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Effect of Drilling Penetration Angle on Delamination for One-Shot Drilling of Carbon Fiber Reinforced Plastic (CFRP)

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ABSTRACT

Carbon-fibre-reinforced plastic is prominent with superb specific mechanical properties that contribute to its application in high technology industries, such as aircraft and automobiles' mechanical structures. These materials are considered hard to cut. The delamination issues frequently arise due to their anisotropy and inhomogeneity. In aircraft manufacturing, thousands of holes are required to assemble the structural parts. Hole perpendicularity issues undoubtedly might happen during manual drilling. The main purpose of this work is to study the effects of various minor slant drilling angles on thrust force generation and delamination by using a special drill reamer. From the investigation, the drilling penetration angle significantly impacted the delamination. The delamination factor for the entry and exit sides of holes relatively decreased from 1.042 and 1.087 to 1.027 and 1.049, respectively, as the thrust force declined from 114.8 N to 106.5 N from 5° to 0° drilling angle.

Keywords:
CFRP, One-Shot Drilling, Delamination, Thrust Force

1. Introduction

Excellent in mechanical properties, carbon-fibre-reinforced plastic (CFRP) is the primary option for the automotive and aviation industries to replace the existing uneconomic materials for mechanical structures [1]. Generally, CFRP is manufactured via autoclave or vacuum bagging and is offered ready to shape to cope with structural specifications [2]. The hole-making process is compulsory to assemble CFRP mechanical parts. Thousands of holes are needed in aircraft manufacturing, and damage-free drilling is essential to prevent rejection and save money [3]. However, drilling CFRP, a hard-to-cut material due to its non-homogeneous and anisotropic properties, leads to the rapid wear of cutting tools and causes low-quality drilled holes [4].

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Commonly, the drilling of CFRP in the industry is performed using the manual drilling process [5]. Consequently, human error might occur, as well as out-of-hole perpendicularity. Minor out-of-hole perpendicularity can still be accepted in aircraft manufacturing. Until now, no scientific study has been performed to investigate the impact of non-perpendicular drilling of CFRP. In most studies, drilling was perpendicular or tangent to a workpiece of CFRP laminates [6].

Delamination is the most common problem in CFRP drilling [7]. Two delamination types frequently occur in the drilling process: i) peel-up delamination on the entry side and ii) push-down delamination on the exit side of the drilled hole [8]. On the entry side of the hole, the peel-up mechanism forms due to improper cutting tool selection, and machining parameters cause the upper layers of CFRP laminates to peel up rather than be cut [9]. By contrast, the push-down mechanism on the exit side of the drilled hole occurs as the drilling progresses towards CFRP and the laminate layers separate from each other [10]. Uncut fibre might also happen on both sides of holes due to improper geometry of the cutting tool and unsuitable combination of feed and speed of machining parameters [11]. Poor selection of cutting tool geometry and machining parameters leads to increased thrust force generation during drilling [12]. Most of the studies conducted proved that the elevated thrust force results in increasing delamination [13-14].

An experiment is carried out using a special drill reamer to conduct the drilling process on a UD-CFRP workpiece from 5° to 0° drilling penetration angle. The effects of drilling penetration angle are investigated based on thrust force and delamination measurement and analysis. It is to determine the implication of drilling angle on delamination and thrust force generation.

2. Methodology

2.1 Materials Preparation

In this study, holes were drilled on a unidirectional CFRP manufactured by local aircraft composite panel makers. The CFRP used in this experiment referred to the final CFRP laminates applied to aircraft. The CFRP specimen thickness was 3.587 mm, which consisted of 26 UD-plies. The areal density for the CFRP laminates was 203 g/m^3, and the two woven fabrics located at the upper and lower parts of the CFRP laminates were 107 g/m^3.

2.2 Cutting Tool

The drill reamer applied in the experiment was made of tungsten carbide (93% WC and 7% Co), as shown in Figure 1. The geometric features of the cutting tool are presented in Table 1. The cutting-edge angles were measured in the normal plane of the cutting edge.

Fig. 1. CAD of special drill reamer

The diameter of the drill reamer was 6.35 mm. The measurement of point and helix angles was based on tool grinder programming and confirmed using AutoCAD software. The flute length for all drills was 40 mm, and the drilling depth was 30 mm for all trials.

Table 1
Drilling tool geometrical features characteristic

Geometry features	Point angle	Helical angle	Web thickness
Specification	90°	4°	17.5%
Drill material	Tungsten carbide (WC 93% & Co 7%)		

2.3 Experimental Setup

All trials were conducted with a fixed spindle speed of 2000 rpm and a feed rate of 300 mm/min. A total of six holes were drilled at various penetration angles of 5°, 4°, 3°, 2°, 1° and 0° from the right angle of the workpiece surface. The drilling trial was performed on 15 kW DMU60 monoBLOCK® CNC machining centre. The CNC machine has the capability for five-axis operations, including a dynamic NC-swivel head for B-axes and spindle speed options, with a maximum of 12,000 rpm. The thrust/cutting force was measured using a dynamometer by Kistler Company. In this experiment, unique fixtures were designed as a backing plate, and a clamping plate to support the CFRP panel and firmly held the workpiece on the CNC machine and vice on the dynamometer to prevent any vibration. The undesirable vibration during the drilling process can affect the thrust force measurement by the dynamometer [15]. Pilot holes were predrilled in this experiment for the accuracy of thrust force measurement. No coolant fluid was used to avoid contamination. Figure 2 shows the experimental setup for further experimental analysis and observation.

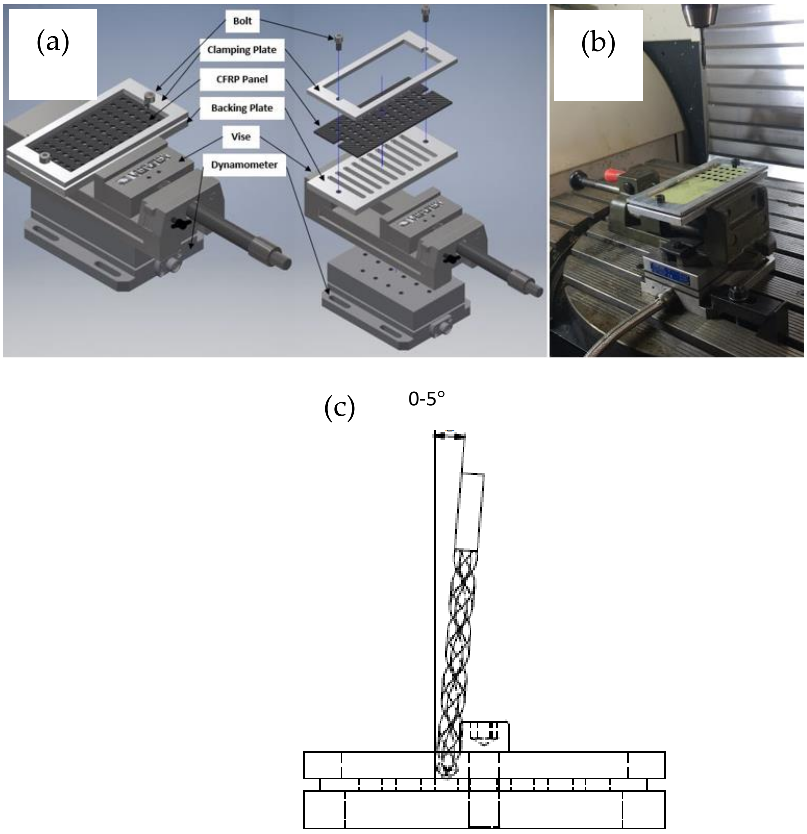


Fig. 2. Experimental setup for the experiment (a) CAD view of backing plate setup (b) actual experiment procedure (c) drilling penetration angle

2.5 Experimental Responses

2.5.1 Maximum Thrust Force

Thrust force measurement data were recorded using Kistler dynamometer type 5223A. The primary measurement concern in the experiment was the maximum thrust force for the point angle drilling phase (Stage I). The maximum thrust force was measured for each drilling condition to study the effect of drilling penetration angle on thrust force generation and damages. The worn drill bit was the significant reason for the increased thrust force [1]. Figure 3 shows the region for maximum thrust force measurement. The DynoWare processing software processed the measurement data, which are shown as the Z-axis force graph.

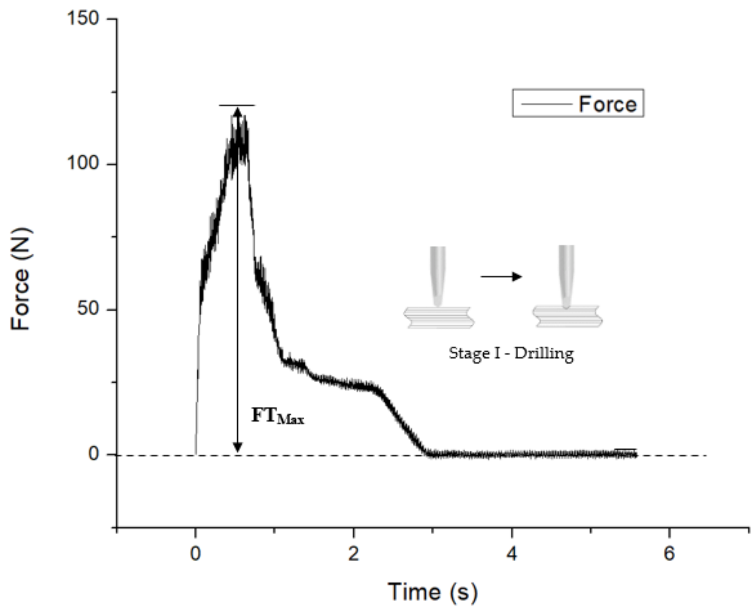


Fig. 3. Region for maximum thrust force measurement for Stage I drilling of the drill reamer

2.5.2 Entry and Exit Delamination

All the drilled holes were inspected through an EMZ-Meiji optical microscope fitted with a digital camera and were processed with image processing software (JAVA ImageJ) with limited luminosity, noise, contrast and threshold for efficient detection and quantification of delamination. Figure 4 depicts the delamination area determined on both sides of the holes. The observed delamination in the drilled holes was measured to obtain the area delamination factor, FA, as in Eq. 1:

$$F_A = \frac{A_d}{A_0} \tag{1}$$

where A_d is the delamination area, and A_0 is the nominal area of the hole.

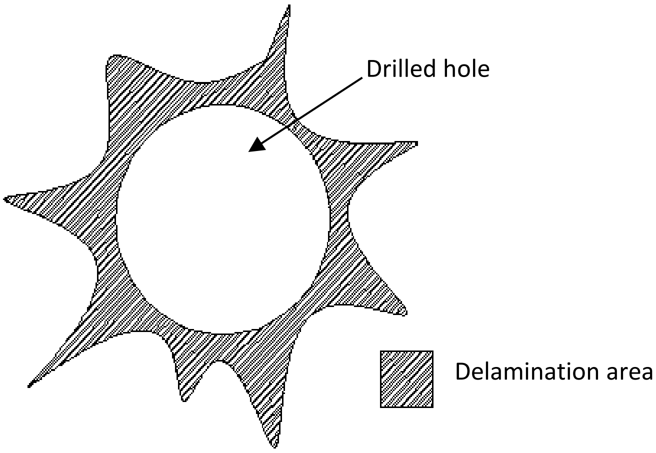


Fig. 4. Schematic diagram of the delamination area

3. Results

3.1 Drilling Thrust Force Analysis

The drill reamer generally presented three stages of drilling, as shown in Figure 5. Stage I represented the point angle of the drill bit, stage II acted as an opener, and Stage III was the reaming process. In Stage I, a spike in thrust force occurred, where the drill tip started to indent the workpiece plate until the point angle region was fully engaged. Stage II began when the angular section of the drill performed drilling and reaming processes. Stage III took place until the drill was backed up.

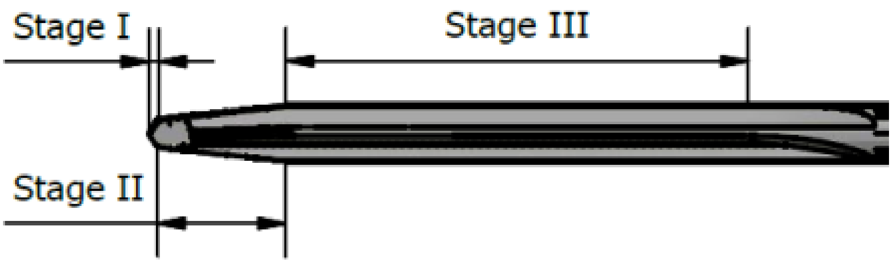


Fig. 5. Drilling process stages for drill reamer

The lowest thrust force was obtained at a 0° drilling angle, and the maximum thrust force was obtained at 5°. The maximum thrust force for each trial is shown in Table 2, whilst Figure 6 illustrates the trend of maximum thrust force obtained from the drilling angles of 5°, 4°, 3°, 2°, 1° and 0°. From the experiment for various drilling penetration angles, no significant discrepancy in maximum thrust force was found, but the measurement increased as the drilling angle increased.

Table 2
Maximum thrust force measurement

Drilling angle (°)	5	4	3	2	1	0
Maximum thrust force (N)	114.8	112.6	110.8	110.1	108.9	106.5

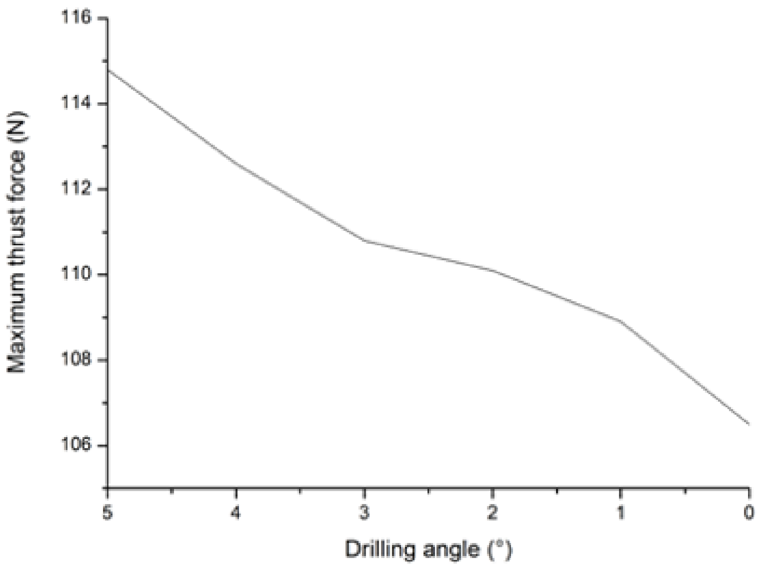


Fig. 6. Maximum thrust force results

The increment in thrust force in Stage I was influenced by the total wide surface of the workpiece, in which it touched the cutting edges of the cutting tool in a complete rotation [16]. As the drilling penetration angle increased, the cut on the surface widened. The cutting area influenced the thrust force because the CFRP is a highly abrasive material [14]. Figure 7 compares the total area for Stage I full engagement on the workpiece at 0° and 5° drilling angles. In Stage I of drilling, the point angle drill tip fully penetrated the workpiece. Specifically, in perfectly perpendicular drilling, the drill tip completely penetrated the workpiece, but the increased drilling angle caused part of Stage II to be involved and widened the cutting area. The 5° drilling angle displayed a higher contact area between cutting edges compared with the lower drilling angles. The drilling angle of 0° obtained 44.787 mm^2 cutting area, whereas 5° obtained as much as 59.462 mm^2. As a result, the thrust force generated at high drilling angles increased. To complete the engagement of Stage I drilling, stage II also needed to engage in the high-drilling-angle application. Therefore, the axial force distribution downwards should increase the driving torques and moments of a force together during the drilling operation.

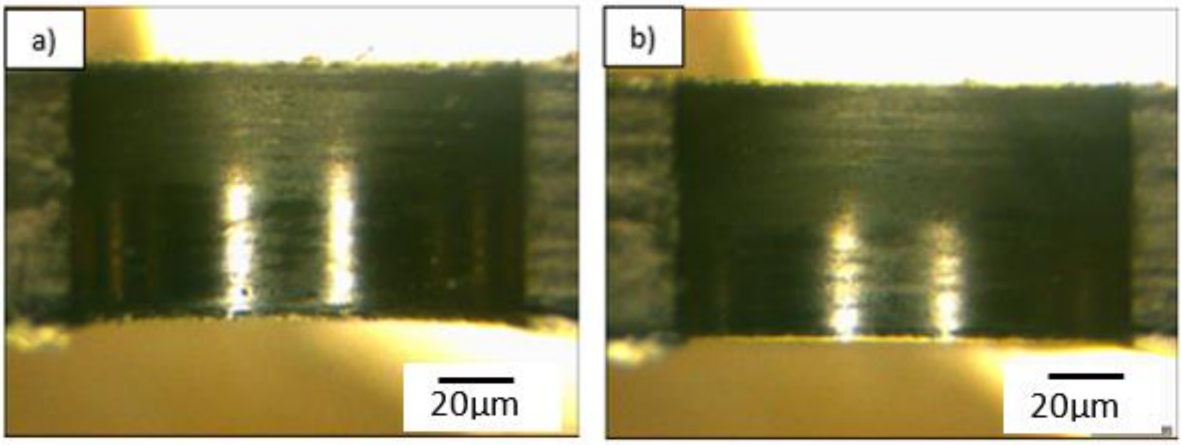


Fig. 7. Total area for Stage I full engagement at a) 0° and b) 5° drilling angles

Figure 8 shows the forces applied during orbital slant drilling. Excessive drilling feed and torque might lead to unravelling and skiving during pilot indentation. However, this experimental work did not consider the deflection because the tool material was hard, the workpiece surface had a rough coating, and minor angle drilling was applied.

Fig. 8. Force modes applied during orbital slant drilling

3.2 Delamination Analysis

The delamination factor was obtained from the image processed using Image-J for further discussion regarding the impact of the drilling angle. The total area of delamination represented the delamination factor accuracy. Figures 9 and 10 show the delamination factor and processed images of the delamination conducted experiment, respectively. The delamination factor was calculated based on the factor of the maximum diameter of delamination. The formula of the delamination factor is given in Eq. 2.

$$F_d = \frac{D_{max}}{D_0} \tag{2}$$

Where, F_d is a delamination factor, D_{max} is a maximum diameter of the delaminated area and D_0 is the nominal hole diameter.

The delamination around the holes was not uniform. From the experiment, slant drilling would cause high delamination. The increases in the drilling penetration angle resulted in the increase in delamination for both the entry and exit sides of holes. The increases in thrust force also increased the delamination [17-19]. The delamination occurred badly at high values of drilling angle due to the higher thrust force generation compared with that at lower drilling penetration angles.

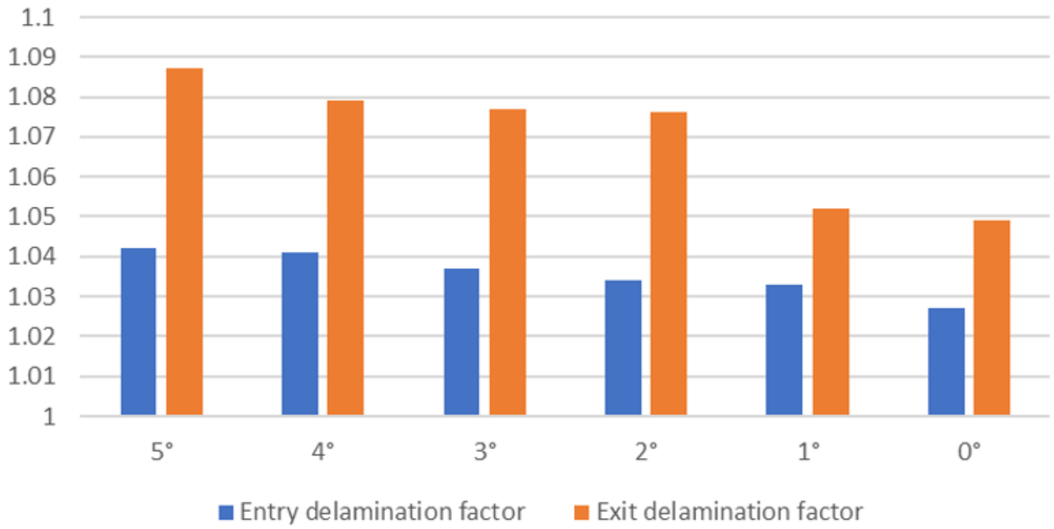


Fig. 9. Delamination factor

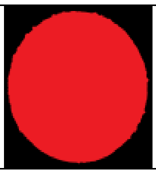
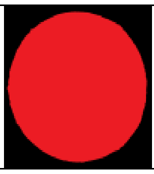
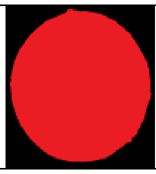
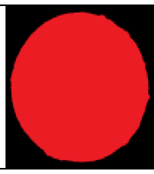
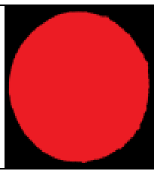
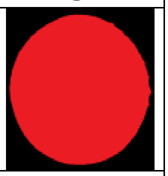
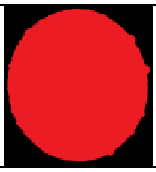
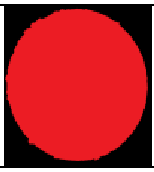
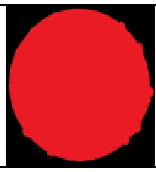
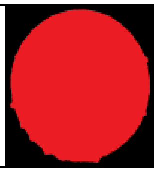
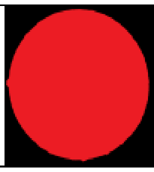
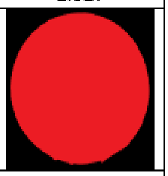
Delamination	5°	4°	3°	2°	1°	0°
Entry						
Entry delamination factor	1.042	1.041	1.037	1.034	1.033	1.027
Exit						
Exit delamination factor	1.087	1.079	1.077	1.076	1.052	1.049

Fig. 10. Processed images for delamination by using Image-J software

Meanwhile, the delamination on the exit side of the holes was more severe than that on the entry side. Figure 11 shows the push-out delamination mechanism with the drill's indentation towards the CFRP workpiece's exit side. The delamination mechanism on the entry side of the holes could be referred to as peel-up, which occurred when the drill cutting edges progressed to the workpiece. The upper layers of the CFRP laminates tended to push through rather than be cut. Comparatively, on the exit side of the holes, the push-out mechanism occurred when the last plies of CFRP laminates were pushed out without being cut with the indentation of the cutting tool [20-21].

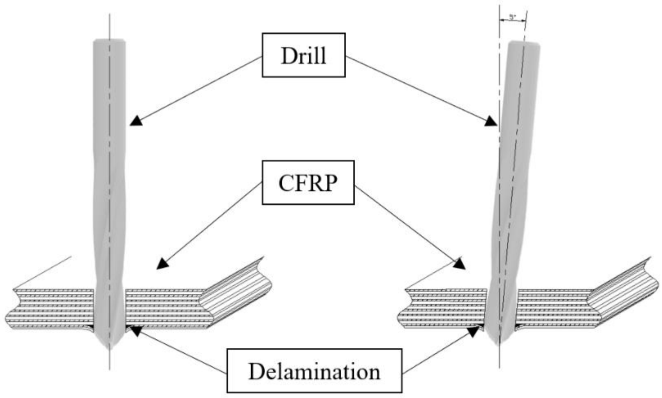


Fig. 11. Push-out delamination mechanism

4. Conclusions

The conclusions from the conducted experiment are as follows:

i. The thrust force increases with the increment in drilling penetration angle.
ii. Perfect perpendicularity of drilling is essential to reduce thrust force generation.
iii. The delamination increases as the drilling penetration angle increases for both the entry and exit sides of holes but in a very minimal manner.
iv. The delamination on the exit side is more severe than on the holes' entry side.
v. To realize drilling-induced delamination, perfectly perpendicular drilling is compulsory to reduce thrust force generation. This experiment proved that vertical drilling is vital to minimize delamination and thrust force. Assuredly, only minimal delamination was observed during drilling at various penetration angles.

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