A Digital Image Analysis to Evaluate Delamination Factor after Drilling GFRP Composites using a Kevlar Drill Bit

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Abstract

Objectives: Evaluation of three important delamination factor models and compare their values with varying spindle speeds and feed rates in drilling GFRP composites. Methods: Digital image analysis is adopted for measurement of the dimensions of delamination damage. Accurate assessment of delamination damage is essential for the analysis and design of optimum drilling parameters. Experiments were conducted on GFRP composite materials with feed rates ranging from 100-400 mm/min and spindle speeds ranging from 1000-2500 rpm. Findings: These experiments reveal that delamination reduces with increase in the spindle speed and reduction in the feed rate, but higher spindle speeds may increase the delamination damage. Results also reveal the consideration of area of delamination damage in the assessment of delamination is more important than the maximum damage diameter. Applications: The good mechanical properties of GFRP composites allow their use in compartment panels and doors. Digital image analysis improves the accuracy in measurement of delamination damage.

Keywords: Delamination, Digital Image Analysis, Feed Rate, GFRP, Kevlar Drill Bit, Spindle Speed

1. Introduction

Composites are extending the horizons of designers in almost all branches of engineering. Many new composites are being developed through research and innovations of recent years, which find applications in a wide range of fields. Examples are: glass fibre reinforced ones in automobiles and particulate composites in aerospace applications. Latest such materials are formed having the matrix embedded with fibres or particles. Glass fibre reinforced polymer or GFRP is such a composite used in structural applications. GFRP composites find applications as fairings, compartment panels and doors.

Drilling is a common secondary machining operation for fiber-reinforced materials. Composite laminates have low machinability resulting in low drilling efficiency and drilling-induced delamination damage. Here structural fastening of these components call for accurate and defect-free drilling to ensure precision and joint strength. However, composite laminates, by their very nature, are non-homogeneous, anisotropic, and highly abrasive with hard reinforcement fibres. Among the machining issues due to these, the major one in drilling operations is the delamination defect.

Many investigations were conducted to assess the influence of input variables (spindle speed, feed rate, and...
Digital image processing has been widely used to determine the delamination damage around the hole by researchers. Its applications are also extended to various other areas including medicine. Till now there is no common agreement on the method of assessing the delamination.

Present study aims to conduct drilling experiments on GFRP composite by using carbide hard diamond coated and brad point (Kevlar) drill bit and also evaluate the delamination around the hole by using digital image analysis. This paper also presents the variation in values of three delamination factors, namely conventional delamination factor ($F_d$), adjusted delamination factor ($F_{da}$) and equivalent delamination factor ($F_{ed}$) and compare these at different spindle speeds and feed rates.

2. Experiment and Calculation

2.1 Materials

GFRP composite laminate of thickness 6 mm has been used as work-piece material and the information related to the same is given in Table 1. Figure 1 show the drill used, namely, Kevlar drill made of Carbide steel of 10 mm diameter. The machine tool is a MAKINO S 56 CNC vertical milling machine with maximum speed of 3000 rpm. The experiment is carried out by varying spindle speeds from 1000-2500 rpm in the steps of 500 rpm, and feed rates from 100-400 mm/min in the steps of 100 mm/min. Damage around the hole is captured using a digital camera. The area of the damage is calculated using ‘Image J’ software. To obtain an image of good quality the parameters: Noise suppression, brightness intensity, edge detection and image enhancement are adopted. These steps are shown in Figure 2. Histogram of array values of delaminated zone was compared with that of undamaged area to set the threshold value for binary conversion of the images.

| Sl.No | Specification | Description/Values |
|-------|---------------|--------------------|
| 1     | No of layers  | 26                 |
| 2     | Thickness     | 6 mm               |
| 3     | Orientation   | 0/90               |
| 4     | Resin         | L-12               |
| 5     | Hardener      | K-5                |
| 6     | Fibres        | Unidirectional E-glass |
Figure 1. KEVLARBOHRER SCD 56279 drill (Carbide).

Figure 2. Stages in digital image processing. (a) Image captured in grey scale. (b) Histogram equalization. (c) Threshold setting. (d) Noise reduction. (e) Processed image.

2.2 Assessment of Delamination

2.2.1 Delamination Factor ($F_d$)

Author in\(^2\) proposed a delamination factor ($F_d$) which is defined as the ratio of maximum delaminated diameter ($D_{\text{max}}$) to the hole nominal diameter ($D_o$).

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

$D_{\text{max}}$ is the maximum diameter created due to delamination around the hole and $D_o$ is the hole or drill diameter.

2.2.2 Adjusted Delamination Factor ($F_{da}$)

Conventional delamination factor ($F_d$) accounts for only the size of delamination and the area of the delaminat- 

tion damage is not included in the calculation. Hence another delamination factor was proposed by\(^3\), named as Adjusted delamination factor ($F_{da}$) which is calculated by using Equation (2). First part of the Equation (2) assesses the crack lengths (as in the conventional delamination factor, $F_d$) and the second part assesses the damage area. The advantage of this measure is that it incorporates the area of damage. It, therefore distinguishes the severity of delamination in cases with different damage areas where the $D_{\text{max}}$ is identical. The $F_{da}$ thus is a better measurement of delamination damage than $F_d$.

$$A_d = \text{Delamination area in the vicinity of the drilled hole},$$
$$A_{\text{max}} = \text{Delamination area related to } D_{\text{max}}$$

$$A_0 = \text{Drilled area with diameter, } D, \text{ which is the nominal hole area}$$

$$F_{da} = F_d + \frac{A_d}{A_{\text{max}} - A_0} \quad (2)$$

2.2.3 Equivalent Delamination Factor ($F_{ed}$)

Another factor has been proposed by\(^2\) for the delamination damage, namely the Equivalent delamination factor ($F_{ed}$) calculated by using Equation (3). The equivalent diameter is calculated using Equation (4). The various terms in the formula of $F_{ed}$ are shown in Figure 3.

$$F_{ed} = \frac{D_e}{D_0} \quad (3)$$

$$D_e = \left[ \frac{4(A_d + A_0)}{\pi} \right]^{0.5} \quad (4)$$

Figure 3. Scheme of the $F_{ed}$ in drilling composite laminate.

3. Results and Discussions

Drilling trials are carried out to evaluate the effect of cutting parameters on the damage to work piece. Damage
around the hole is scanned using a digital camera. The area of the damage zone is calculated using 'Image J' software. After obtaining the values of maximum delamination diameter and area of delaminated zone, conventional delamination factor \( F_d \), adjusted delamination factor \( F_{da} \) and effective delamination factor \( F_{ed} \) are calculated using the Equations (1), (2) and (3), (4) respectively. The results are tabulated in the Table 2.

3.1 Conventional Delamination Factor \( (F_d) \)
From the Table 2, it can be observed that the conventional delamination factor \( (F_d) \) is increasing with the feed rate and decreasing with the spindle speed. Highest delamination factor is observed at the combination of low spindle speed (1000 rpm) and high feed rate (400 mm/min) and lowest delamination factor is observed at the combination of spindle speed (2500 rpm) and feed rate (100 mm/min). This is in good agreement with the\(^{41}\). Further increase in spindle speed to 3000 rpm may increase the delamination as reported by\(^{35,42}\).

3.2 Adjusted Delamination Factor \( (F_{da}) \)
From the Table 2, it is also observed that adjusted delamination factor \( (F_{da}) \) gradually decreases with increasing speed and increases with increasing feed rate. It was also observed that for the combination of highest feed and highest spindle speed the value of adjusted delamination factor is high. This may be due to the heat generated in the drilling area causing softening of the fibre and matrix, which makes it difficult for the cutting edges of the tool to cut the fibres and damage the area in the vicinity of the hole. This is reflected in higher value of adjusted delamination factor. These results are in good agreement with those obtained by\(^{42}\).

3.3 Equivalent Delamination Factor \( (F_{ed}) \)
From the Table 2, it is also observed that the trend of variation of equivalent delamination factor \( (F_{ed}) \) is similar to that of the adjusted delamination factor \( (F_{da}) \) for varying spindle speeds and feed rates. This can be explained with the same reasonings as given in Section 3.2. The variation of the three delamination factor values with drilling parameters is illustrated in Figure 4.

3.4 Comparison between \( F_d, F_{da}, F_{ed} \)
Figure 5 shows the variation of different delamination factors \( F_d, F_{da}, F_{ed} \) with respect to the feed rates at different spindle speeds. From the figure it is observed that adjusted delamination factor is higher when compared with the conventional delamination factor and effective delamination factor, for all the spindle speeds and feed rates. This is due to the fact that it considers both the crack length contribution and damaged area contribution on delamination whereas conventional delamination factor considers only the maximum crack diameter and effective delamination factor considers only damaged area for the assessment of delamination factor. For the entire spindle speeds equivalent delamination factor shows lower values when compared to the other two delamination factors, except at the spindle speed 2500 rpm. The reason for this may be at high spindle speeds the heat generated in the drilling area causing softening of fibre and matrix make fibre cutting difficult for cutting edges of the tool and causing more damage in the vicinity of the hole but with minute cracks, which in turn causing the conventional delamination factor values lower compared to those of equivalent delamination factor and adjusted delamination.
factor. Delamination damage is initiated in the vicinity of the drilled hole and then propagates as cracks and hence adjusted delamination factor and equivalent delamination factor are the most suitable factors as compared to the conventional delamination factor for the assessment of delamination damage.

Figure 5. Correlation between various delamination factors with feed rate at various spindle speeds. (a) 1000. (b) 1500. (c) 2000. (d) 2500 rpm.

4. Conclusion

This paper presents the assessment of delamination by using digital image analysis and comparison of various delamination factor models. The important conclusions of this investigation are

- Conventional delamination factor \( F_d \) increases with the feed rate and decreases with the spindle speed. The induced delamination decreases with spindle speed (1000 rpm-2500 rpm) and increases with feed rate (100 mm/min to 400 mm/min).
- Highest value of delamination factor is observed at the combination of low spindle speed (1000 rpm) and high feed rate (400 mm/min) and lowest value of delamination factor is observed at the combination of spindle speed (2500 rpm) and feed rate (100 mm/min).
- Both the factors, adjusted delamination factor \( F_{da} \) and Equivalent delamination factor \( F_{ed} \) gradually decrease with increasing spindle speed and increase with the increasing feed rate.
- At the combination of highest feed rate and highest spindle speed the values of these factors are high.
- The reason for this trend for both the factors may be, the heat generated in the drilling area at high spindle speeds and high feed rates causes soften-

Table 2. Experimental results

| Drilling conditions | Delamination parameter | Delamination factor models |
|---------------------|------------------------|---------------------------|
|                    | \( D(\text{mm}) \)    | \( D_{\text{max}}(\text{mm}) \) | \( A_{d}(\text{mm}) \) | \( D_{t}(\text{mm}) \) | \( F_d \) | \( F_{da} \) | \( F_{ed} \) |
| 100 1000            | 10 10.55 6.42 10.40   | 1.06 1.10 1.04           |
| 100 1500            | 10 10.5 6.79 10.42    | 1.05 1.09 1.04           |
| 100 2000            | 10 10.4 3.15 10.20    | 1.04 1.06 1.02           |
| 100 2500            | 10 10.08 6.65 10.41   | 1.01 1.05 1.04           |
| 200 1000            | 10 10.6 8.00 10.49    | 1.06 1.11 1.05           |
| 200 1500            | 10 10.57 6.50 10.40   | 1.06 1.10 1.04           |
| 200 2000            | 10 10.45 6.07 10.38   | 1.05 1.08 1.04           |
| 200 2500            | 10 10.22 8.54 10.53   | 1.02 1.08 1.05           |
| 300 1000            | 10 10.65 9.01 10.56   | 1.07 1.12 1.06           |
| 300 1500            | 10 10.6 7.00 10.43    | 1.06 1.11 1.04           |
| 300 2000            | 10 10.5 6.53 10.40    | 1.05 1.09 1.05           |
| 300 2500            | 10 10.35 9.39 10.58   | 1.04 1.10 1.06           |
| 400 1000            | 10 10.75 9.48 10.58   | 1.08 1.14 1.06           |
| 400 1500            | 10 10.65 7.58 10.47   | 1.07 1.11 1.05           |
| 400 2000            | 10 10.52 6.95 10.43   | 1.05 1.10 1.04           |
| 400 2500            | 10 10.4 17.55 11.06   | 1.04 1.15 1.11           |
ing of the matrix and fibre, which may make fibre cutting difficult for the cutting edges of the tool causing more areas to be damaged in the vicinity of the hole. These result in lower values for the conventional delamination factor compared to the adjusted delamination factor and equivalent delamination factor.

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