DRILLING FIBRE REINFORCED PLASTIC: A NOVEL DELAMINATION FACTOR

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Abstract. *Drilling is probably the machining processes most widely used in composite materials owing to the fact that components made out of composite materials are usually near net shaped, thus requiring holes for assembly integration. Delamination is the principal problem associated with drilling fibre reinforced composite materials. In this work the effects of feed rate and spindle speed on the resulting delamination factor value are assessed. A novel delamination factor used to characterize the defects in drilled hole employs digital image analysis. The experimental results indicated that the use of digital analysis is suitable to estimate the damages produced after drilling glass fibre reinforced plastics.*

Keywords*: Delamination, Drilling, Polymer-matrix composites.*

1. INTRODUCTION

Fibre reinforced composites are widely recognized for their superior mechanical properties and advantages for applications in aerospace, defense and transportation sectors. Frequently, composite materials are composed of just two phases; one is named matrix (soft and tough), which is continuous and surrounds the other phase, often called dispersed phase (hard reinforcing). The properties of composites are dependent on of the properties of the constituent phases [Callister, 2002].

Epoxy resins are widely used as matrix in many fibre reinforced composites. Epoxy resins are a class of thermoset materials of particular interest to structural engineering because they provide a unique balance of chemical and mechanical properties combined with broad processing versatility. Some of their most interesting applications are found in the aerospace, automotive and recreational industries where resins and fibres are combined to produce complex composite structures [Boyle et al., 2003].

As far as the reinforcing material is concerned, glass fibres are the most widely used in structural constructions due to their specific strength properties [Callister, 2002]. In strategic applications composites with higher fibre volume fraction are used to ensure higher order energy absorption. In this study the performance of a glass/epoxy composite material was investigated when subjected to drilling with two different tools and various cutting parameters.

Drilling is the machining process most widely employed to composite materials owing to the fact that components made out of composite materials are usually near net shaped, thus requiring mounting holes for assembly integration. Neverthelss, delamination is the principal problem associated with drilling fibre reinforced polymeric (FRP) composite materials and, in addition to reducing the structural integrity of the material, delamination also results in poor assembly tolerances and has the potential for long-term performance deterioration. The key factor for solving the matter lies in reducing the drilling thrust force. Two delamination mechanisms associated with drilling FRP composites are known as peel-up at entrance and push-out at exit [El-Sonbaty et al., 2004], see Fig. 1.

Several techniques have been employed to measure delamination after drilling composites, such as optical microscopy, S-Can and digital photography. Generally speaking, a quantitative evaluation is required in order to assess the effect of the cutting parameters and drill geometry [Davim et al, 2007]. The delamination factor has been widely used to characterize the level of damage on the work material at the entrance and exit of the drill. The delamination factor (F_d) may be calculated from the ratio of the maximum diameter (D_{max}) at the delamination zone to the drill diameter (D_0), as $F_d=D_{max}/D_0$. Alternatively, the ratio of the delaminated area to the hole area has also been used.

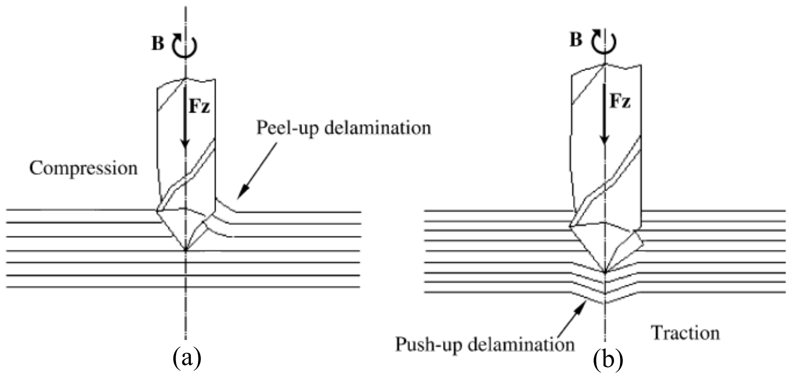


Figure 1. - Delamination at the tool entry (a) and exit (b) when drilling FRP laminate.

Davim et al. (2004) compared the influence of different drill geometries on the delamination in a hand lay-up glass fibre reinforced plastic (GFRP) laminates. A tool maker's microscope with a magnification of 30 times was used to evaluate the damage as the machining parameters were changed. The delamination factor was considered as the ratio of maximum diameter in the damage zone to the drill diameter. The findings indicated that the damage increases with both cutting speed and feed rate.

Aoyama et al. (2001) investigated the damage after drilling holes with small diameter in printed wiring boards and concluded that delamination (which leads to ion migration) is generated along the fibre in the hole wall surface, where the surface roughness increases. According to these authors, the thickness of the fibre bundle affects the internal damage of the hole. The internal damage increases as the thickness of the fibre bundle increases at same edge position angle.

Capello (2004) studied the different delamination mechanisms observed when drilling with and without backing the workpiece. The author states that the relationship between delamination and the thrust force exerted by the drill point is valid only for drilling with backing. When drilling without backing, the delamination mechanism is more complex (for instance, the presence of a peak in the actual feed rate and the overload on the peripheral part of the cutting lips). The author used the delaminated area to characterized the damage.

2. PROPOSED DELAMINATION FACTOR

Equation 1 shows the most popular delamination factor, which provides satisfactory results when delamination possesses a regular pattern, as in glass fibre reinforced composites. However, when carbon fibre reinforced plastic materials are machined, delamination presents an irregular form, containing breaks and cracks at the hole entry and exit. In this case, the conventional delamination factor is not appropriated due to the fact that the size of crack is not a convenient representation of the damage magnitude. Additionally, this procedure does not indicate the damage area, as shown in Figure 2, where the same delamination factor is recorded under two distinct conditions. Therefore, a novel approach devised to measure the delamination factor is proposed, namely adjusted delamination factor (F_{da}), and calculated through Equation (2). The first part of Equation (1) represents the size of the crack contribution (conventional delamination factor, F_d), and the second part represents the damage area contribution.

$$F_{dc} = \alpha \frac{D_{max}}{D_0} + \beta \frac{A_{max}}{A_0} \tag{1}$$

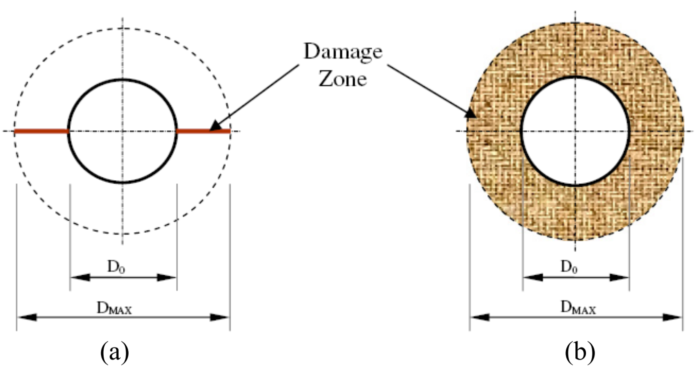


Figure 2 - Critical cases when drilling FRP laminate: (a) fine cracks and (b) uniform damage area.

Where, A_{max} is the area related to the maximum diameter of the delamination zone (D_{max}) and A_0 is the area of the nominal hole (D_0). The parameters α and β are used as weights to the parts of Equation (3). Thus:

$$A_{\max} = \pi \cdot \frac{D_{\max}^2}{4} \tag{2}$$

$$A_0 = \pi \cdot \frac{D_0^2}{4} \tag{3}$$

Replacing Equations 1, 3 and 4 into Equation 2 yields to:

$$F_{da} = \alpha \cdot F_d + \beta \cdot F_d^2 \tag{4}$$

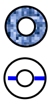
In this work, β is considered as the ratio of the damage area (A_d) to the area corresponding to D_{max} (A_{max}) minus the nominal hole area (A_0). The parameter α is the complement of β, i.e., α=1-β. Therefore, Equation (6) can be rewritten as:

$$F_{da} = (1-\beta) \cdot F_d + \beta \cdot F_d^2 \tag{5}$$

$$F_{da} = F_d + \frac{A_d}{(A_{\max} - A_0)}\left(F_d^2 - F_d\right) \tag{6}$$

Thus,

$$\text{If } \begin{cases} A_d \to (A_{\max} - A_0) \Rightarrow F_{da} \to F_d^2 \\ A_d \to 0 \ \Rightarrow F_{da} \to F_d \end{cases}$$



i.e., if the trend is a delamination area equal to the crown area embody of maximum diameter (D_{max}) of the delamination zone, the adjusted delamination factor (F_{da}) gives a value equal to the square of the conventional delamination factor (uniform behaviour). However, if the delamination area is minimal, the adjusted delamination factor (F_{da}) presents a value tending to the conventional delamination factor (see Figure 2).

3. EXPERIMENTAL PROCEDURE

Drilling experiments were conducted on a machining centre with 11 kW spindle power and a maximum spindle speed of 8000 rpm. Experiments were performed on laminated glass reinforced epoxy resin, which are made out of woven glass cloth. The following cutting parameters were tested: rotational speeds of 4000 and 8000 rpm and feed speeds of 1000, 3000, 6000 and 9000 mm/min. One replicate for each test run was conducted.

The composite laminates, with 3,0 ± 0,2 mm thickness, were fabricated using hand lay-up technique. The constituent materials of the composite laminate are indicated in Table 1.

Table 1 - Composition of the glass fibre reinforced composite laminate samples.

Material	***Type***
Matrix	Epoxy: Araldite M
Hardener	HY 956
Matrix Modulus of elasticity	2,15GPa
Matrix Maximum strength stress	82,55MPa
Reinforcing material	E-glass fibre (woven), 400 g/m^2

Glass fibre reinforced plastic laminates (epoxy matrix reinforced with 50% wt. glass fibre with an orientation of 0/90°) made up of 10 alternating layers of fibres with an average thickness of 3 mm were used as work material. A cemented carbide drill ISO grade K20 “Brad & Spur” (Guhring oHG) with geometry WN R FK was used as cutting tool

(Davim et al., 2004). This drill possesses a diameter of 5mm and 25° helical angle. The composite laminates were fixed in machining centre using an appropriate clamping system. Two composite laminates were simultaneously drilled.

The damage around the holes was measured with a Mitutoyo toolmaker's microscope model *TM 500* ® with 30X magnification and 1μm resolution. The damage was analysed and measured by means of an image acquisition system. The system allows digitalizing with a 600 dpi resolution scanner (see Fig. 3).

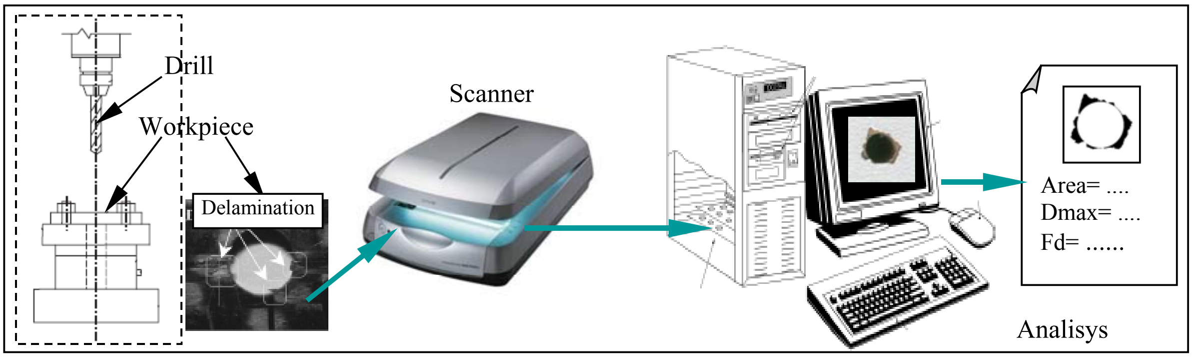


Figure 3. Acquisition system for measuring delamination.

3. RESULTS AND DISCUSSION

Composite laminates usually present harsher delamination at the drill exit. However, when drilling double board laminates and using high cutting speeds more severe damage was observed at the drill entrance (peel-up delamination). Table 2 shows the calculated F_d and F_{da} values for distinct test conditions. The effect of both feed and spindle speeds on peel-up delamination can thus be assessed.

Table 2 -.Cutting parameters tested and correspondent delamination factor.

Test run	Rotational speed (rpm)	Feed speed (mm/min)	Entrance Delamination factor [(1)]		$\frac{(F_{da}-F_d)}{F_{da}}x100\%$
			F_d	**F_{da}**	
1	4000	1000	1.258	1.353	7.01
2	4000	3000	1.551	1.706	9.08
3	4000	6000	2.041	2.328	12.33
4	4000	9000	2.094	2.512	16.65
5	8000	1000	1.178	1.229	4.16
6	8000	3000	1.511	1.669	9.48
7	8000	6000	1.507	1.667	9.61
8	8000	9000	1.741	2.030	14.25

[(1)] Average of two tests.

Figure 4 shows the raw and processed images at the holes entrance. The features observed can be used to evaluate the characteristic damage at higher speed drilling (8000 rpm). It can be seen that holes produced at spindle speed of 4000 and 8000 rpm present an increasing damage as feed speed is elevated.

Figure 5 shows both delamination factors (F_d and F_{da}) obtained under distinct cutting conditions. The effect of the damage area on the adjusted delamination factor can be assessed for spindle speeds of 4000 and 8000 rpm. It can be seen that for low spindle speeds the conventional delamination factor is closer to the adjusted factor, indicating that the damage area (A_d) is small; however, the difference between F_d and F_{da} increases as feed speed is elevated. Furthermore, for a spindle speed of 4000 rpm, the difference between the conventional and adjusted delamination factors remains almost unaltered.

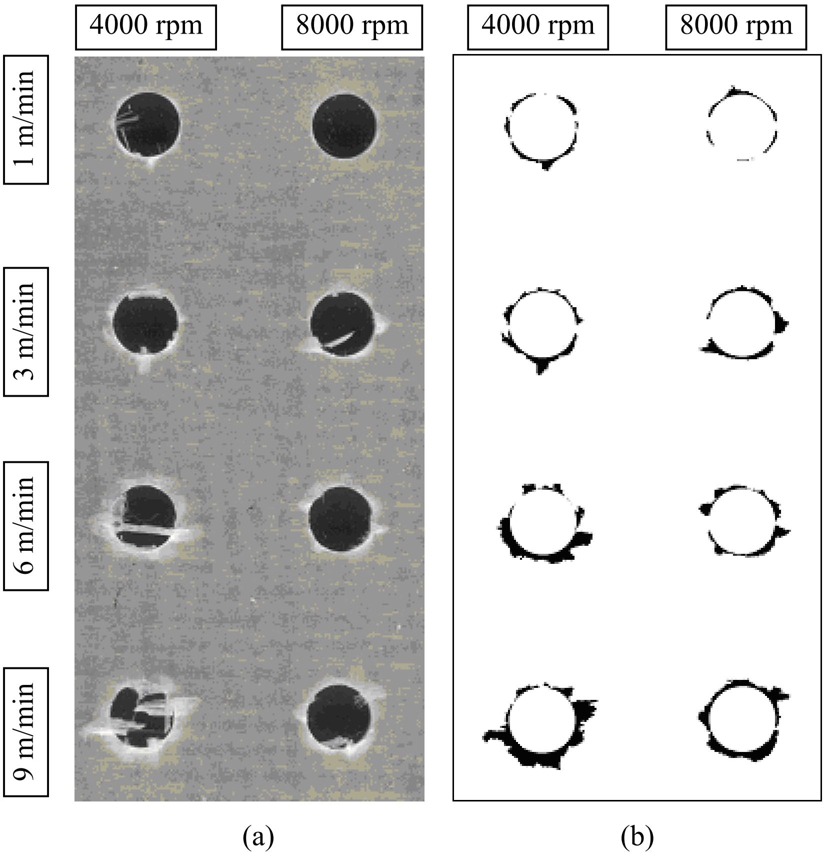


Figure 4 – Raw (a) and processed (b) images of the damage on glass fibre reinforced laminates.

In addition to that, the results presented in Figure 5 suggest that the adjusted delamination factor is more sensitive to the machining parameters (spindle speed and feed speed) than the conventional delamination factor, therefore, the former seems to be more suitable for mathematical modelling of the damage, as reported by Sardiñas et al. (2006) and Tsao and Hocheng (2006).

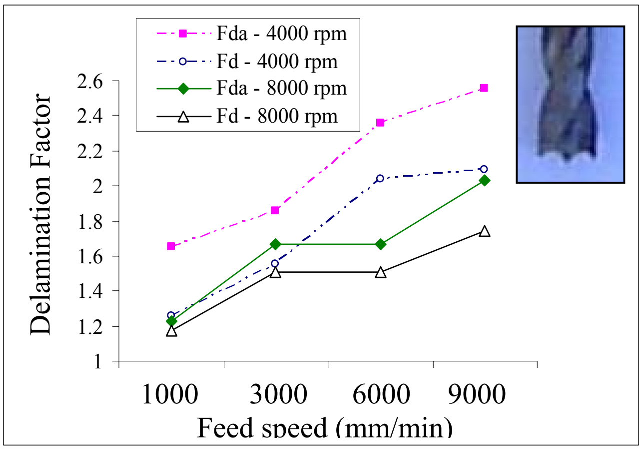


Figure 5 – The effect of feed speed on the conventional (F_d) and adjusted (F_{da}) delamination factors.

4. CONCLUSIONS

Based on the experimental results obtained concerning the damage induced after high speed drilling glass fibre reinforced laminates using a cemented carbide drill, the following conclusions can be extracted:

- Within the cutting range tested, delamination decreases as the spindle speed is elevated;
- For spindle speeds of 4000 and 8000 rpm delamination increases with feed speed;
- In order to obtain larger material removal rates associated with minimal delamination, higher spindle speeds should be used when drilling glass fibre reinforced composites;

- The inclusion of the damage area in the adjusted delamination factor (F_{da}) obtained through digital image processing allows a better assessment of the effect of the drilling parameters on the damage observed in GFRP laminates;
- The digital image acquisition system has shown to be quite satisfactory for obtaining the damage area after drilling composites.

5. ACKNOWLEDGEMENTS

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