Minimizing Push-out Delamination in Glass Fiber Reinforced Polyester Using RSM

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Abstract

Delamination of glass fiber reinforced polymer (GFRP) was studied using face centered central composite design (CCD) of Response Surface Methodology (RSM). The parameters investigated were drill diameter (4.5-11.5mm), speed (580-1420rpm) and feed rate (83-167mm/min). Mathematical models were developed and verified with confirmation runs. The statistical significance of main parameters and their interactions were determined using Analysis of Variance (ANOVA). Drilling of GFRP was performed using a CNC machine under dry conditions. The results showed that feed rate and speed were significant in influencing the formation of push-out delamination. Delamination occurs least when speed is high and feed rate is low.

Keywords: Glass Fiber Reinforced Polymer; Push Out Delamination; Dry Drilling Parameters; Response Surface Methodology; ANOVA.

1. Introduction

Fiber reinforced polyester (FRP), commonly used to construct aircraft bodies or ships, is widely used in making a wide range of products such as rocket launchers, windmill blades, VHS trains, automobiles and sports equipment. Due to its excellent physical properties, it now finds applications in civil engineering, such as in the making of pipes due to their simple geometry. Glass fiber reinforced polymer (GFRP), one common type of FRP, is also widely used in various industries because of its excellent physical and mechanical properties such as high specific strength, high specific stiffness, excellent fatigue performance, light weight, good corrosion resistance and low thermal expansion (Abrao et al., 2007, Rubio et al.,2008, Connor and Zelen, 1959, Gaitonde et al., 2008, Hocheng and Dharan 1990, Hocheng and Tsao, 2003, Mohan et al., 2007, ,Tsao and Hocheng, 2004). Despite its apparent advantage, GFRP is difficult to machine. Delaminating is one of the major concerns when drilling holes in GFRP, resulting in reduction of its strength and fatigue life, which in turns compromises the material usefulness. Therefore, in this study, glass fiber reinforced polyester (GFRP) is fabricated in FET, Multimedia University (El-Tayeb et al., 2006 and El-Tayeb et al., 2008) and the holes of different diameters are drilled on the GFRP using different speed and feed rates to identify optimum parameters to eliminate or reduce delamination.

Delamination happens easily when drilling holes in composite materials, especially when the top and bottom surfaces of work piece are exposed (Rubio et al.,2008 and Mohan et al., 2007). In addition to reducing structural integrity of the laminate, delamination also results in poor assembly tolerance and long term performance deterioration (Connor and Zelen, 1959, Hocheng and Dharan, 1990, Jain and Yang, 1994, Marques et al., 2009, Tsao and Hocheng, 2004, Tsao and Hocheng, 2008). According to statistics, it is estimated that drilling-associated delamination accounts for 60% of all part rejections during final assembly of an aircraft in the aircraft industry (Montgomery, 2005).

Delamination is a mode of failure in composite materials which causes the laminates to separate. This leads to the forming of a mica-like structure of separate layers, reducing the mechanical of toughness of the material. There are several types of delamination that can occur during drilling. However, two distinguishable types of delamination, namely peel-up and push-out delamination, are common. The earlier occurs at the entrance of the drill hole while the latter occurs at the exit plane of the material. The damage caused by the push-out delamination is more extensive and is considered severer (Connor and Zelen, 1959). During drilling, the drill exerts a compressive thrust force on the work material. The laminate under the drill tends to be drawn away from the inter-laminar bond around the hole. Thus, as the drill approaches the end of the hole, the uncut thickness becomes lesser and hence the resistance to deformation decreases.

This type of delamination is known as push-out delamination. At a certain point the loading exceeds the inter-laminar bond strength and causes delamination to occur. On the other hand, the peel-up delamination occurs during initial stages where the cutting edge of the drill abrades the laminate. Subsequently, once the drilling starts, the abraded material is pulled away along the flute causing the material to spiral up. This action introduces an upwards peeling force to separate the upper laminas from the un-cut portion of the material held by the downward acting thrust force. The force acting in the tangential direction is the thrust force for delamination. A peeling force in the axial direction is generated through the slope of the drill flute and is a function of tool geometry and friction between the work piece and the tool. In push-out delamination, the damage depends on the nature of fibre but also on the resin type and respective properties since it occurs in the inter-laminar region. Whereas, the peel-up delamination only occurs during the beginning stages of drilling, owing to the fact that delamination gradually becomes difficult as the drilling proceeds and the thickness resisting the lamina increases (Jain and Yang, 1994, Marques et al., 2009, Tsao and Hocheng, 2008). In the case of GFRP, delamination causes fiber pull out and cracks in the interplay regions, thus reducing the stiffness and structural integration of the GFRP.

GFRP has been the subject of extensive study during the past decades. It was estimated that laminates made of an epoxy matrix reinforced with glass fibres account for over 50% of the total investigated polymeric composites, followed by carbon fibre reinforced epoxy of 30% and lastly, glass fibre reinforced with polyester resin of 14%. All in all, glass fiber reinforced polymer accounts for almost 70% of the investigated polymeric composite material (Abrao et al., 2007). Its prevalence in the current manufacturing industry as well as in past researches is the primary motivation for the choice of material in this study. In addition, the Response Surface Methodology (RSM) employed in the present study is also a proven research methodology, in which a collection of mathematical and statistical analysis techniques is used to optimize a response of interest that is influenced by several variables (Husnawan et al., 2007 and Montgomery, 2005). Gaitonde et. al. (2008) for instance, had studied the parametric influences on delamination using RSM and concluded that low feed rates and high cutting speeds heavily influences the delamination at the entrance while validating the accuracy of the model (Gaitonde et al., 2008, Karnik et al., 2008). Mohan et.al. (2007) on the other hand, used RSM to predict optimal parameters and verify the model with experimental results to be within 99% in agreement.

In the present work, delamination of the GFRP was studied and analyzed using RSM under dry drilling conditions. A second order linear regression model was developed for the range of data used in the experiment. The parameters used for this study are drill diameter, speed and feed rate. The mathematical model developed was later tested for significance using ANOVA. The results were then compared to experimental observations.

2. Methodology

Specimen Preparation

The glass fiber reinforced composite used in this project is fabricated as previous method using a hand lay-up technique (El-Tayeb et al., 2006). The composition type is Chopped Strand Mat (CSM) (randomly oriented small cut lengths of fiber bonded together), as shown in Figure 1, with 450 R-glass fibers as reinforcement and polyester as the thermosetting resin material (El-Tayeb et al., 2006 and El-Tayeb et al., 2008). The material was fabricated in large slabs and then cut into pieces of 30mm × 30mm. The composition of the GFRP material used in the experiment is shown in Table 1.

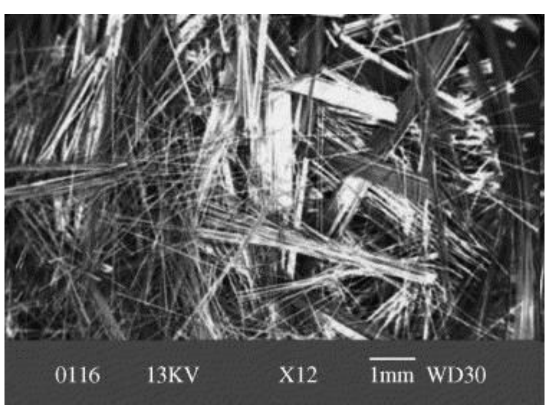

Figure 1. SEM Micrograph of Chopped Strand Mat R-glass Fibre (El-Tayeb et al., 2006)

Table 1: Composition of GFRP (El-Tayeb et al., 2006).

Items	Quantity/Type
Fiber Length	20 - 30 mm
Mass of Fiber	450 g/m^2
Matrix	Thermosetting resin
Catalyst	Methyl Ethyl Ketone Peroxide
Reinforcing	CSM Glass Fiber

Experimental Work

Drilling was conducted on Master 10HVA CNC machine, Yamazaki Mazak, using high-speed steel drilling tool under dry conditions. The delamination factor (F_d) is calculated by dividing the maximum delaminated diameter (D_{max}) by the hole nominal diameter (D) (Abrao et al., 2007, Rubio et al.,2008, Gaitonde et al., 2008, Hocheng and Tsao, 2003, Marques et al., 2009, Mohan et al., 2007, Tsao and Hocheng, 2004). This is shown in Equation 1. Figure 2 shows the scheme of the delamination factor.

$$F_d = \frac{D_{max}}{D} \quad (1)$$

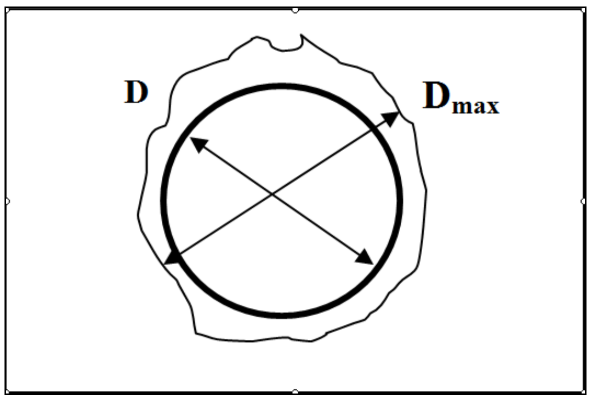

Figure 2. Scheme of Delamination Factor.

Response Surface Methodology

The data collected is analyzed statistically using regression. In this case, where a non-linear relationship between the response and input variables are observed, a second order quadratic equation is used to describe the functional relationship between the estimated variable (delamination factor) and the input variables {drill diameter (x_1), speed (x_2) and feed rate (x_3)}. The relationship may be described by Equation 2.

$$\begin{aligned} y = x_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \\ \beta_{12} x_{12} + \beta_{23} x_{23} + \beta_{13} x_{13} + \\ \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{33} x_3^2 \end{aligned} \quad (2)$$

The least square method is used to fit the model equation containing the regressor or the input variables. The β values can be obtained by performing matrix operations where β is replaced with matrix *b*. The solution of the normal equation can be written as

$$b = \left(X^T X\right)^{-1} X^T y \quad (3)$$

where X^T is the transpose of matrix X (input variables) and matrix $(X^TX)^{-1}$ is the inverse of matrix (X^TX). y is to be defined as n × 1 matrix, X as n × m matrix of independent variables and b as an m × 1 matrix.

Design of Experiment

A total number of eighteen holes were drilled into the GFRP specimen to develop a second order regression model to investigate the effects of drill diameter, speed and feed rate on delamination. For this experiment, we used the Central Composite Design (CCD) as shown in Figure 3 with a 3 factorial design with factor levels coded at -1 and +1. The axial portion (star points) is located on the coordinate axes of the factorial portion at an augment distance of α = 1.682 from the design centre, as shown in Table 2. Equation 4 shows how the raw data is converted into coded form. The transformation of the independent variables into five levels of coded form is as below

$$\frac{x - centre}{high - centre} \tag{4}$$

Table 2: Coded Form Distribution.

	Coded Form				
Parameter	Lowest-1.682	Low -1	Center 0	High +1	Highest 1.682
Diameter (mm)	4.5	6	8	10	11.5
Speed (rpm)	580	750	1000	1250	1420
Feed Rate (mm/min)	83	100	125	150	167

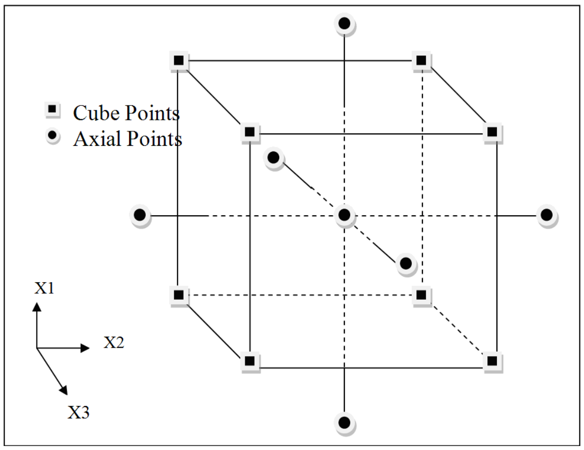

Figure 3. Central Composite Design.

3. Results And Discussion

The y parameter represents the delamination factor (F_d) while x_1, x_2 and x_3 represent drill diameter, speed and feed rate respectively. The second order regression equation obtained from performing the matrix operations yielded Equation 5.

$$\begin{aligned} y &= 1.63391 - 0.00925x_1 - 0.03798x_2 \\ &+ 0.04067x_3 + 0.05281{x_1}^2 - 0.01613{x_2}^2 \\ &- 0.05326{x_3}^2 - 0.0175x_1x_2 + 0.01x_1x_3 \\ &+ 0.0775x_2x_3 \end{aligned} \tag{5}$$

ANOVA is performed with a 95% confidence level. This means an acceptance of type one error, α of 5%. As such, a term can apply only be considered insignificant when its P-value is more than 0.05. The results show that some of the interaction and quadratic terms are statistically not significant. These higher order terms with P>0.05 are removed from equation (5) and the mathematical model thus reduced to equation (6).

$$\begin{aligned} y &= 1.61329 - 0.00925x_1 - 0.03798x_2 \\ &+ 0.04067x_3 + 0.05281{x_1}^2 - 0.04849{x_3}^2 \\ &+ 0.0775x_2x_3 \end{aligned} \tag{6}$$

Table 3 (a): Analysis of Variance (ANOVA) Before Reduction.

([a.] Parameters main effects and interactions; [b.] coefficient of model; [c.] standard error of coefficient; [d.] T-Ratio for testing hypotheses; [e.] Significance probability for each T-ratio; [f.] Degree of Freedom; [g.] F-ratio for testing hypotheses; [h.] Significance probability for each F-ratio)

[a.]Term	[b.]Coef	[c.]SE Coef	[d.]T	[e.]P
Constant	1.63391	0.04322	37.801	0
x_1	0.00925	0.02030	-0.456	0.662
x_2	0.03798	0.02030	-1.871	0.104
x_3	0.04067	0.02030	2.004	0.085
x_1*x_1	0.05281	0.02234	2.364	0.050
x_2*x_2	0.01613	0.02234	-0.722	0.494
x_3*x_3	0.05326	0.02234	-2.384	0.049
x_1*x_2	-0.01750	0.02652	-0.66	0.530
x_1*x_3	0.01000	0.02652	0.377	0.717
x_2*x_3	0.07750	0.02652	2.922	0.022
Source	**[f.]DF**	**[g.]F**	**[h.]P**	
Regression	9	3.71	0.049	
Linear	3	2.57	0.137	
Square	3	5.53	0.029	
Interaction	3	3.04	0.102	
Residual Error	7	--	--	
Lack-of-Fit	5	5.66	0.157	
Pure Error	2	--	--	
Total	16	--	--	

The result of ANOVA performed is tabulated in Table 3(a) for the original model and Table 3(b) for the reduced model. It is observed that the P-values for the remaining terms after reduction, except the main effect drill diameter (x_1) are less than 0.05, indicating that the remaining terms are statistically significant. This in turn leads to engineering observations that the interaction between speed and feed rate (x_2x_3), as well as the quadratic terms of drill diameter and feed rate (x_3x_3) are significant in contributing to push-out delamination of the composite under study. There is no interaction of drill diameter with the other two parameters, implying that the effect of drill diameter on delamination is independent. Looking at the p-values of the lack of fit being greater than 0.05, it can be deduced that the reduced model appropriately describes the relationship between the input parameters and the output response.

Table 3 (b): Analysis of Variance (ANOVA) After Reduction.

Term	Coef	SE Coef	T	P
Constant	1.61329	0.0292	55.241	0
x_1	0.00925	0.01827	-0.507	0.623
x_2	0.03798	0.01827	-2.079	0.064
x_3	0.04067	0.01827	2.226	0.05
x_1*x_1	0.05758	0.01921	2.997	0.013
x_3*x_3	0.04849	0.01921	-2.524	0.03
x_2*x_3	0.0775	0.02387	3.247	0.009
Source	**DF**	**F**	**P**	
Regression	6	6.65	0.005	
Linear	3	3.18	0.072	
Square	2	9.92	0.004	
Interaction	1	10.54	0.009	
Residual Error	10	--	--	
Lack-of-Fit	8	4.13	0.209	
Pure Error	2	--	--	
Total	16	--	--	

Figures 4 to Figure 6 are graphical representations of two-parameter interactions based on the reduced mathematical models, taken at the mid setting of the unrepresented third parameter.

These figures compare the effects of parameter interactions (drill diameter/speed, feed rate/speed and feed rate/drill diameter) against the delaminaton response in the form of response surfaces.

Figure 4(a) and 4(b) show that a high drilling speed significantly reduces the delamination while the influence of diameter does not exhibit a clear trend. Figure 5(a) and 5(b) clearly substantiates that high drilling speed, when coupled with low feed rate, further minimizes delamination. In addition, since increasing speed at high feed rate does not help to reduce delamination, a strong interaction exists between feed rate and speed. It is evident from Figure 6(a) and 6(b) that a larger or smaller than center value of drill diameter tends to increase delamination. This corresponds to the statistical significant quadratic x_1-term demonstrated in equation (6) and again in the saddleback shape of the surface plot in Figure 6(a). The fact that increased speed lowers the amount of delamination may possibly be explained by elevated cutting temperature, which promotes the softening of the matrix and therefore the ease of machining. On the same token, increasing feed rate increases the thrust force, resulting in higher delamination.

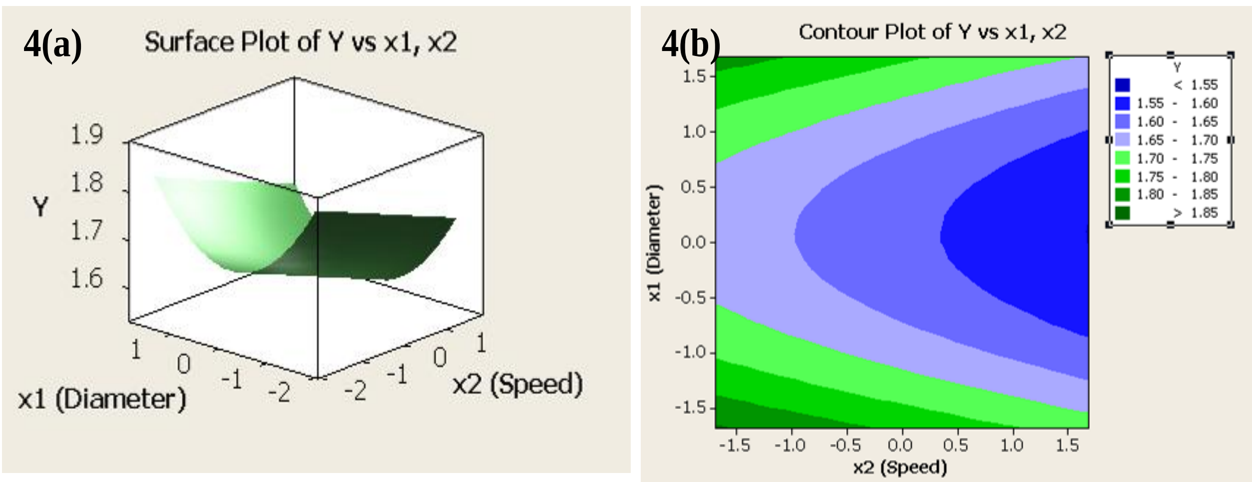

Figure 4. (a) Response Surface and; (b) Contour Plot of Effect of Drill Diameter and Drilling Speed on the Delamination.

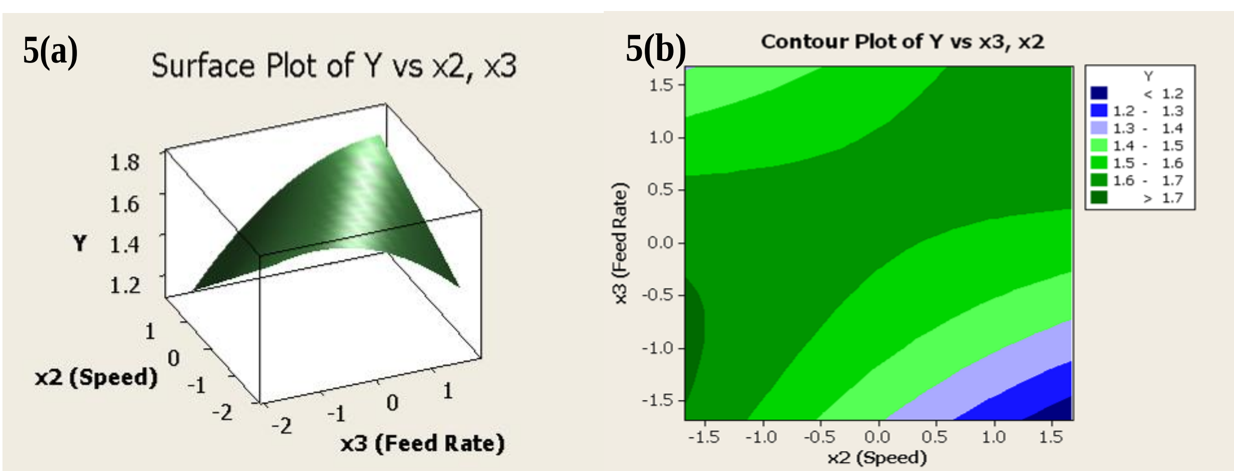

Figure 5. (a) Response Surface and; (b) Contour Plot of Effect of Feed Rate and Drilling Speed on the Delamination.

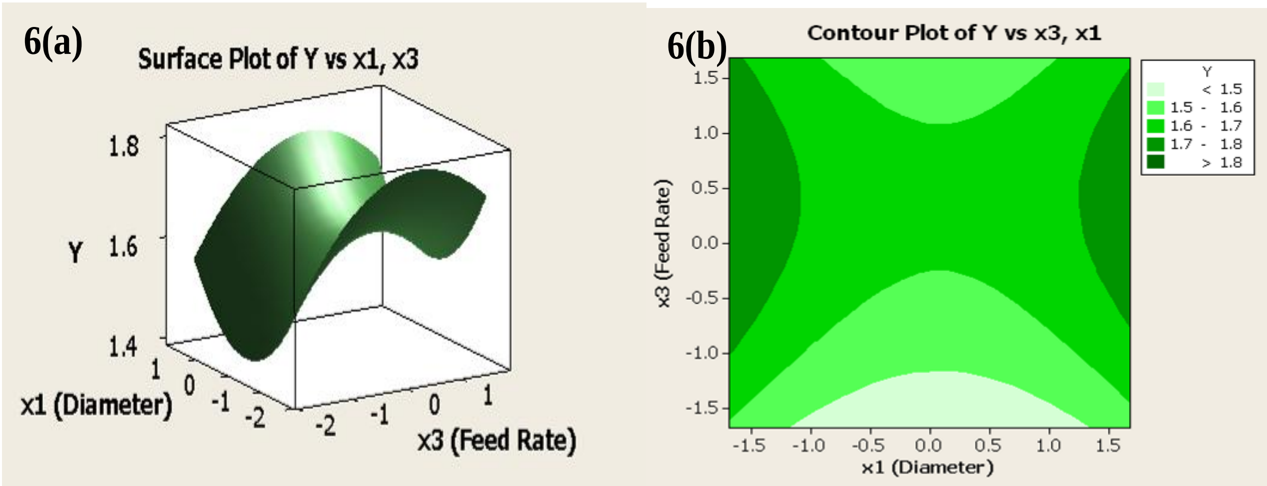

Figure 6. (a) Response Surface and; (b) Contour Plot of Effect of Feed Rate and Drill Diameter on the Delamination.

Figures 7(a) to Figure 7(d) show the residual plots for the reduced regression model. The normal probability plot (Figure 7(a)) reveals that the residuals generally fall on a straight line implying that the residuals are normally distributed. Figure 7 (b) continues to imply that there are no obvious patterns and unusual features. Figure 7 (c) and Figure 7 (d) further verifies these analyses, as the residuals are random and there are no violations of the independence or equal variance assumptions.

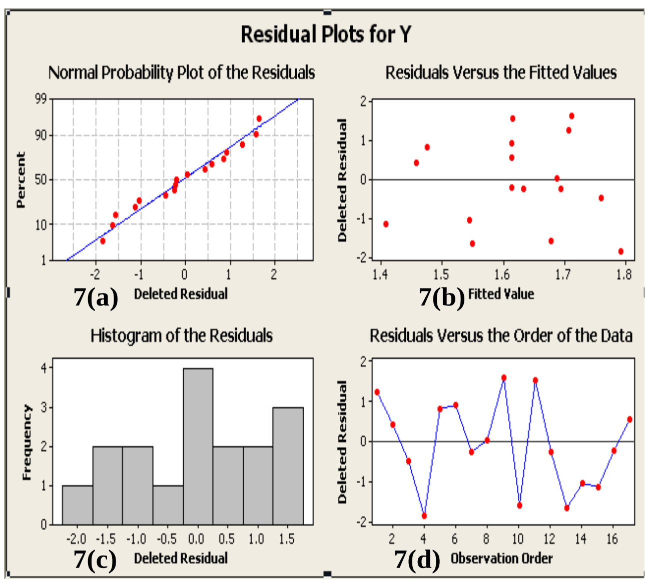

Figure 7. (a) Normal Probability Plot of Residual; (b) Residuals versus Fitted Values; (c) Histogram of Residuals; (d) Residuals Versus Order of Data.

The comparison of the effect of speed and feed rate on the delamination phenomenon can be observed in Figures 8(a)-(d). In Figure 8(a) and Figure 8(b), the same feed rate (125 mm/min) and two different speeds (1000 rpm and 580 rpm) had been used. It can be seen that the occurrence of the push-out delamination is more severe in Figure 8(b)--the one with lower speed. A similar observation is made in Figure 8(c) and Figure 8(d). In Figure 8(c) speed and feed rate were set at 1250 rpm and 100 mm/min respectively and minimum delamination was observed. Whereas in Figure 8(d) when speed and feed rate were set at 580 rpm and 150 mm/min respectively, severe delamination were seen.

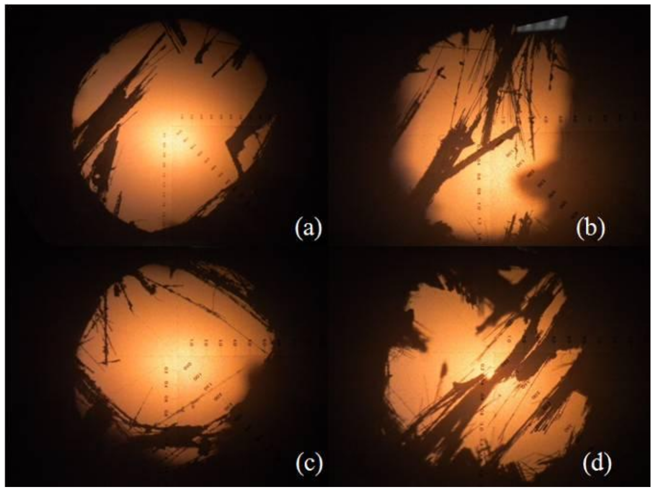

Figure 8. Delamination Observed in GFRP Using the Profile Projector at speed and feed rate. (a) 1000 rpm and 125 mm/min; (b) 580 rpm and 125 mm/min; (c) 1250 rpm and 100 mm/min; (d) 750 mm and 150 mm/min respectively.

The mathematical model in equation (6) leads to minimum predicted delamination of 1.125 at optimized settings of drilling speed at 1420 rpm and feed rate at 83 mm/min, with a drill diameter of 8 mm. Three confirmation runs were conducted at the optimum settings and the optimum responses averaged at 1.19, which is about 6% error compared to the predicted delamination value. These confirmation runs verified the mathematical model.

4. Conclusion

RSM was employed in this study based on a Central Composite Design (CCD) to develop a mathematical model that describes the effects of drill diameter, speed and feed rate on the push-out delamination in the GFRP material. A second order regression model was developed and 3D surface plots and contour plots were generated to analyze the two-factor interaction of the parameters. The second order model developed is valid within the ranges of the selected experimental parameters. ANOVA was done on the model to test for statistical significance. Based on the experimentations and statistical analyses carried out, the following conclusions are drawn:

- ANOVA shows insignificant lack of fit, validating the second order regression model.
- Speed and feed rate were significant parameters involved in affecting delamination. Strong interactions between the two variables were noticed.
- Interactions involving the drill diameter are insignificant.
- Increasing drilling speed and decreasing feed rate reduces delamination and minimum delamination is achieved when drilling speed is 1420 rpm and feed rate is 83 mm/min, when a nominal drill diameter of 8 mm

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