Experimental Studies on Effect of Process Parameters on Delamination in Drilling GFRP Composites using Taguchi Method

Tom sunny, J.Babua*, Jose Philip

*Department of Mechanical Engineering, St. Joseph' College of Engineering&Technology, Choonadacherry, Palai, Kerala-686579, India

Abstract

Currently composites are being used to replace conventional metallic materials in a wide range of industries including aerospace, aircraft and defense which require structural materials with high strength-to-weight and stiffness-to-weight ratios. GFRP composites are used in fairings, passenger compartments, and storage room doors due to their high mechanical properties. Out of all the machining operations, most commonly used operation is drilling. But drilling of these composite materials, irrespective of the application area, can be considered a critical operation, owing to their tendency to delaminate when subjected to mechanical stresses. With regard to the quality of machined component, the principal drawbacks are related to surface delamination, fibre/resin pull-out and inadequate surface roughness of the hole wall. Hence it is essential to understand the drilling behaviour by conducting a large number of drilling experiments and drilling parameters such as feed rate and spindle speed should be optimized. This paper presents the effect of speed and feed on delamination behaviour of composite materials by conducting drilling experiments using Taguchi’s L25, 5-level orthogonal array and Analysis of variance by using three different tools namely Twist drill, End mill and Kevlar drill. ANOVA was used to analyse the data obtained from the experiments and finally determine the optimal drilling parameters in drilling GFRP composite materials. Results of these experiments revealed that increasing the spindle speed and reducing feed rate can reduce the delamination within limits of specified speed and feed rates. Too low feed rate and too high spindle speed can also increase the delamination. Results also revealed that feed rate is the more influential factor on delamination than spindle speed.
1. Introduction

Mankind was aware of and using composite materials from ancient times in improving the quality of life. In recent times the development and application of composite materials in all branches of engineering are occurring at an increasingly fast pace. Contemporary composites are the results of research and innovations during the last few decades when these progressed from glass fibre for automobiles to particulate composites for aerospace. Some define composite as “materials composed of two or more distinctly identifiable constituents”. But modern composites developed for specific purposes like flake, particulate and laminar composites defy such definitions. Fibres or particles embedded in matrix of another material which are mostly structural are latest developments. Glass fibre reinforced polymer (GFRP) is one such composite developed for structural applications.

GFRP composites are used in fairings, passenger compartments, storage room doors due to their high mechanical properties. Drilling using twist drill is the most common operation of secondary machining for fiber-reinforced materials. However, composite laminates are regarded as hard-to-machine materials, which results in low drilling efficiency and undesirable drilling-induced delamination. For rivets and bolted joints, damage-free and precise holes must be drilled in the components to ensure high joint strength and precision. However, composite laminates are non-homogeneous, anisotropic, and highly abrasive and have hard reinforcement fibers, which make them difficult to machine. Among the problems caused by drilling, delamination is considered the major damage. It was reported that, in aircraft industry, the rejection of parts consist of composite laminates due to drilling-induced delamination damages during final assembly was as high as 60%; Wong T.L et.al, (1982)

Defu Liu, Yongjun Tang and W.L Cong. (2012) mentioned that amongst all machining operations, drilling using twist drill is the most commonly applied method for generating holes. A large number of experiments were conducted by Lee SC, Park J N, Chen W C,(1995), Wang X, Davim JP(2004), Tsao CC, Hocheng H(2004, 2005) to research the influence of input variables (spindle speed, feed rate, and drill bit geometry) on output variables (delamination & thrust force). Park KY, Choi JH & Lee DG (1995) firstly introduces grinding drilling to reduce delamination by improving drilling performance. Tsao CC & Hocheng H(2004) investigated that delamination generally resulted from excessive thrust force and smaller delamination holes could be obtained when grinding drilling composite laminates. A low (<1000 Hz) or high (>1000 Hz) frequency and low amplitude vibration if superimposed on a twist drill bit along the feed direction during drilling could reduce the delamination. Ramkumar J, Malhothra SK, Krishnamurthy R (2004) found that the thrust by (vibration-assisted twist drill) VATD was reduced by 20–30%, compared with conventional drilling. Therefore, VATD used to reduce the delamination damage during drilling of composite laminates. Unlike conventional drilling operation, high speed drilling operation of composite laminates has to be conducted in a high speed drilling machine system which is very expensive. Investigators revealed that the delamination tendency decrease with increased in cutting speed and the combination of low feed rate and point angle was also essential in minimizing delamination during high speed drilling of composite laminates.

H. Hochenga, C.C. Tsao(2006) studied effects of special drill bits on delamination of composite materials and found that core drill was able to withstand the highest feed rate with reduced delamination. From literature it is clear that twist drill bits made of HSS or carbides are the primary attraction in drilling of composite laminates among various drill bits. However, the applications of other drill bits in drilling of composite laminates are also very extensive to improve machinability of composite laminates. Most of investigators found that using drill bits with different geometry and materials in drilling of composite laminates gave more advantages & benefits.

For practical machining of GFRP, it is necessary to determine the optimal machining parameters to achieve less delamination etc. Optimization of process parameters is the important criterion in the machining process to achieve high quality. Most of the studies on GFRP show that eliminating delamination is very difficult. K Palanikumar.K. (2011) conducted experiments on GFRP composites using Brad & Spur drill and optimized drilling parameters by using two input variables with four levels and concluded that low feed rate and high spindle speeds were beneficial to reduce delamination. Previous researchers carried out the experiments with three or four levels for optimisation of input parameters. In the present study the experiments are carried out using Twist drill (HSS), end mill (Carbide)and Kevlar drill( Carbide) to find the optimum drilling parameters using 5-level Taguchi’s L_{25} orthogonal array and also to analyse the effect of drill bit material and geometry on delamination.
2. Materials and experimental procedure

2.1. Materials

The laminates were composed of 26 layers, laid-up in the symmetrical form [0, 90]. The fibers were unidirectional (UD) E-Glass. The applied resin was of grade L-12 with K-5 hardener. The thickness of the laminate was 6mm. Twist drill made of HSS and End mill, Kevlar drill made of Carbide steel each of 10 mm diameter, were used for the drilling operation shown in fig.1, 2 and 3. Drilling was carried out on a MAKINO S 56 CNC vertical milling machine with maximum rpm of 3000. The experimental set-up is shown in fig.4. Profile projector was used to measure the maximum diameter due to delamination around the hole.

Fig.1. Twist Drill (HSS)

Fig.2. Four Fluted End Mill (Carbide)

Fig.3. KEVLARBOHRER SCD 56279 Drill (Carbide)

Fig.4. Experimental setup


2.2. Design of experiments

DOE is an important tool for designing processes and products. DOE is a method for quantitatively identifying the right inputs and parameter levels for making a high quality product or service. A proper design of experiments (DOE) is conducted to perform more accurate, less costly and more efficient experiments.

In order to minimize the number of tests required, Taguchi experimental design method, a powerful tool for designing a high quality system, was developed by Taguchi. This method uses a special design of orthogonal arrays to study the entire parameter space with a small number of experiments. In this study, two machining parameters were used as control factors and each parameter was designed to have five levels, denoted 1, 2, 3, 4 and 5 (Table 1). Each experiment was repeated twice for getting reliable data. The averages of two tests were taken for determining delamination factor. The experimental design was according to an L_{25} array based on Taguchi method (Table 2). Minitab software was used for Taguchi analysis. Using Analysis of Variance (ANOVA), the effect of input parameters on delamination factor is studied.

Table 1. Drilling parameters and levels

| Parameters | Level 1 | Level 2 | Level 3 | Level 4 | Level 5 |
|------------|---------|---------|---------|---------|---------|
|            | (Very low) | (Low) | (Medium) | (High) | (Very high) |
| Feed (mm/min) | 1000 | 1500 | 2000 | 2500 | 3000 |
| Speed (rpm) | 50 | 100 | 200 | 300 | 400 |

Table 2. Orthogonal array of Taguchi L_{25}

| Experiment No. | Feed rate | Spindle speed |
|----------------|-----------|---------------|
| 1              | 1         | 1             |
| 2              | 1         | 2             |
| 3              | 1         | 3             |
| 4              | 1         | 4             |
| 5              | 1         | 5             |
| 6              | 2         | 1             |
| 7              | 2         | 2             |
| 8              | 2         | 3             |
| 9              | 2         | 4             |
| 10             | 2         | 5             |
| 11             | 3         | 1             |
| 12             | 3         | 2             |
| 13             | 3         | 3             |
| 14             | 3         | 4             |
| 15             | 3         | 5             |
| 16             | 4         | 1             |
| 17             | 4         | 2             |
| 18             | 4         | 3             |
| 19             | 4         | 4             |
| 20             | 4         | 5             |
| 21             | 5         | 1             |
| 22             | 5         | 2             |
| 23             | 5         | 3             |
| 24             | 5         | 4             |
| 25             | 5         | 5             |

2.3. Delamination Factor ($F_d$)

An index or factor called delamination factor ($F_d$), $F_d = \frac{D_{max}}{D}$ is used to determinate the extent of delamination. Capello E (2004), Davim J.P, et.al.(2004). The scheme of evaluating delamination factor is shown in figure 5. Alternatively the ratio of delaminated area to the hole area has been used to determine the extent of delamination by Dini G. (2003).
D\textsubscript{max} is the maximum diameter created due to delamination around the hole and D is the hole or drill diameter.

3. Results and discussions.

A drilling test was conducted to evaluate the effect of cutting parameters on the damage to work piece. The damage around the drilled hole was measured using a profile projector with magnification 20. After measuring the maximum diameter D\textsubscript{max} of the damage around each hole, the delamination factor is determined by using the equation as mentioned in the section 2.3. Table 3 illustrates the influence of cutting parameters on the delamination factor.

| Experiment No | Feed, mm/min | Spindle speed, rpm | Delamination factor |
|---------------|--------------|--------------------|--------------------|
|               | Coded | Actual | Coded | Actual | Twist drill | End mill | Kevlar drill |
| 1             | 1     | 50     | 1     | 1000   | 1.0800      | 1.0825   | 1.1000      |
| 2             | 1     | 50     | 2     | 1500   | 1.0900      | 1.0900   | 1.1100      |
| 3             | 1     | 50     | 3     | 2000   | 1.0750      | 1.0800   | 1.0700      |
| 4             | 1     | 50     | 4     | 2500   | 1.1350      | 1.1250   | 1.1200      |
| 5             | 1     | 50     | 5     | 3000   | 1.0975      | 1.0850   | 1.0950      |
| 6             | 2     | 100    | 1     | 1000   | 1.0700      | 1.0475   | 1.0550      |
| 7             | 2     | 100    | 2     | 1500   | 1.0675      | 1.0450   | 1.0500      |
| 8             | 2     | 100    | 3     | 2000   | 1.0600      | 1.0400   | 1.0400      |
| 9             | 2     | 100    | 4     | 2500   | 1.0375      | 1.0250   | 1.0080      |
| 10            | 2     | 100    | 5     | 3000   | 1.0700      | 1.0800   | 1.0775      |
| 11            | 3     | 200    | 1     | 1000   | 1.0850      | 1.0600   | 1.0600      |
| 12            | 3     | 200    | 2     | 1500   | 1.0800      | 1.0550   | 1.0570      |
| 13            | 3     | 200    | 3     | 2000   | 1.0775      | 1.0525   | 1.0450      |
| 14            | 3     | 200    | 4     | 2500   | 1.0600      | 1.0350   | 1.0220      |
| 15            | 3     | 200    | 5     | 3000   | 1.0850      | 1.0900   | 1.0900      |
| 16            | 4     | 300    | 1     | 1000   | 1.0900      | 1.0850   | 1.0650      |
| 17            | 4     | 300    | 2     | 1500   | 1.0875      | 1.0800   | 1.0600      |
| 18            | 4     | 300    | 3     | 2000   | 1.0825      | 1.0775   | 1.0500      |
| 19            | 4     | 300    | 4     | 2500   | 1.0650      | 1.0650   | 1.0350      |
| 20            | 4     | 300    | 5     | 3000   | 1.1000      | 1.0975   | 1.1000      |
| 21            | 5     | 400    | 1     | 1000   | 1.1250      | 1.1000   | 1.0750      |
| 22            | 5     | 400    | 2     | 1500   | 1.1200      | 1.0900   | 1.0650      |
| 23            | 5     | 400    | 3     | 2000   | 1.1000      | 1.0850   | 1.0520      |
| 24            | 5     | 400    | 4     | 2500   | 1.0850      | 1.0775   | 1.0400      |
| 25            | 5     | 400    | 5     | 3000   | 1.1150      | 1.1050   | 1.1050      |
From the above table it can be observed that the delamination is increasing with the feed rate and decreasing with the spindle speed except at the feed rates of 50 mm/min and spindle speeds of 3000 rpm for all the drilling tools used in this study. In the Taguchi method, Signal to noise ratio (S/N) is the measure of quality characteristics and deviation from the desired value. By applying equation given below, the S/N values for each experiment of L25 (Table 3) was calculated and tabulated in Table 4. The signal-to-noise ratios were calculated using the condition smaller is the better.

$$\eta = -10 \log_{10} \left[ \frac{1}{n} \sum_{i=1}^{n} (F_d - F_i)^2 \right]$$

$F_d$ is the measured delamination, $F_i$ is the ideal delamination = 1 and $n$ is the number of trials

| Experiment No | Feed , mm/min | Spindle speed, rpm | Delamination factor | S/N ratio |
|---------------|---------------|--------------------|---------------------|-----------|
|               | Twist drill   | End mill           | Kevlar drill        | Twist drill | End mill | Kevlar drill |
| 1             | 50            | 1500               | 1.0800              | 1.0825      | 1.1000   | 21.9382     | 21.6709      | 20.0000 |
| 2             | 50            | 2000               | 1.0750              | 1.0800      | 1.0700   | 22.4988     | 21.9382      | 23.0980 |
| 3             | 50            | 2500               | 1.1350              | 1.1250      | 1.1200   | 17.3933     | 18.0618      | 18.4164 |
| 4             | 50            | 3000               | 1.0975              | 1.0850      | 1.0950   | 20.2199     | 21.4116      | 20.4455 |
| 5             | 100           | 1500               | 1.0700              | 1.0475      | 1.0550   | 23.0980     | 26.4661      | 25.1927 |
| 6             | 100           | 2000               | 1.0675              | 1.0450      | 1.0500   | 23.4139     | 26.9357      | 26.0206 |
| 7             | 100           | 2500               | 1.0375              | 1.0250      | 1.0080   | 28.5194     | 32.0412      | 41.9382 |
| 8             | 100           | 3000               | 1.0700              | 1.0800      | 1.0775   | 23.4139     | 27.9588      | 27.9588 |
| 9             | 200           | 1500               | 1.0600              | 1.0400      | 1.0400   | 24.4370     | 27.9588      | 27.9588 |
| 10            | 200           | 2000               | 1.0375              | 1.0250      | 1.0080   | 28.5194     | 32.0412      | 41.9382 |
| 11            | 200           | 2500               | 1.0775              | 1.0525      | 1.0450   | 22.2140     | 25.1927      | 24.8825 |
| 12            | 200           | 3000               | 1.0850              | 1.0600      | 1.0600   | 21.4116     | 24.4370      | 24.4370 |
| 13            | 200           | 1000               | 1.0800              | 1.0550      | 1.0570   | 21.9382     | 25.1927      | 24.8825 |
| 14            | 200           | 2000               | 1.0775              | 1.0525      | 1.0450   | 22.2140     | 25.5968      | 26.9357 |
| 15            | 200           | 2500               | 1.0600              | 1.0350      | 1.0220   | 24.4370     | 29.1186      | 33.1515 |
| 16            | 200           | 3000               | 1.0850              | 1.0900      | 1.0900   | 21.4116     | 20.9151      | 20.9151 |
| 17            | 200           | 1500               | 1.0900              | 1.0850      | 1.0650   | 20.9151     | 21.4116      | 23.7417 |
| 18            | 200           | 2000               | 1.0875              | 1.0800      | 1.0600   | 21.1598     | 21.9382      | 24.370 |
| 19            | 200           | 2500               | 1.0825              | 1.0775      | 1.0500   | 21.6709     | 22.2140      | 26.0206 |
| 20            | 200           | 3000               | 1.0650              | 1.0650      | 1.0350   | 23.7417     | 23.7417      | 29.1186 |
| 21            | 200           | 1000               | 1.1000              | 1.0975      | 1.1000   | 20.0000     | 20.2199      | 20.0000 |
| 22            | 200           | 1500               | 1.1250              | 1.1000      | 1.0750   | 18.0618     | 20.0000      | 22.4988 |
| 23            | 200           | 2000               | 1.1200              | 1.0900      | 1.0650   | 18.4164     | 20.9151      | 23.7417 |
| 24            | 200           | 2500               | 1.0850              | 1.0775      | 1.0400   | 21.4116     | 22.2140      | 27.9588 |
| 25            | 200           | 3000               | 1.1150              | 1.1050      | 1.1050   | 18.7860     | 19.5762      | 19.5762 |

Based on the results of the S/N ratio, the optimal cutting parameters for the delamination were obtained as feed rate at Level 2 (100mm/min) and the cutting speed at Level 4 (2500rpm) for all the three tools, where S/N values are high (see table 4). The effects of feed rate and spindle speed on delamination factor and interactions plots are shown.
From these graphs, it can be observed that at 3000 rpm there is a sudden increase in the delamination factor against the expected lower value. This is due to the reason that when the drill speed increases, the thrust force increases and the consequent severe heat generation in the drilling area leads to softening of the fiber and matrix. As a result, fiber cutting becomes harder for the cutting edges of the drill and drilling thrust force increases. It can also be observed that the feed rate increases from 50 mm/min to 100 mm/min, the delamination factor decreases. The reason may be at the feed rate of 50 mm/min, more heat is generated and transferred to the laminate in the drilling area as the time of drilling increases with decrease in feed rate. This is in good agreement with the results obtained by Faramarz Ashenai Ghasemi et.al. (2011). The same behaviour was observed for all the three tools. Further it can be observed from the table 3, that lowest delamination is at the spindle speed of 2500 rpm and feed rate of 100 mm/min. Table 5 and table 6 describe the ANOVA of the input parameters and the response table for means respectively.

| FEED RATE | DELAMINATION FACTOR |
|-----------|----------------------|
| 50        | 1.06                 |
| 100       | 1.07                 |
| 200       | 1.08                 |
| 400       | 1.09                 |
| 800       | 1.10                 |
| 1200      | 1.11                 |

(a) Twist drill

(b) End mill

(c) Kevlar drill
Fig. 6. Main effect plot for means

Fig. 7. Interaction plot for means
Table 5. Analysis of variance for means

| Source         | DF | Seq SS  | Adj SS  | Adj MS  | F     | P     |
|----------------|----|---------|---------|---------|-------|-------|
| Twist drill    |    |         |         |         |       |       |
| Feed Rate      | 4  | 0.006584| 0.006583| 0.001646| 6.47  | 0.003 |
| Spindle Speed  | 4  | 0.001099| 0.001099| 0.000275| 1.08  | 0.399 |
| Residual Error | 16 | 0.004071| 0.004071| 0.000254|       |       |
| Total          | 24 | 0.011754|         |         |       |       |
| End mill       |    |         |         |         |       |       |
| Feed Rate      | 4  | 0.008199| 0.008199| 0.002050| 9.41  | 0.000 |
| Spindle Speed  | 4  | 0.002162| 0.002162| 0.000540| 2.48  | 0.086 |
| Residual Error | 16 | 0.003486| 0.003486| 0.000218|       |       |
| Total          | 24 | 0.013847|         |         |       |       |
| Kevlar drill   |    |         |         |         |       |       |
| Feed Rate      | 4  | 0.008142| 0.008142| 0.002035| 8.10  | 0.001 |
| Spindle Speed  | 4  | 0.007205| 0.007205| 0.001801| 7.17  | 0.002 |
| Residual Error | 16 | 0.004022| 0.004022| 0.000251|       |       |
| Total          | 24 | 0.019369|         |         |       |       |

Table 6. Response table for means

| Drilling tool   | Level | Feed   | Spindle speed |
|-----------------|-------|--------|---------------|
| Twist drill     | 1     | 1.095  | 1.090         |
|                 | 2     | 1.061  | 1.089         |
|                 | 3     | 1.078  | 1.079         |
|                 | 4     | 1.085  | 1.077         |
|                 | 5     | 1.109  | 1.094         |
|                 | Delta | 0.048  | 0.017         |
| Rank            |       | 1      | 2             |
| End mill        | 1     | 1.093  | 1.075         |
|                 | 2     | 1.048  | 1.072         |
|                 | 3     | 1.059  | 1.067         |
|                 | 4     | 1.081  | 1.065         |
|                 | 5     | 1.091  | 1.091         |
|                 | Delta | 0.045  | 0.026         |
| Rank            |       | 1      | 2             |
| Kevlar drill    | 1     | 1.099  | 1.071         |
|                 | 2     | 1.046  | 1.068         |
|                 | 3     | 1.055  | 1.051         |
|                 | 4     | 1.062  | 1.045         |
|                 | 5     | 1.067  | 1.094         |
|                 | Delta | 0.053  | 0.048         |
| Rank            |       | 1      | 2             |
From the Table 6, the delta values for feed rate are more compared to the delta values of spindle speed. The rank for feed rate is 1 and that of spindle speed is 2. Thus from the table 5 (F value larger). It is clear that feed rate affects the delamination factor more than spindle speed. Thus from the level 5 experiments it is clear that optimized value or the least delamination factor input parameters are feed rate of 100 mm/min and spindle speed of 2500 rpm and feed rate is the more influential factor on delamination than spindle speed.

3.1. Prediction for Optimized Value and Confirmation Test

From S/N analysis and mean response characteristics, the optimum levels of delamination factors were calculated as Level 2 ($A_2$) for feed rate and Level 4 ($B_4$) for spindle speed. Hence, the predicted mean of delamination factor is calculated using the equation given below by Nilrudra Mandal, B et.al. (2011)

$$F_{d_{opt}} = \bar{y} + (\bar{A}_2 - \bar{y}) + (\bar{B}_4 - \bar{y})$$

$\bar{y}$ is the average of delamination factor corresponding to all the 25 readings(delamination factor) in table3. $A_2$ and $B_4$ are the average values of the delamination factor with input parameters at their respective optimal levels and $F_{d_{opt}}$ denotes the predicted mean of delamination factor at optimum condition.

The calculated values of various response averages for twist drill are $\bar{y} = 1.0856$, $A_2 = 1.061$ and $B_4 = 1.077$. So substituting these values in above equation the mean optimum value of delamination factor has been predicted as $F_{d_{opt}} = 1.0524$

The calculated values of various response averages for end mill are $\bar{y} = 1.0742$, $A_2 = 1.048$ and $B_4 = 1.065$. So substituting these values in above equation the mean optimum value of delamination factor has been predicted as $F_{d_{opt}} = 1.0388$

The calculated values of various response averages for Kevlar drill are $\bar{y} = 1.06586$, $A_2 = 1.046$ and $B_4 = 1.045$. So substituting these values in above equation the mean optimum value of delamination factor has been predicted as $F_{d_{opt}} = 1.0251$

In Taguchi optimization technique confirmation experiment was required to be conducted for validating of the optimized condition. Table 7 shows the result obtained and compared with the predicted values. The experimental values pose less than 5% error with the predicted values.

Table 7. Results of confirmation experiments and predicted values of delamination factor

| Delamination factor | Trial 1 | Trial 2 | Mean | Predicted |
|---------------------|--------|--------|------|-----------|
| Twist drill         | 1.04   | 1.0425 | 1.041| 1.0524    |
| End mill            | 1.025  | 1.03   | 1.0275| 1.0388    |
| Kevlar drill        | 1.008  | 1.010  | 1.090| 1.0251    |

3.2. Comparison between the effect of use of Twist Drill, End Mill and Kevlar drill on delamination.

The thrust force during drilling of composite laminates depend on input variables such as cutting speed or spindle speed, feed rate, drill bit geometry, number of drilled holes (tool wear) and drilling operation. Most investigators find that the effect of cutting speed on the thrust force in drilling of composite laminates is insignificant and the thrust force decreases slightly with increasing cutting speed, while the effect of feed rate on the thrust force is remarkable and the thrust force increases with increasing feed rate. The cutting speed has insignificant effect on thrust force in drilling GFRP composite laminates with fresh drill bits, while thrust force increases noticeably with increasing cutting speed when using worn drill bits. Drill bit geometry also affects significantly the thrust force during drilling composite laminates. It is observed that the point angle of twist drill bit has a clear effect on the delamination when drilling composite laminates. The thrust force increased noticeably with increasing point angle of twist drill bit. Therefore, in order to decrease the thrust force, the smaller point angle is a good choice for drilling of composite laminates.
The tools used for drilling in the present study are Twist drill (HSS) of point angle 90°, End Mill (four fluted) made up of carbide and Kevlar drill (carbide). The experiments results reveal that twist drill is having more or large value of delamination factor compared to End mill and Kevlar drill. This is due to the reason that the delamination tendency increased with the point angle. The end mill used was four fluted which reduces delamination to a lower value compared to twist drill because of its geometry, that is four flutes and flat end, which may reduce the thrust force and in turn lower the delamination. It was also observed that the delamination is very much less as compared to both Twist drill and End mill. Kevlar drill bit is a specially designed for drilling of GFRP composites it geometry includes two fluted with a point angle from the centre which acts as pre drilling and this result in reduce the thrust force, thereby reducing delamination. Further from the figure 8, it can be observed that values of delamination factors are nearly same at very low feed rates all the tools. There is a large variation at intermediate and high feed rates. From the figure 9, one can conclude that at higher spindle speeds mean delamination factor is high, irrespective of the tool geometry and the material. Tool geometry and the material affect the delamination at lower spindle speeds and higher feed rates. It quite interesting to note that at very low feed rates (level1) and very high spindle speeds (level5) all three tools shows almost same mean delamination factor irrespective of their material and geometry. It implies too low feed rate and too high spindle speeds are also not preferable to reduce the delamination. But very high spindle speeds in the order of ten thousands rpm will reduce the delamination as mentioned by Campos Rubio J et al. (2008). This is may be due to the severe heat generated because of friction between the tool and work, which may completely make the reinforce matrix weak and makes drilling much easier and hence thrust force is minimum causing lower delamination.

4. Conclusion

This paper has presented an application of the Taguchi method for the delamination study of drilling of GFRP composites. The conclusions of this present study are
The analysis of experimental results is carried out using Taguchi’s orthogonal array and analysis of variance. The level of the best of the cutting parameters on the drilling induced delamination is determined by using ANOVA.

- The drilling induced delamination increases with spindle speed (1000rpm-2500rpm) and decreases with feed rate (100mm/min to 400mm/min).
- The results for very low feed rate i.e., 50mm/min and high spindle speed 300rpm show the opposite trend. In both the cases delamination factor increases instead of decreasing.
- The reason for higher delamination at spindle speed 3000rpm may be, when the drill speed increases, the thrust force increases because severe heat generation in the drilling area leads to softening of the fiber and matrix. As a result, fiber cutting becomes harder for the cutting edges of the drill and drilling thrust force increases further causing more delamination.
- The reason for higher delamination at the feed rate 50mm/min may be that at the feed rate of 50 mm/min, more heat is generated and transferred to the laminate in the drilling area. This may be cause local thermal destruction of the work piece with undesirable results on delamination.
- The results of ANOVA reveals that feed rate is the main cutting parameter, which has greater influence on the delamination factor.
- Based on the S/N, optimal parameters for the minimum delamination are the spindle speed at Level 4 (2500 rpm) and the feed rate at Level 2 (100mm/min).
- Predicted values of delamination at optimized process parameters were in good agreement with the test results.
- Feed rate is the more influential factor on delamination than spindle speed.
- Almost similar trend that is delamination decreases with increasing the spindle speed and decreasing with feed rate for all the tools, but delamination was observed to be less in the case of Kevlar drill.
- At higher spindle speed delamination is high, irrespective of the tool geometry and material, all the tools shows higher values of mean delamination factor at higher spindle speeds.
- Similarly feed rate delamination is high, irrespective of the tool geometry and material, all the tools shows higher values of mean delamination factor at very low feed rate.

References

Capello E, 2004. “Work piece damping and its effects on delamination damage in drilling thin composite laminates,” Journal of Materials Processing Technology, 148(2), 186-95
Campos Rubio. J, Abrao A.M., Faria P.E, Esteves Correia. A and Paulo Davim, J, 2008. “Effect of high speed in drilling of Glass Fiber Reinforced Plastic; Evaluation of delamination factor”; International Journal of Machine Tools & Manufacture, vol. 48, 715-720
Davim J.P, P. Reis and C.C. Antonio, 2004 “Experimental study of drilling glass fiber reinforced plastics (GFRP) manufactured by hand lay-up,” Composites Science and Technology 64, 289-297
Davim J.P, P. Reis and C.C. Antonio, 2004 “Drilling fiber reinforced plastics (FRPs) manufactured by hand lay-up: influence of matrix(Vippal VUP 9731 and ATLAC 382-05),” & Design 236, 54, Journal of Materials Processing Technology, 155-156: 1828–1833.
DeFu Liu, YongJun Tang, W.L. Cong, 2012 “A review of mechanical drilling for composite laminates,” Composite Structures 94, 1265-1279
Ding G.2003 “On-line prediction of delamination in drilling of GFRP by using neural network approach” Mach Sci Technol:7(3) 295-314
Faramarz Ashenai Ghasemi, Abbas Hyvadi, Gholamhassan Payganeh, Naeollah Bani Mostafa Arab ,2011 “Effects of Drilling Parameters on Delamination of Glass Epoxy Composites” Australian Journal of Basic Applied Sciences, 5(12): 1433-1440
Hochenga, H. Tsao, C.C, 2005“The path towards delamination-free drilling of composite materials,” Journal of Materials Processing Technology, 167, 251-264
Hochenga, H. Tsao, C.C, 2006 “Effects of special drill bits on drilling-induced delamination of composite materials,” International Journal of Machine Manufacture 46, 1408-1416
Nirudra Mandal, B. Doloi , B. Mondal , Reeta Das 2011 “Optimization of flank wear using Zirconia Toughened Alumina (ZTA) cutting tool: Taguchi method and Regression analysis” Measurement 44, 2149–2155
Park KY, Choi JH and Lee DG, 1995 “Delamination-free and high efficiency drilling of carbon fiber reinforced plastics,” J Compos Mater 29, 1998-2002
Palanikumar. K.2011 “Experimental investigation and optimization in drilling of GFRP composites,” Measurement 44, 2138-2148
Ramkumar J, Aravindan S, Malhotra SK and Krishnamurthy R.2004, “An enhancement of machining performance of GFRP by oscillatory assisted drilling” International Journal of Advance Manufacturing Technology 23 240–244
Tsao CC, Hocheng H. Taguchi, 2004 “Analysis of delamination associated with various drill bits in drilling of composite material,” Int J Mach Tools Manuf44,1085-90
Wong T.L, Wu S.M, Croy C.M.1982. An analysis of delamination in drilling composite materials, In; Proceedings of 14th SAMPE Technology Conference, Atlanta, GA, USA , 471-483