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Hole Quality Assessment of Drilled Carbon Fiber Reinforced Polymer (CFRP) Panel Using Various Custom Twist Drill Geometries

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ABSTRACT

Excellent hole quality is necessary for the aerospace industry's highly abrasive carbon fiber reinforced polymer (CFRP) drilling process. This work considered three different twist drill designs, tapered web, burnishing, and subland drill reamer for the drilling process. The drill bits were made of tungsten carbide and machined with custom helix angle, primary clearance, point angle, and chisel angle. The primary objective of this research is to determine the thrust force signature for each custom drill bit design and the delamination factor for the hole drilling at 3000 rev/min and 0.05 mm/rev. The finding indicates that the tapered web gave the best design by improving the maximum thrust force by 14.6% in drilling CFRP panels. Additionally, the tapered web design led to a low delamination factor on both entrance (1.0186) and exit sides (1.0475). The thrust force is directly proportional to the delamination factor when drilling a CFRP material in a single shot operation. The subland drill reamer produces higher thrust force, and delamination proved that the combination of drill and reamer design was unsuitable for high-speed drilling.

Keywords: CFRP, delamination, single shot, thrust force

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INTRODUCTION

Carbon fiber reinforced polymer (CFRP) is extensively utilized in the automobile and aerospace sectors (Jaafar et al., 2019). They have outstanding properties such as high density, high compressive and tensile tension, high operating temperature, and lightness, which reduce a vehicle's weight and fuel usage.

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Drilling is one of the most common operations needed for post-processing components made from CFRP materials. Screws and rivets are often used in the assembly process to assemble the CFRP stack with other materials (Jia et al., 2020; John et al., 2021). Although most CFRP components were manufactured in the near-net form to minimize work, additional manufacturing, such as drilling, is still needed for the post-processing work. However, due to the heterogeneity and anisotropy of the CFRP material, the drilling phase can result in a different types of damage, such as fiber pull out and fiber-matrix debonding (Hou et al., 2020). Delamination is the primary damage found after the drilling of composite material. It happens because of the binder surrounding the drilled hole is damaged. This type of damage impairs installation tolerance, compromises structural stability, and is likely to degrade the CFRP product's long-term efficiency.

Assuring the hole accuracy on both sides of the CFRP composite at the entry and exit is challenging. When drilling CFRP, the right selection of drill bit's features, such as helix angle, point angle, cutting angle, and the drill bit's material composition is vital. It is reported that the drill bit with a smaller point angle of 90° successfully reduces the exit damage of the CFRP composite (John et al., 2021). Additionally, utilizing a drill bit with a small point angle results in a lower thrust force while drilling than a drill bit with a wide point angle. The comparative performance of standard twist drill design and special drill (namely "dagger drill") design in the drilling of a high-strength carbon-fiber-reinforced composite process is reported by Feito et al. (2019) and An et al. (2014 & 2013). The dagger drill has been found to promote a better surface finish, i.e., less burr defect and less damage to the delamination than the twist drill design due to smaller point angle and helix angles. However, due to the poor chip evacuation capacity compared to the small helix angle, the "dagger drill" is not preferable for metallic part drilling.

Wika et al. (2011) performed several drilling trials of CFRP-Ti stack-up materials using four types of twist drills with different flute and helix angles. Results revealed that with the large flute volume for chip evacuation and heat dissipation, the two-flute drill bit with a higher helix angle produced the smallest cutting force and the lowest cutting temperature compared to the drill with the three flutes. SenthilKumar et al. (2013) used 118° and 130° point angle drills to examine the effects of point angle on tool performance when drilling the composite/Ti stack. It was determined that the higher point angle (130°) drills outperformed those with lower point angle (118°) in terms of the tool wear and chip evacuation analysis.

Delamination occurs through two distinct mechanisms: entry delamination (peel-up) and exit delamination (push-out). Peel-up delamination occurs due to the drill's advancement; the upper layers of material appear to draw up the drill's cutting face rather than being removed (Higuchi et al., 2020). On the other side, push-out delamination occurs due to the drilling chisel tip indenting the uncut layers of the CFRP laminate. According to work reported by Liu et al. (2018), delamination initiates when the thrust force of the drill reaches the toughness of the interlaminar layers. This study considers three custom designs of twist drill types have been to achieve the lowest possible thrust force and the least amount of delamination on drilled CFRP panels. In addition, the significant effect of the drill geometry of the design like helix angle and chisel edge angle has been discovered in this research study.

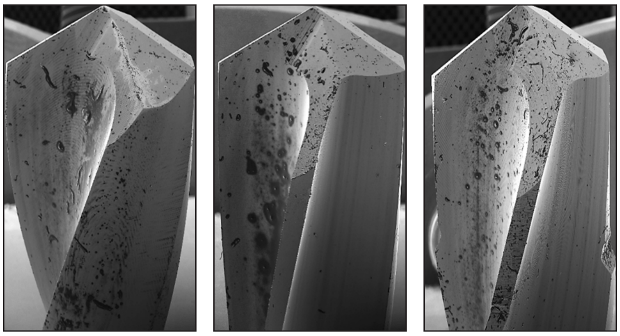
METHODOLOGY

Work Piece Material

The CFRP material was made from 26 plies of unidirectional prepregs carbon composite manufactured by Hexcel Composite Sdn. Bhd. The CFRP panel is 3.25 mm thick, with 0.125 mm thick carbon fiber material in each ply. The stacking of the layers is symmetrical, following the sequences of $[45/135/90_2/0/90/0/90/0/135/45_2/135]_{s.}$ At the top and bottom of the CFRP laminate, a 0.08 mm thin layer of glass/epoxy woven fabrics was used to avoid delamination at the hole's entry and exit throughout the drilling operation. It results in a cumulative thickness of 3.587mm for the whole CFRP panel, including the paint application. The CFRP was compacted using a vacuum pump in a controlled atmosphere throughout the curing process. A mold for the laminate was prepared and placed inside the autoclave. The cure cycle consisted of raising the temperature to 180 °C at 3 °C/min and maintaining it for 120 minutes. Then the temperature was brought down to room temperature at 3 °C/min. The whole cycle was carried out at the pressure of 700 kPa in an autoclave and placed in a vacuum bagging which was evacuated to 70 kPa. Hence, the nominal fiber volume fraction is 60% by applying that curing recipe.

Drill Bit Geometries

Figure 1 depicts three distinct designs of twist drill types: tapered web, burnishing, and subland drill reamer. Gandtrack Asia Sdn. Bhd. manufactures this drill bit with a diameter of 6.35mm and a tolerance of h8 (+0, -20µm). The drill bit was made of tungsten carbide due to its unique properties, such as tolerance to extreme temperatures



(a) (b) (c)

Figure 1. Tungsten carbide drill bit: (a) tapered web; (b) burnishing; and (c) subland reamer design

and retaining a strong cutting edge even after drilling multiple holes (Katiyar et al., 2016). The Tungsten Carbide (WC) rod composition consists of WC~93.36 wt % and Cobalt~6.64 wt %. It has a density of 14.35 g/cm^3 and a hardness value of 1625 HV, significantly higher than the workpiece material. Therefore, the drilling tools can easily shear the surface of the workpiece material without causing the breakage of the tool itself. Table 1 summarizes the detailed range of the drill geometry used in this study.

Table 1
Drill bit geometry configurations

	Tapered web	Burnishing	Subland reamer
Helix angle	25º	11º	25º
Primary clearance	6º	6º	8º
Point angle	120º	120º	120º
Chisel edge	30º	30º	45º

Thrust Force Measurement

As shown in Figure 2, the drilling process was carried out on a CNC High-Speed Milling unit, model Alpha T2liFB. The thrust force signal was recorded during the drilling operation using a dynamometer (Kistler four-component dynamometer model 9272) mounted at the bottom of the jig. The data acquisition system, connected to the dynamometer, consists of a multichannel charge amplifier (type 5070) and Kistler DynoWare software. The thrust force and torque signature were generated when the four-component dynamometer transferred the charge signal to the multichannel charge amplifier. The multichannel charge amplifier converts the resulting charge signal to voltage, proportional to the applied force. The resulting signals were converted to force by the calibrated data displayed in the software. Drilling conditions were similar for the three drill bit designs, with a 3000 rev/min speed

(a) (b) (c)

Figure 2. Setup for CFRP drilling: (a) Positioning of work-piece in the CNC; (b) data acquisition system for thrust force measurement; and (c) labeling of hole location

and a 0.05 mm/rev feed rate. Five holes were drilled (Figure 2c) to obtain the average thrust force for each drill bit. As force is sensed during the drilling process, data is sent to the data acquisition system for force signature against cutting time.

Delamination Observation

Delamination was measured at the entry and exit of drilled holes using a 5×/0.15 magnification Alicona Infinite Focus Optical microscope (IFM G4 System). As shown in Figure 3, the CFRP panel was positioned next to the lens to facilitate scanning and capturing the image of the hole. The delamination of the CFRP panel was evaluated on both the entry and exit sides to distinguish between the two types of delamination.

The scanned hole images were post-processed in the *Image J* program (Figure 3b) to measure the delamination area on the CFRP panel's entrance and exit sides. The following Equation 1 is used to calculate the value of the delamination factor,

$$F_d = \frac{A_{\max}}{A_{nom}} \quad [1]$$

Where F_d is the delamination factor, $A_{\max}$ is the hole damaged area, and A_{nom} is the nominal area.

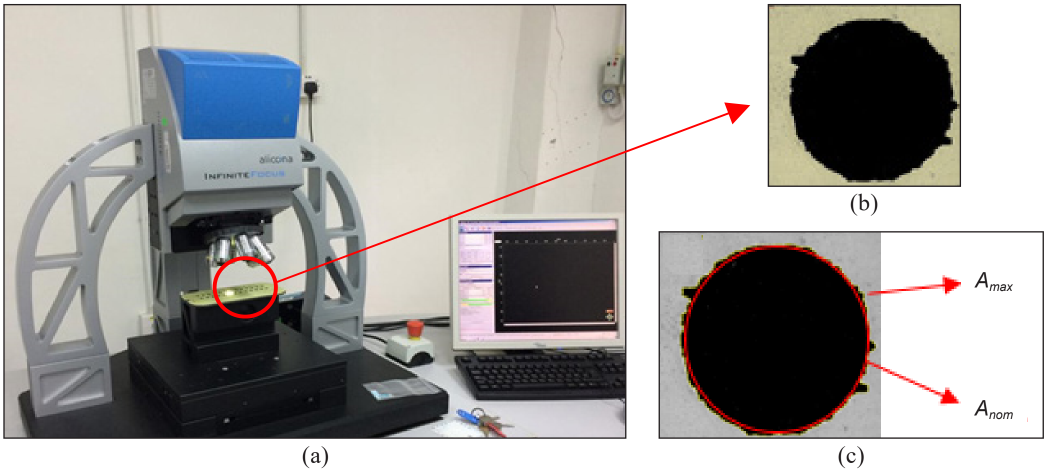


Figure 3. (a) Hole delamination observation; (b) sample delamination image recorded at the hole entrance location; and (c) processing image used for delamination factor measurement

RESULTS AND DISCUSSION

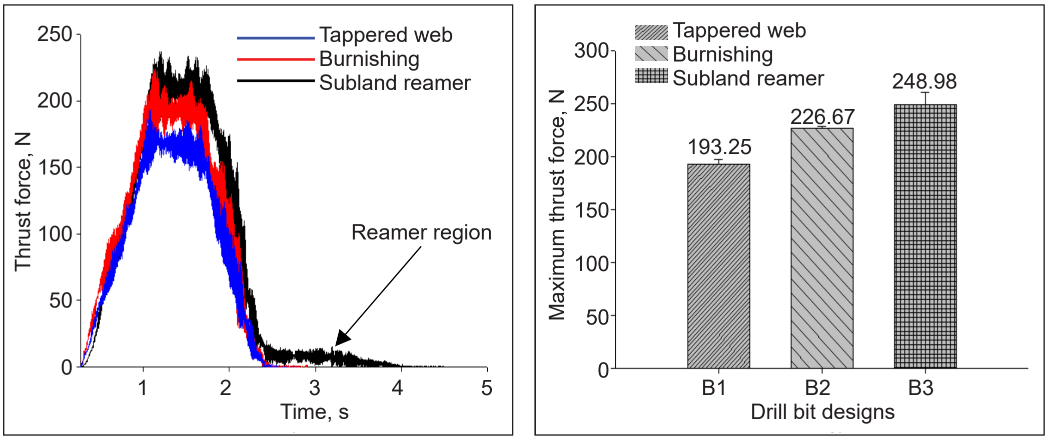
Thrust Force Analysis

Figure 4 depicts the thrust force signature and average maximum thrust force of tapered web, burnishing, and subland drill reamer. The thrust force signature for tapered web and burnishing drills can be separated into three regions: the initial stage after the drill bit contacts the CFRP panel along the cutting lips, the drilling phase, the CFRP thickness, and the final stage after the drill bit has penetrated the panels. However, for the subland drill reamer configuration, the thrust force signature consists of five regions, where the two additional regions are associated with the reamer phase. The drilling operation for the subland drill reamer configuration began with a 6.2 mm drill diameter and progressed to a 6.35 mm drill diameter with four cutting edges that act as reamers.

The maximum thrust force, F_{tmax}, was introduced in this study to determine the optimal thrust force output of a drill bit configuration. The F_{tmax} is the maximum value of force measured from the force signature during the drilling process. Figure 4(b) shows that the tapered web produced a minimum F_{tmax} value of 193.25 N. It is believed that the fast helix angle of the tapered web was improved by 14.6% from burnishing design which is a slow helix type. The fast helix type would help evacuate the chips from the hole to the surrounding, hindering the hot dust chip from accumulating at the cutting surface of the drill bit. It is agreed with Ashrafi et al. (2013), which also drilled a CFRP panel at the fast helix geometry and achieved minimum delamination at the hole exit.

Subland drill reamer contributed the largest thrust force signature, with a F_{tmax} value of 248.99 N. At the drilling stage of the subland drill reamer design, the drill bit was hard to penetrate the CFRP panel due to the higher chisel edge angle, which is 45°. It is worth noting that raising the chisel edge angle of the drill bit from 30° to 45° increases the F_{tmax} by 18.59%. When the chisel edge angle increases, the shortened cutting lips result in a less effective cutting operation.

Similarly, Figure 5 shows the torque measurement ranging from 0.4 Nm to 0.5 Nm for drilling CFRP materials. Again, the highest torque values are produced by subland drill



(a) (b)

Figure 4. (a) Thrust force distribution for all drill bit design; and (b) maximum thrust force generated during the drilling process

reamer design. The lowest torque values are produced by tapered web design. Again, the thrust force and torque trend are the same, influenced by the tool geometry.

Delamination Analysis

Figure 6 illustrates the results for entry delamination (peel-up) and exit delamination (push-out). The formation of entry delamination at the hole entrance is considered a minimum for all drill bit designs. The various bit designs only result in substantial damage and uncut fiber at the drilled hole's exit. The subland drill reamer's delamination was more severe than the tapered web and burnishing drill bit. This severe exit delamination issue happens as the drill bit acts like an extruder rather than a cutter. Uncut fiber is also visible on the exit tapered web, which happens because of push-out delamination in the fiber's final layer. The work of Yang et al. (2019) has claimed that while using a reamer drill bit, the pace of the cut must be reduced to prevent these two issues while drilling. That was stated that using the reamer drill bit must be cut at a lower speed.

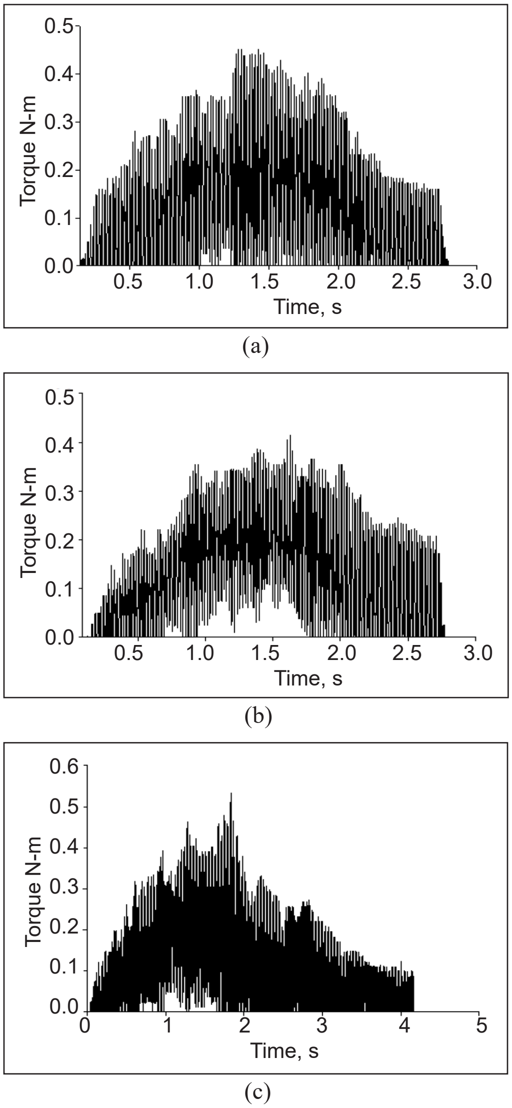


Figure 5. Measurement of torque: (a) tapered web design; (b) burnishing design; and (c) subland drill reamer design

As shown in Figure 7, the composite matrix will be affected if the thrust force exceeds the bonding strength between laminate during the drilling process. It will lead to delamination damage, especially at the exit part of the panels. Besides, when drilling CFRP materials at a higher point angle, the cutting edge will easily produce downward bending deformation; then, the fibers cannot be cut by the cutting edge, which leads to the uncut fiber in the hole exit. According to the drilling process in Figure 7, the point angle of the drill was φ; the force of the drill on the hole-exit CFRP can be simplified as the force F, which can be illustrated as radial cutting force F_x and thrust force F_z. As the resin bonded to the fiber, the intensity of the bonding force was P_b, and the fiber plastic/

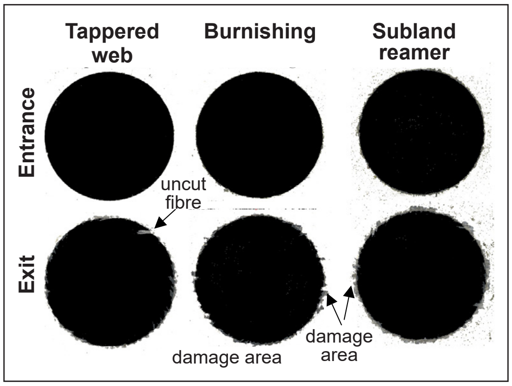


Figure 6. Observation of delamination at the entrance and exit sides of the hole drilled by each drill bit design

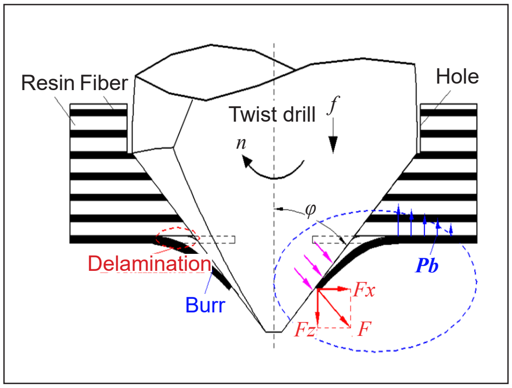


Figure 7. Delamination formation at different point angle

polymer bonding strength was σ_b. When drilling a CFRP at a constant point angle (120°) and higher primary clearance (8°), it would provide a higher trust force and torque hence contributing to the disbond of the laminate at the hole-exit.

The F_d's delamination factor was introduced, as illustrated in Figure 8, to quantify the value of delamination at the entrance and exit of the drilled hole. The $F_{d\text{-entrance}}$ and $F_{d\text{-exit}}$ values were 1.0186-1.0221 and 1.0475–1.0759, respectively. The tapered web drill bit type recorded the lowest delamination factor on the entrance and exit sides because the value is closer to the nominal value of 1.0. This nominal value signifies the tapered web's best cutting efficiency than burnishing and subland reamer drill bits. On the other hand, the subland reamer drill bit demonstrated the largest delamination factor, 1.0221 and 1.0759, respectively, with an increment of 2.21 % and 7.59 % from the nominal line. It may be because the drilling parameters, 3000 rev/min and 0.05 mm/rev, are incompatible with the subland reamer drill bit type used to drill the CFRP panel.

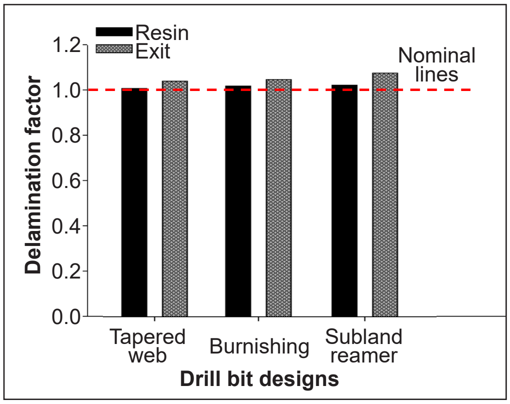


Figure 8. Magnitude of delamination factor measured at the entrance and exit sides of the hole drilled by each drill bit design

CONCLUSION

This paper investigated custom twist drill designs' thrust force magnitude and delamination factor while drilling CFRP panels. The experimental results lead to the following conclusions.

The best design of the twist drill type is a tapered web since it generates the least thrust force during the CFRP drilling operation.

When the helix angle design was increased from the fast helix to the slow helix, the effect of the helix angle would improve the F_{tmax} by 14.6% when drilling a CFRP panel. However, for the chisel edge angle, when increasing the chisel edge angle from 30º to 45º, the F_{tmax} would increase to 18.59%.

The delamination factor of the CFRP panel is directly proportional to the F_{tmax} obtained from the drill bit design. Therefore, the higher F_{tmax} would be contributed to the higher delamination factor.

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