Analysis and evaluation of drilling induced damage in fiber reinforced polymer composites: A review

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Abstract. Fiber reinforced composite materials are very competent materials to be used in a wide spectrum of engineering applications ranging from household appliances to aerospace components. Drilling operation is heavily performed machining operation while fabricating a fiber reinforced polymer composite based product. Delamination at the entry and exit side of the laminate is dominant damage while making holes in composites which leaves the component unusable. The analysis and evaluation of delamination should follow some standards in order to compare the damage effectively. The present paper reviews various methods adopted by the researchers to analyze and evaluate the drilling induced damage commonly known as delamination in fiber reinforced polymer composites.

Keywords: Delamination, Polymer composites, drilling induced damage, Machining, laminates.

1. Introduction
In recent past years, the fiber reinforced polymer composite (FRPC) materials have attracted the attention of engineers and scientists to exploit their unique properties like high strength to weight ratio, corrosion resistance, high specific modulus of elasticity and low weight [1, 2, 3]. The fiber reinforced polymeric composite materials are inhomogeneous, anisotropic and laminated structures due to which machining of these materials becomes very complex [4]. As the spectrum of application expands, the requirement of various machining operations especially drilling have increased drastically to assemble various FRP components into a product. Drilling is an unavoidable operation required within an industry working in the field of fiber reinforced polymer composite based products. During the drilling operation, various concentrated forces could be generated which can lead to catastrophic failure of the product [5]. Along with the aesthetic look of the component, the risk of failure of the component also increases with the drilling induced damages. Delamination is the major problem encountered in the field of FRPC occurring at the entrance and exit side of the workpiece [6]. The problem of delamination can be correlated to various parameters of drilling operation like feed rate, spindle speed, geometry of the cutting tool etc. [7]. At the starting of drilling operation, laminate thickness is enough to withstand the cutting forces but as the operation proceeds towards the exit plane of the laminate, the thickness reduces to such level that the laminate is no more able to withstand the cutting force which in turn results in the separation of lower layers from upper layers. This phenomenon is known as delamination [5]. In order to avoid the problem of delamination, the process parameters must be optimized by rigorous experimentations. Various authors studied the effect of various parameters on
the drilling induced delamination. Measurement of the delamination is generally done by comparing the damage area with the required area of drilled hole/area corresponding to the diameter of drilling tool [5]. Alvarez et al. [8] studied the effect of various drilling parameters on the drilling induced damage. Authors developed fully bio-degradable composite material by using cotton/flax/jute as reinforcement and PLA (Polyactic acid) as matrix material. Authors studied the damage area at both the side of laminate thickness i.e. entry side and exit side of the drill tool. Authors concluded that the extension of the damage was dependent on the matrix material, fiber type and geometry of the drill. Hocheng et al. [4] studied the quality of hole at the entrance and exit side of the hole. Authors used two types of matrix materials namely ABS (thermoplastic) and epoxy (thermoset) while carbon fiber was the only reinforcement. Authors concluded that the surface of the drilled hole was better in the case of thermoplastic matrix due to smooth chips generation in comparison to composite with thermoset matrix.

Selection of the optimum parameters can be done only after the successful evaluation of the quality of drilled hole. The evaluation of the drilled hole must be done on the basis of some standards in order to effectively compare the quality of hole produced. In the present review, various methods which have been successfully adopted by the researchers to evaluate the drilling induced delamination are explored with their advantages and limitations.

2. Analysis of Delamination

The intensity of drilling induced damage is generally characterized by the delamination factor. Several other techniques also have been employed to analyze the intensity of the damaged hole as qualitative microscopic analysis, digital photography, S-Can and other quantitative methods [9, 10]. Seif et al. [11] used a non-destructive visual inspection technique to determine the intensity of the delamination which utilizes a shadow moire laser-based imaging. Several other researchers also used optical microscope [12, 13, 14], ultrasonic C-scan [15, 16, 17] and digital photography [18, 19] to determine the intensity of the drilling induced damage. The damaged hole image is generally obtained from some scanning apparatus and then counting of the pixels of damage area gives the damage area. Abilash et al. [20] used an inexpensive method to find out the delamination size using personal computer, color flatbed scanner and an image software namely “CorelDraw”. In first step, the damaged hole was scanned showing the clear image of delamination zone. In second step, this BMP format image was exported to the “CorelDraw” software and the image was magnified. Two circles were drawn to measure the delamination zone and drill diameter. In last step, photoshop software was used to measure the diameters of the delamination zone and original drill diameter. Delamination factor was used to quantify the intensity of delamination. Quantification of the delamination proposed by various authors are as follows.

2.1 Delamination factor ($F_d$)

Delamination factor is the ratio of the maximum diameter of the circle which includes all the damaged area to the diameter of the drill used to make hole in the laminate as indicated by equation 1 [21]. Arul et al. [22] studied the effect of frequency and amplitude of axial vibrations in the direction of feed during the hole making operation in glass fiber reinforced plastic (GFRP) composites. Authors used optical microscope coupled with an image analyzer in order to establish the intensity of the defects and authors obtained the delamination factor from the ratio of the maximum diameter covering all area of the damaged zone to the drill diameter. Davim and Reis [23, 24] studied the drilling induced damage by comparing the delamination factors on both the sides of carbon fiber reinforced plastic (CFRP) laminates. Authors used tool maker’s microscope of very high magnification to evaluate the intensity of drilling induced damage. The authors calculated the delamination factor as the ratio of maximum diameter ($D_{max}$) covering the complete damaged area to the drill diameter ($D_d$) as represented in figure 1(a). Authors studied the effect of various drilling parameters on the damage and concluded that the delamination factor at the entry side was highly influenced by the feed rate of drilling operation, whereas at the tool exit side, delamination was mostly influenced by cutting speed. Some authors
defined the delamination factor as the ratio of delaminated area to the desired area of the hole as indicated by equation 2 [25].

\[
F_d = \frac{D_{\text{max}}}{D_0} \quad \text{(1)}
\]

\[
F_d = \frac{A_{\text{max}}}{A_0} \quad \text{(2)}
\]

Where \(D_{\text{max}}\) and \(A_{\text{max}}\) are the diameter and area of the drilling induced damage and \(D_0\) and \(A_0\) are the required diameter and area of the hole respectively.

Bajpai et al. [25] used an image processing software namely Image J to analyze the damage intensity of the hole. Authors quantified the delamination factor as the ratio of maximum damaged area (hole area + damage area) to the hole area. The maximum delamination factor achieved was 1.8 at 900 RPM for the Jo type of drill geometry while minimum delamination factor of 1.0 was achieved by twist drill at 1800 RPM. Patel et al. [26] investigated the drilling of banana fiber reinforced polyester composites. These authors also defined the delamination factor according to the equation 2. Authors found that maximum and minimum delamination factor achieved at the entry side were 1.0906 and 1.0126 respectively. This delamination factor is generally known as conventional delamination factor and due to the simplicity of the calculation, various authors have used conventional delamination factor to evaluate the drilling induced damage [27-34].

### 2.2 Adjusted Delamination Factor (\(F_{da}\))

Conventional delamination factor considers that the size of crack is a representation of the magnitude of damage since delamination of few fibers may give larger diameter resulting in large delamination factor [35]. According to the Davim et al. [21], the size of crack is not a true and convenient representation of the intensity of the damage. It is very much possible that a small linear crack of very low area may result in failure of component due to crack propagation nature of the materials. So, Davim et al. [21] proposed a novel approach to quantify the damage intensity namely adjusted delamination factor as represented by equation 3.

\[
F_{da} = \alpha \frac{D_{\text{max}}}{D_0} + \beta \frac{A_{\text{max}}}{A_0} \quad \text{(3)}
\]

Where \(D_{\text{max}}\) and \(A_{\text{max}}\) are the diameter and area of the drilling induced damage and \(D_0\) and \(A_0\) are the required diameter and area of the hole. The parameters \(\alpha\) and \(\beta\) are used as weights. Authors defined the \(\beta\) as the ratio of the damage area \(A_d\) to the area corresponding to \(D_{\text{max}}\) minus the nominal hole area \((A_0)\) as indicated in equation 4. The parameter \(\alpha\) is the complement of \(\beta\), i.e. \(\alpha = 1 - \beta\). Therefore, Equation 3 can be rewritten as equation 5.

\[
\beta = \frac{A_d}{A_{\text{max}} - A_0} \quad \text{(4)}
\]

\[
F_{da} = F_d + \frac{A_d}{A_{\text{max}} - A_0} (F_d^2 - F_d) \quad \text{(5)}
\]

Authors obtained the damaged area through the image digitalization and processing using a software namely Image J. The binary image obtained after image processing through software was subjected to the threshold filter to separate the gray and black points and after that the area of damaged hole was measured. Authors showed that the adjusted delamination factor was lower than the conventional delamination factor but the behavior of adjusted delamination factor was similar to the conventional delamination factor. Authors concluded that the adjusted delamination factor can be suitably used to characterize the drilling induced damage.

### 2.3 Equivalent Delamination Factor (\(F_{eq}\))

Though, adjusted delamination factor gives more accurate values compared to the conventional delamination factor but it is not able to provide exact information about the minimum or maximum delamination area as the adjusted delamination factor never becomes equal to the conventional delamination factor in any case [9, 35]. Therefore, Tsao et al. [9] proposed a novel method to evaluate
the delamination factor namely equivalent delamination factor \((F_{ed})\) calculated as equation 6. In this method, the equivalent area of the damaged area was used to compare with nominal area.

\[
F_{ed} = \frac{D_e}{D_0}
\]  

(6)

Where \(D_0\) is the nominal drill diameter and \(D_e = \left[ \frac{4(A_d + A_0)}{\pi} \right]^{1/2}\). \(A_d\) and \(A_0\) are the damaged area and nominal drill area respectively. Experimental study showed that the adjusted delamination factor gave larger values than equivalent delamination factor. Authors concluded that adjusted delamination factor and equivalent delamination factor had better representation of the damaged intensity than conventional delamination factor. Figure 1 (b) shows the equivalent diameter \((D_e)\), maximum diameter \((D_{max})\) and nominal diameter \((D_0)\) in case of irregular damaged area while drilling of laminate.

2.4 Effective equivalent delamination factor (FEED)

Babu et al. [35] explained that it is quite not possible to define accurately various regions of damage required to calculate the refined delamination factor. Therefore, authors proposed an approach to evaluate the damage intensity after the drilling operation namely effective equivalent delamination factor abbreviated as FEED. FEED gives equal weightage to the length of crack and damaged area. FEED was calculated as equation 8.

\[
FEED = \frac{D_{ea} + D_{ep}}{2D_0}
\]  

(8)

Where \(D_{ea} = \left( \frac{A_e}{\pi} \right)^{0.5}\) and \(D_{ep} = \frac{P_e}{\pi}\) (\(A_e\) and \(P_e\) are the area and perimeter of the envelope of damage zone respectively).

Experimentations conducted by the authors showed that the value of FEED lies in between the equivalent delamination factor and adjusted delamination factor.
3. Conclusions

Different methods were proposed by various researchers to evaluate the intensity of the delamination in composites. Measure of the delamination can be done by various delamination factors proposed by various researchers. In spite of the shortcomings involved in the calculation of conventional delamination factor, it is mostly used measure due to its simplicity. The values of conventional delamination factor were found to be misleading in the case of very fine cracks. Adjusted delamination factor was proved to be an effective measurement method to calculate the intensity of drilling induced damage. The values of equivalent delamination factor was found to be in between the conventional and adjusted delamination factor.

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