. It has attracted the attention of several researchers because it is typically used to determine the final product's quality.[10] Additionally, the surface roughness of the drill hole has a significant effect on the assembly tolerance and can be minimized yet again by parametric optimization

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like that of delamination.[11,12] The surface roughness of the drilled hole is a critical design parameter that influences precision fit, fastener load, and fatigue load. Along with tolerance, proper selection of the cutting parameter is a critical precondition for surface roughness control.[13]

Several researchers have focused on optimizing delamination[9,14-22] and surface roughness[10,23-30] damages in the past decade for different parameters and levels of the selected parameters. Several researchers have focused on drilling speed, feed, and drill tool geometry to minimize the above-mentioned-induced damages.[9] Hocheng and Tsao investigated the effect of drill tool geometry along with feed and speed on the delamination damages. The authors in their study utilized a saw drill, candlestick drill, core drill, and step drill.[31] Davim *et al.* studied the effect of speed and feed while using two different drill geometries (helical flute stub length drill and Brad and spur drill) to achieve a better surface finish of the drilled hole minimizing the delamination damage.[32,33] Liu *et al*. indicated a significant effect of drill tool geometry along with the feed and drilling speed while drilling the glass fiber reinforced polymer (GFRP) composite samples with a twist drill and a candlestick drill.[9,34] Kumar *et al.* emphasized that unconventional drill tool geometries and materials give better results concerning drill-induced damages.[35] Similarly, Thakur *et al*. concluded with their detailed comprehensive literature review that special drill geometries facilitate minimized damages.[36] The widely reviewed literature indicates that the process parameters (feed and speed) and the tool geometry (drill types) significantly affect the drilling-induced damages in the FRP composites. Thus, the present study investigates the effects of three different drill geometries on the delamination and drilled hole surface roughness for a selected range of feed and drilling speed values. The study utilizes the Taguchi approach to decide the experimental design and analyze the effects of selected process parameters and drill geometry. Linear regression, a supervised learning approach concerning machine learning, is later used to develop mathematical models for predicting damages within the selected experimental limits for each drill geometry.

2. Material and methods

Figure 1 represents the schematic representation of the undertaken work. The hand lay-up technique is used to create the GFRP laminate. A laminate is formed by stacking 13 layers of woven roven glass fiber in the zero-degree stacking order. The fiber volume fraction of the prepared laminate is 58.63 %. The laminate is prepared using epoxy (LY566) resin and 5200 hardeners. Atul Industries Ltd., of Gujarat, India, provided the resin and hardener. 200 × 200 mm laminates with a thickness of 4 mm were prepared. Drilling specimens were cut to an 80 mm × 120 mm size. The drilling operations were carried out in the computer-numerically controlled ACE vertical machining center. Each of the nine holes drilled was with a new drill bit to prevent the effect of the tool wear on the damange mechanism. The GFRP plates were well-clamped in place to prevent vibration and displacements during the drilling process.

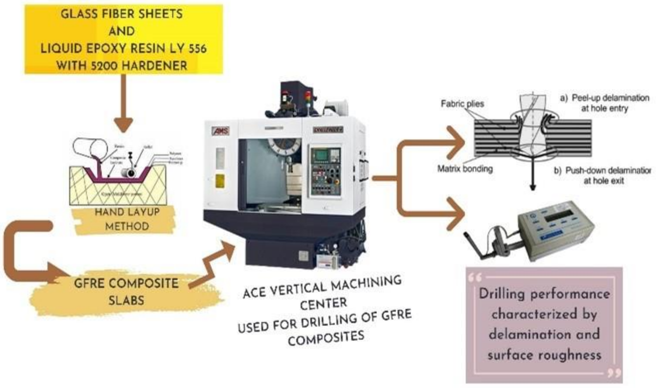

Fig. 1 Schematic representation of the present study.

The independent variables are drilling speed (rpm), feed (mm/rev), and drill geometry, where drilling speed and feed are treated as continuous variables and drill geometry is treated as a categorical variable. Due to the fact that three distinct types of drills are considered, and the experimentation includes three different levels of drilling speed and feed, the L9 orthogonal array Taguchi design is used as the experimental design. Table 1 provides the details of the variables and the respective levels.

To quantify the delamination factor, a dimensionless numeric value, images of the drilled specimens were taken with the CANON EOS 1200D and imported into AUTOCAD 2019, where the required diameter values at the damaged zone were determined. The delamination factor is determined using Chen's one-dimensional model, a widely used procedure for enumerating delamination. Equation 1 mathematically represents Chen's model, where ‘F_d’ denotes the one-dimensional delamination factor, ‘D_{max}’ denotes the maximum diameter of the delaminated zone, and ‘d’ denotes the diameter of the drilled hole.

$$F_d = \frac{D_{max}}{d} \tag{1}$$

The surface roughness of the drilled holes is quantified using the arithmetic mean value, R_a, in µm. The measurement was accomplished using the Taylor Hobson Surtronic 3+ instrument. Five readings for each hole were measured to reduce the variance effect and the average roughness was treated as the final value for each experimental combination. Equation 2 represents a mathematical form of determining the

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Table 1. Variables and respective levels were used in the present study.

S. No	Variable	Symbol	Unit	Type	Level (1)	Level (2)	Level (3)
1	Drilling speed	S	rpm	Continuous	500	1000	1500
2	Feed	F	mm/rev	Continuous	0.02	0.06	0.10
3	Drill geometry	DG	---	Categorical	Twist	Slot	Spur

final R_a value.

$$\sum_{i=1}^{5} R_{a_i} = R_a \qquad (2)$$

Linear regression, a known basic type of supervised machine learning approach is used to investigate the effect of each predictor in detail and develop the mathematical models, capable of predicting the delamination damage and the drilled hole surface roughness values concerning each drill type for the known values of feed and drilling speed.

3. Results and discussion

Table 2 details all nine experimental combinations and the respective values of the response variables recorded in the present study. Tables 3 and 4 provide the result of linear regression-based analysis of variance (ANOVA) for surface roughness and delamination damage respectively.

The drill geometry followed by the drilling speed is seen to have a significant effect on the response variables. In contrast, the feed is seen to be an insignificant factor and thus, the investigation concerning feed is neglected in the further portion of the study. To analyze in detail the influence of grill geometry and speed, the main effect plots are depicted in Figs. 2 and 3. Figs. 2(a) and 2(b) illustrates the main effect plots for surface roughness versus drill geometry and drilling speed respectively. Similarly, Figs. 3(a) and 3(b) illustrates the main effect plots for delamination versus drill geometry and drilling speed respectively.

It has been determined that the drill geometry has the strongest influence on delamination and surface roughness, as

Table 2. Response variable values were recorded for the nine experimental combinations.

Trial No.	Drill Geometry (DG)	Drilling Speed (S) rpm	Feed (F) mm/rev	Surface Roughness (R_a) µm	Delamination (F_d)
1	Twist	500	0.02	4.48	1.482
2	Twist	1000	0.06	3.68	1.457
3	Twist	1500	0.10	3.59	1.393
4	Slot	500	0.06	2.26	1.281
5	Slot	1000	0.10	2.00	1.257
6	Slot	1500	0.02	1.48	1.207
7	Spur	500	0.10	3.20	1.441
8	Spur	1000	0.02	2.55	1.354
9	Spur	1500	0.06	1.96	1.347

Table 3. Regression-ANOVA results for surface roughness of the drilled hole.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Regression	4	7.67013	98.26%	7.67013	1.91753	56.46	0.001
S	1	1.41349	18.11%	1.41349	1.41349	41.62	0.003
F	1	0.01256	0.16%	0.01256	0.01256	0.37	0.576
DG	2	6.24409	79.99%	6.24409	3.12204	91.92	0.000
Error	4	0.13586	1.74%	0.13586	0.03396		
Total	8	7.80599	100.00%				

Table 4. Regression-ANOVA results for the delamination damage.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Regression	4	0.071281	98.40%	0.071281	0.017820	61.55	0.001
S	1	0.011062	15.27%	0.011062	0.011062	38.21	0.003
F	1	0.000400	0.55%	0.000400	0.000400	1.38	0.305
DG	2	0.059819	82.58%	0.059819	0.029909	103.31	0.000
Error	4	0.001158	1.60%	0.001158	0.000290		
Total	8	0.072439	100.00%				

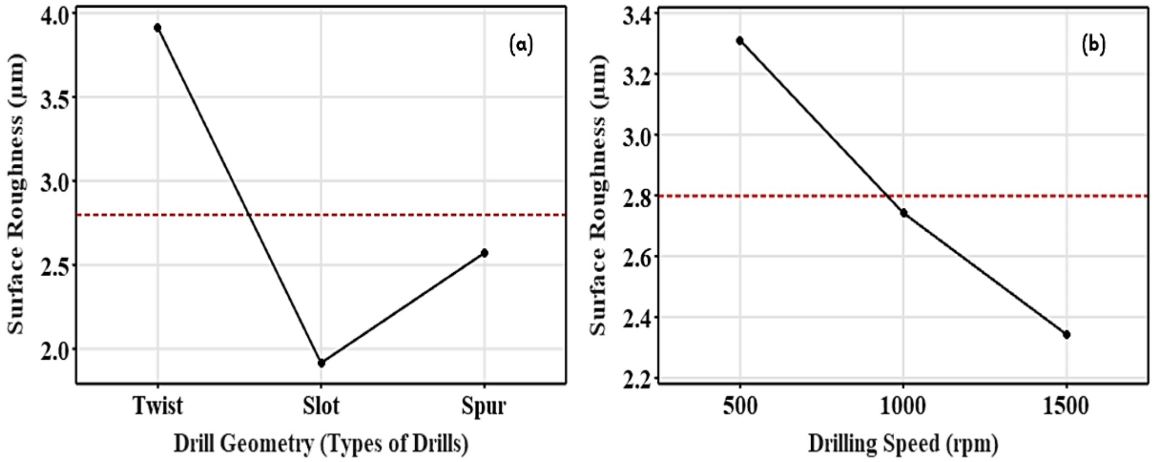

Fig. 2 Main effect plots: (a) surface roughness versus drill geometry; (b) surface roughness versus drilling speed.

it is the most influential factor in composite drilling performance.[37] Several researchers have demonstrated, to date, that a change in tool geometry, or the use of different types of drill bits, makes a discernible difference in drill-induced damage to composites.[31,38,39] Accordingly, the results of this experiment are congruent with those of earlier research, as 79.99 and 82.58% of the variance in surface roughness and delamination damage is attributed to drilling geometry. The wear rate of the tool and the thrust force created during the machining process at the tool-material contact area are the primary causes of variance in damage caused by a change in drill geometry.[40–43]

The statistical examination of both of the aforementioned damages suggests that the slot drill is the best of the three drill bits. This is because, unlike other drill bits, the slot drill has just two peripheral cutting edges that come into contact with the workpiece material throughout the drilling process. In addition, the slot drill makes a smaller indentation than other drill bits.[44] Therefore, the thrust force generated during drilling is less. In addition, the slot drill is observed to have a substantial clearance, which facilitates the easier and quicker removal of machined chips, hence enhancing the drilling performance. Regarding the effect of drilling speed, it is observed that regardless of drill geometry, higher speeds have been advantageous. At a speed of 1500 rpm, both the surface roughness of the drilled holes and the drill-induced delamination damage are observed to be less intense than at a speed of 500 rpm. This finding is consistent with previous research by Lin and Chen,[45] who reported a reduction in cutting force developed at higher drilling speeds, resulting in a decrease in drill-induced damages. The increased drilling speed also causes thermal softening and a decrease in the interfacial strength of the composite.[46] In addition to reducing thrust force, thermal softening facilitates drilling, improves drilling performance, and inhibits the fiber pullout phenomenon. Thermal softening in composites refers to the transformation of the matrix material into lump masses together with the fibers.[47] However, a thorough investigation of the thermal softening and lump mass formation of matrix material is not within the scope of the present study and can therefore be considered an extension. Moreover, system dynamics has proven to be one of the best data-driven approaches for a more in-depth investigation of the thrust force developed due to variations in the selected input parameter over the past decade,[48–51] and thus could be considered as a potential extension of the present work to gain additional insights into the findings.

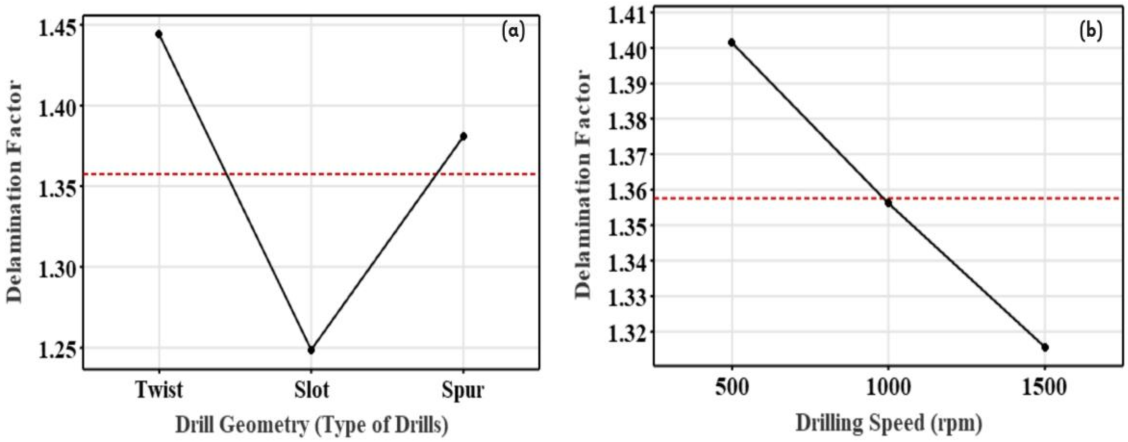

Fig. 3 Main effect plots: (a) delamination versus drill geometry; (b) delamination versus drilling speed.

Regression analysis is further used to develop mathematical models with the ability to predict the damages for a given drill geometry at various drilling speeds and feed. Equations 3, 4, and 5 represent the mathematical model for predicting the surface roughness for a given drill geometry and Equation 6, Equation 7, and Equation 8 represent the mathematical model for predicting the delamination damages.

$$Ra_{twist} = 4.816 - 0.000971\,S + 1.14\,F \qquad (3)$$

$$Ra_{slot} = 2.815 - 0.000971\,S + 1.14\,F \qquad (4)$$

$$Ra_{spur} = 3.417 - 0.000971\,S + 1.14\,F \qquad (5)$$

$$F_{D\,twist} = 1.5176 - 0.000086\,S + 0.204\,F \qquad (6)$$

$$F_{D\,slot} = 1.3219 - 0.000086\,S + 0.204\,F \qquad (7)$$

$$F_{D\,spur} = 1.4542 - 0.000086\,S + 0.204\,F \qquad (8)$$

The developed model for both surface roughness and delamination has not only a high R^2 value but also a very low difference between adjusted R^2 and predicted R^2, which infers a high degree of fit. The R^2, adjusted $R^{2,}$ and predicted R^2 values concerning the regression models for surface roughness are 98.26, 96.52, and 91.34% respectively and for delamination, they are 98.40, 96.80, and 90.89, respectively. Similar to the results indicated by main effect plots, the equations obtained using regression modeling indicate that surface roughness irrespective of the drill tool used decreases with the increase in the speed value. The constant term is the least in the case of the surface roughness equation for the slot drill, which indicates that the finish is best for the holes when the slot drill bit is used. Similarly, considering the delamination damage, with the increase in the speed, the delamination reduces. Moreover, the least value of constant for slot drill, again proves it to be the best drill geometry of the three. The regression analysis mathematical model results thus agree with the experimental observations.

4. Conclusions

Glass fiber-reinforced polymer composites were fabricated using epoxy as the resin and woven roving glass fiber as the reinforcing material. Both delamination and surface roughness were measured to represent the drilling performance of the selected glass fiber-reinforced epoxy (GFRE) composites. The drilling operations were carried out using different drill geometries obtained by varying the drill types at three different levels of drilling speed and feed. The slot drill is determined to be the best option of the selected types as it proved to yield minimal damage to the GFRE composite during drilling. The reduction of damage with the use of a twist drill was because of the reduction in the development of thrust force resulting from its simple tool geometry compared to twist and spur drill bits. The tool geometry followed by the drilling speed proved significant effect on both the selected response variables, whereas the feed proved to be insignificant within the experimental limits. The regression models developed are also in agreement with the statistical analysis. Moreover, the models developed exhibited very high values of R^2, adjusted $R^{2,}$ and predicted R^2, representing high goodness of fit and accuracy of prediction.

Conflict of Interest

The authors declare no conflict of interest.

Supporting information

Not applicable.

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