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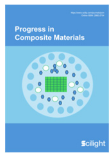

Article

Effect of Support and Adhesive Tape to Reduce Delamination of Carbon Fiber Reinforced Polymer during Drilling

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Abstract: Drilling carbon fibre reinforced polymers (CFRP) often causes several kinds of damage around the hole, such as delamination, which is considered one of the main issues that may occur when drilling the CFRP laminate. It significantly decreases the structural strength of the composite material and reduces its long-term performance. Using support plates and stacked materials as layers on the composite material has been identified as one of the main methods often used to reduce delamination. This research investigates the variations in delamination, fibre pull-out, thrust force, drilling torque, circularity and diameter error when drilling with and without adhesive tape layers. Furthermore, the research paper also explores the effect of varying drilling conditions and drill bit geometries on those output parameters. It has been revealed from the results that the proposed use of both adhesive tape layers and support plates can significantly limit delamination and fibre pull-out damages, thereby achieving a better-quality hole when drilling CFRP, as opposed to just using adhesive tape layers.

Keywords: CFRP; support; drilling; delamination; carbon fibre reinforced polymer

1. Introduction

Growing demand for lightweight structures with high-performance characteristics has seen a spur in research and development of polymer composite laminates engineered with fibre reinforcements [1,2] such as carbon fibre-reinforced polymers (CFRP). Carbon fibre-reinforced polymers are among the most widely used composite materials in the aerospace industry to manufacture more reliable and fuel-efficient vehicles. The superior nature of this material such as its high strength-weight ratio, high stiffness, low density, low thermal expansion, high corrosion [3], corrosion-wear resistance [4] and low friction coefficient [5,6] arguably makes it an ideal structural material for replacing various conventional materials such as steel, titanium and aluminium in aerospace applications. Production of CFRP based products sees parts produced very near to the end-product, however machining is often required to finish or complete product assembly [3,5]. Bolts and rivets are amongst the most common joining methods for CFRP parts, and this results in drilling being a vital technique to prepare the components for joining [7,8]. The entire process of drilling composite laminates can be sectioned into two different regions that consist of the chisel edge and cutting lips. Initially, the drilling of the workpiece is performed by the drill chisel edge (extrusion) that has no linear speed, followed by the cutting mechanisms (removal of material) which are usually carried out by the cutting lips that operate at a certain speed [9]. Although the cutting mechanism is unique and complex, drilling of CFRP involves coping with various undesirable changes, which are usually not encountered in machining other conventional materials.

Carbon fibre-reinforced polymers (CFRP) are prone to damage from drilling, with burr [10,11], delamination, swelling and splintering are common defects as a result of drilling, as well as the formation of micro-cracks [12] in the material. The nature of carbon fibre-reinforced structures such as their in-homogeneity, anisotropic characteristics, the high abrasiveness of the fibres and lack of plastic deformation, varying mechanical and physical properties often leads to difficulties during the machining of their components [13]. Delamination at the entry and exit points of the newly drilled holes are amongst the critical faults that arise from drilling, as this significantly detracts from the material's strength properties. It was mentioned that, in aircraft industry, drilling induced delamination account for about 60% of the overall damage of the structural component [14]. Therefore, any drilling-induced delamination that results in the components rejected represents an expensive loss since drilling is often a final machining operation during assembly of components made of composite laminates [15]. Additional manufacturing techniques are required to overcome this to ensure the final product meets the design specification, and that the product is durable under fatigue loads [16]. Various studious have indicated that the primary cause of delamination during drilling processes is due to the thrust force and that the extent of this is governed by factors including workpiece and drill geometry, feed rate, cutting speed and the drill material [15,17].

Factors such as cutting parameters, tool geometry and material must be chosen carefully in order to attain best performance during drilling operation, i.e., best hole quality, which correlates to minimal damage to the surroundings of the hole wall and acceptable machined surface [18]. As suggested by various researchers [19,20], input cutting parameters such as cutting speed have a major influence on thrust forces and torques. Thus, cutting speed and feed of the drill bit were identified as the most significant factors influencing the drilling process after drill bit geometries; such as the drill diameter, point angle and type of drill. Drilling-induced delamination damage can be reduced by placing stacked materials and/or support plates on either side of the composite laminate to prevent push-out deformations. In an investigation carried out by Shyha et al. [21], the authors analysed the quality of drilled holes of titanium/CFRP/aluminium stacks with uncoated and coated CVD diamond and hard metal tungsten carbide drills. The results attained outlined that the degree of delamination around the hole periphery of the CFRP laminates effectively reduced due to the presence of aluminium and titanium support stacks. In a similar study conducted by Rimpault et al. [22] that involved analysing aluminium/CFRP/titanium stacks, the authors examined the effect of different drilling techniques namely orbital drilling and convention drilling on hole integrity/quality. The results in regards to surface integrity of drilled holes revealed that the orbital drilling of stacked materials achieved a better quality hole, as opposed to conventional drilling of CFRP composite workpiece alone [23]. Davim and Reis [24] conducted investigation that involved the delamination during drilling of woven CFRP using HSS drills and several cemented carbide drills. Their findings suggested that delamination factor (F_d) was larger with higher cutting speeds and feed rates, with the former being the more significant parameter affecting delamination. When drilling holes, a combination of sufficient feed rate and tool geometry have demonstrated to prevent the effects of delamination. Utilizing active backup force, as demonstrated by Tsao et al. [25] can minimize delamination effects by 60–80% at the drilling exit. Grilo et al. [26] executed an experimental protocol to examine the impact of cutting parameters and tool framework on delamination. Gaitonde et al. [27] proposed the Taguchi optimization method in attempt to establish the most advantageous parameters and to analyze their effect on delamination factor.

From theoretical knowledge it was understood that the delamination induced during the drilling process could be effectively reduced when the thrust force applied to the work piece does not exceed the critical thrust force obtained by the theoretical model. Hence, most publications on delamination-free drilling of composites focused mainly on either increasing the critical thrust force or decreasing the thrust force during the process of drilling. An investigation that was done by Edward Capello [28] analyzed the difference in delamination mechanisms when drilling with and without a support placed under the workpiece. One of the most widely used mechanisms to minimize this induced delamination is to place a support below the work piece, as it prevents deformation leading to push out delamination. Furthermore, it also effectively increases the thrust force exerted by the drill point as opposed to unsupported drilling, as a result limiting delamination. Similar study was done by Tsao et al. [25] and Hocheng et al. [5] which involved the effects of backup plate on delamination in drilling of composite materials using saw drill and core drill. Another observation was that the chisel edges contributed to about 40% of the overall drilling thrust forces when being operated at lower feed rates, as opposed to about 60 when operated at high feed rates [29]. To counter such large influence on the thrust forces, pre-drilled pilot holes on the work piece were generated, where the diameter of the pilot hole is set equal to the chisel edge length of the drill or inner diameter of the core drill [5].

In regards to drilling of composite materials, the hole quality in a material is often described by a variety of output parameters such as the material integrity, hole diameter, surface textures as well as delamination and exit burrs of drilled holes. The latter, delamination and exit burrs of drilled holes are critical aspects to the structural durability of composite structures as they may be holistically classified as the exit hole damage [30]. There are number of proposed method to represent the delamination quantitively such as conventional delamination factor (F_d) [31], alternative delamination factor (F_a) [32,33], adjusted delamination factor [34], equivalent delamination factor (F_{ed}) [19], refined delamination factor (F_{dr}) [35] and arbitrary delamination factor (F_{ar}) [20].

There are many investigations to reduce the delamination during drilling of CFRP through optimizing the drilling parameters, drill bit design and drilling strategy [2]. In addition, there are investigations to explore the geometric properties of the drilled holes [37–39]. Unfortunately, none of those strategies were able to eliminate the delamination effectively. It was found that the presence of adhesive tape layers as stacked material on one side of the composite had no significant impact in reducing the degree of the damage induced [36]. This is due to the fact that they are not thick and rigid enough to avoid such damages induced. Furthermore, due to the adhesive tape layers not being intact at the CFRP plate significantly affected the outcome of the results. Thereby, making it not an ideal alternative to reduced drilling induced delamination and fibre pull-out factor. Thus, further studies could include analyzing the combined effect of adhesive tape layers and wooden support plates on delamination and other output parameters, which appear as a knowledge gap and addressed in the present study. Thus, this research paper studies the variations in delamination, thrust forces, drilling torque, circularity and surface roughness when drilling with and without adhesive tape layers together with wooden plate support. Furthermore, this research paper also explores the correlation between various input parameters and output parameters, such as thrust forces, drilling torque, delamination, circularity and diameter error.

2. Materials and Methodology

2.1. Workpiece Material

Carbon fibre reinforced polymer (CFRP) composite laminate was used throughout the entire investigation. The composite laminate used in the drilling experiment was 5 mm thick EconomyPlate^{TM} CFRP with a stack sequence of 0°/90° and dimensions of 12 mm × 12 mm. This CFRP is composed of a tough and rigid carbon fibre. The resin matrix is Bisphenol A which get cured at room temperature. The hardener was not disclosed by the supplier. The EconomyPlate^{TM} is a particular type of carbon fibre reinforced plastic composite manufactured by DragonPlate (New York, NY, USA); designed for a less significant application where the properties of the material are not a crucial aspect. Twelve (12) layers of clear transparent mounting tape (scotch tape), was used as layers of stacked material on either side of the composite laminate for experiments that were designed to investigate the effect of adhesive tape layers on drilled hole quality. Plywood was used as wooden support on both sides of the laminate, where required.

2.2. Drilling Operation

The drill bits used were made of standard high speed steel twisted drills (HSS) with varying diameter and point angle as reported in Table 1.

Table 1. Drill bit characteristics.

Drill Type	Drill Diameter (mm)	Point Angle (°)	Helix Angle (°)
HSS	4	125	30
	6	125, 130, 140	
	8	125	
	10	125	

A set of 28 investigations were designed and carried out, as shown in Table 2. Drilling experiments were conducted on a Leadwell V-30 CNC machining with a maximum spindle feed of 2750 rpm and a maximum spindle feed rate of 0.13 mm/min. The CFRP composite workpiece was clamped to the base of the CNC machine using three support clamps to ensure rigidity during drilling operation.

Table 2. Design of experiments.

Experiment No.	Drill Bit Diameter (mm)	Point Angle (°)	Adhesive Tape Layers	Cutting Speed (rpm)	Feed Rate (mm/min)
1	4	125	12	2250	0.11
2	6	125	12	2250	0.11
3	8	125	12	2250	0.11
4	10	125	12	2250	0.11
5	4	125	0	2250	0.11
6	6	125	0	2250	0.11
7	8	125	0	2250	0.11
8	10	125	0	2250	0.11
9	6	130	12	2250	0.11
10	6	140	12	2250	0.11
11	6	130	0	2250	0.11
12	6	140	0	2250	0.11
13	6	125	12	2000	0.11
14	6	125	12	2500	0.11
15	6	125	12	2750	0.11
16	6	125	0	2000	0.11
17	6	125	0	2500	0.11
18	6	125	0	2750	0.11
19	6	125	12	2250	0.1
20	6	125	12	2250	0.12
21	6	125	12	2250	0.13
22	6	125	0	2250	0.1
23	6	125	0	2250	0.12
24	6	125	0	2250	0.13
25	6	125	12 (with wooden plate)	2250	0.1
26	6	125	12 (with wooden plate)	2250	0.11
27	6	125	12 (with wooden plate)	2250	0.12
28	6	125	12 (with wooden plate)	2250	0.13

The drilling thrust forces and torques induced by the cutting tool were measured using a fully calibrated Kistler piezoelectric force dynamometer systems. A computerized pro-microscan microscope, was employed to obtain the required clear images of the delamination areas around the drilled holes. The damage caused at the surroundings of the hole was quantified by alternative delamination factor (F_a), which was defined as the ratio of maximum area of damage to nominal are of the hole as shown below:

$$F_a, \text{alternative delamination factor} = \frac{\mathrm{A_{max}}}{\mathrm{A_{nom}}}$$

In order to obtain the alternative delamination factor, the optical micro-graphs were analyses by "Image J" software. Figure 1a shown a sample of the image fed into the software. The larger diameter circle in the figure represents the maximum area of the damage induced due to drilling and the smaller diameter circle represents the nominal diameter of the holes. Furthermore, each of the areas were found by selecting the measure area functions available in the software. The software then calculates the desired area. Similar methodology was sued to quantify the fibre pull-out factors, as shown in Figure 1b. After obtaining the values of maximum area of the zones, fibre pull-out factor was calculated using the expression shown below:

$$F_p = \frac{\mathrm{A_{pull-out}}}{\mathrm{A_{nom}}}$$

The fibre pull-out damages were shown as the material that is highlighted in yellow.

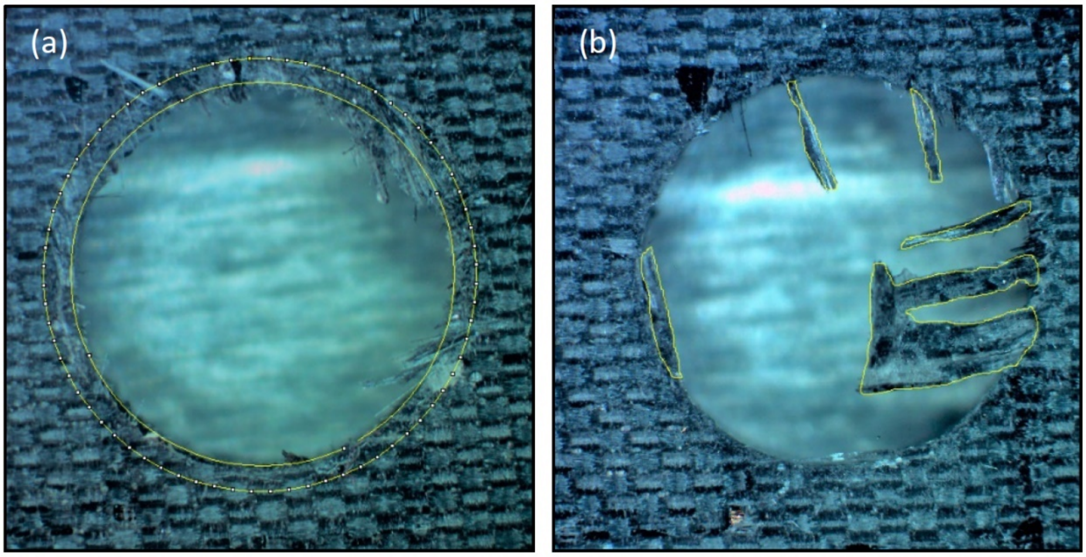

Figure 1. Evaluation of (**a**) delaminated and (**b**) fibre pull-out zone on holes drilled with following parameters: 0.12 mm/min feed, 2250 rpm with the presence of adhesive tape layers.

The circularity and diameter error were measured using a three-point axis coordinate measuring machine (CMM) known as Discovery II Model D-8 CMM. Figure 2 shows the schematic of drilling process. Figure 2b shows the drilling operation of CFRP with adhesive tape layers, Figure 2c shows the measurement of circularity and diameter error with CMM.

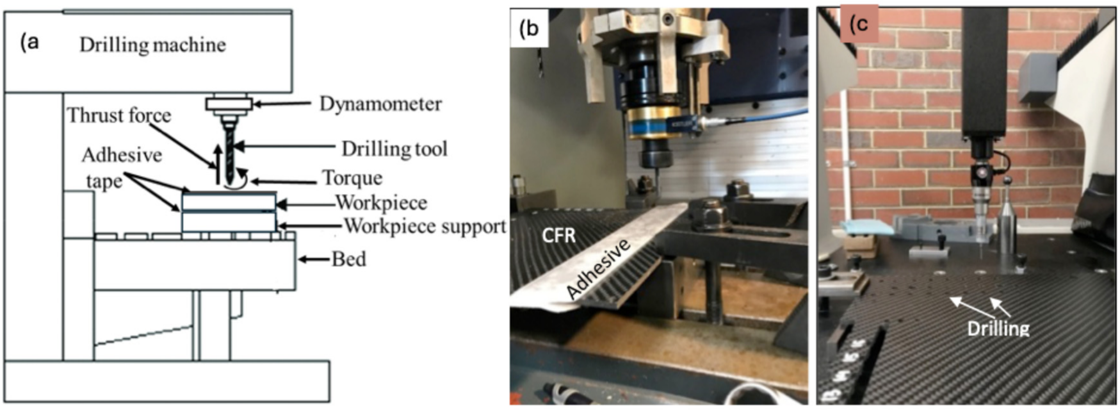

Figure 2. (**a**) Schematic of drilling process, (**b**) Drilling of CFRP with the presence of adhesive tape layers, and (**c**) circularity and diameter error measurement with CMM.

3. Results and Discussion

3.1. Drilling Induced Thrust and Torque

The generation of thrust force and torque during drilling took place whose magnitude depends on the range of input parameters. The evolution of thrust force during drilling the CFRP workpiece under different input parameters was shown on Figure 3a,b, respectively for with and without adhesive tape layers. Similarly, the evolution of torque was shown on Figure 4a,b, respectively for with and without adhesive tape layers. Irrespective of the drilling condition (with or without adhesive tape layers), an increase in the drill diameter increased the cross-sectional area of the unremoved chip and greater chisel edge length at higher diameter. This led to an increased load on the tool; thus, the thrust forces generated by using larger diameter drills are greater. Increasing tool diameter from 6 to 8 mm increased the thrust force for drill condition with adhesive tape layers by 1.5 times from 35.2 N to 52.77 N; however this increment was only 1.2 times from 25.71 N to 30.19 N for drill condition without any adhesive tape. The similar tread was also observed for the torque evolution.

The thrust force increases gradually as the point angle of the drill bit increases for both drill conditions (with or without adhesive tape layers). However, in saying that, increasing point angle from 125° to 130° decreased the thrust force for drill condition of adhesive tape layers by 1.7 times from 35.2 N to 20.17 N. This was primarily

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because as the point angle increases, the rake angle of the tool at each point on the cutting edges gradually increases. Therefore, reducing the tool-chip contact area with increasing drill point angle, reduce the thrust forces. On the other hand, it was noticed that the thrust forces were significantly lower for drill condition with adhesive tape layers, as opposed to without it. For example, the thrust force measured for the drilling with adhesive tape layers and point angle of 130° was 20.17 N. At the same point angle but without adhesive tape layers the thrust force was measured as 26.66 N. It can be said that smaller point angle was an ideal choice. Moreover, the use of adhesive tape layers further reduced the amount of drilling thrust force by 24% when using a drill point angle of 130°. In general, the torque trend seems to be fairly constant as point angle increases irrespective of the drilling condition. However, it could be noticed that the torque drops effectively from 0.156 Nm to 0.081 Nm when the drill point angle increases from 125° to 130°. This may be due to the fact that the drill was subjected to lower thrust force of 20.17 N at 130°, as opposed to 35.2 N at 125°, by the chisel cutting edge which compresses and winds the drill.

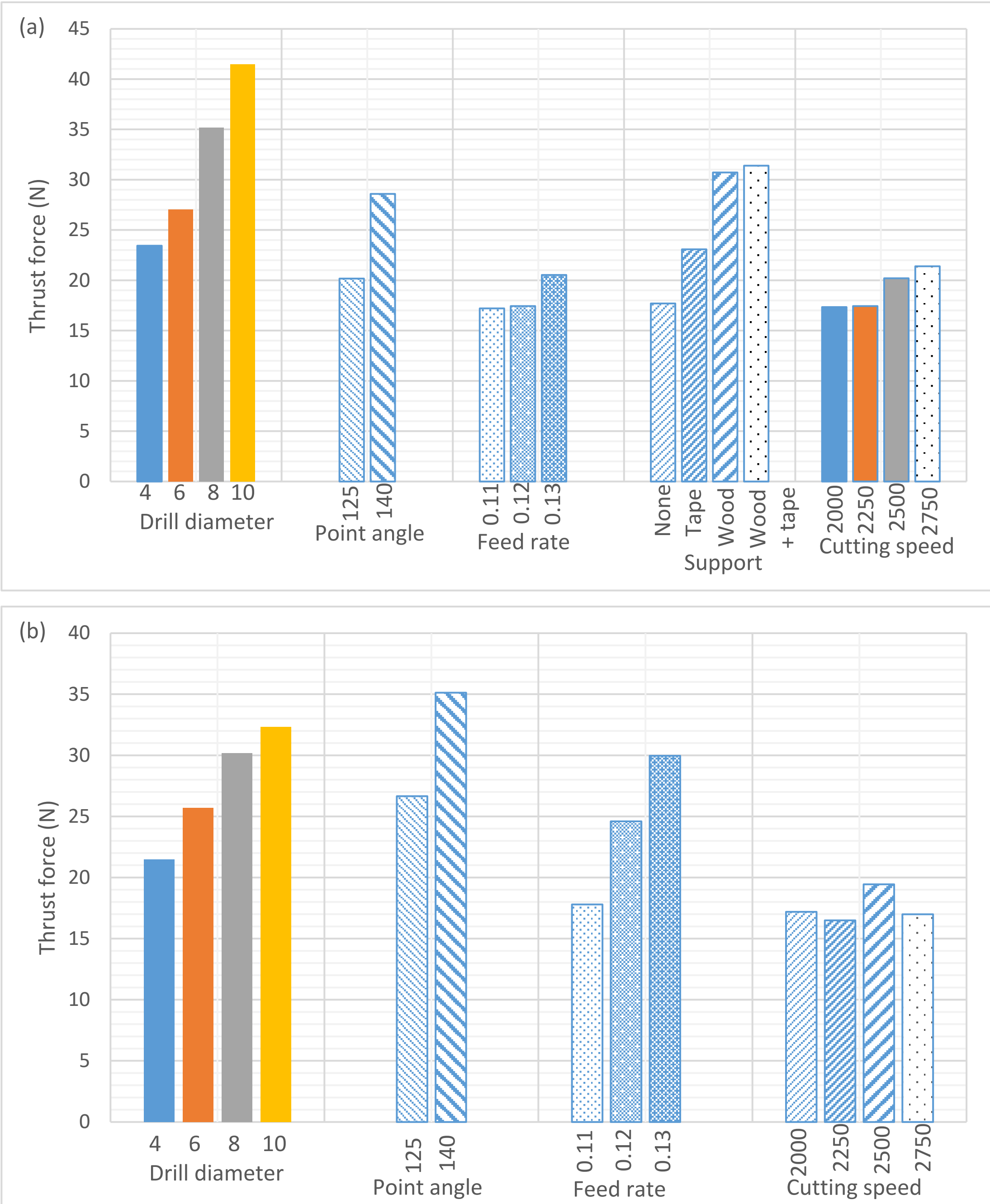

Figure 3. Effect of varying input parameters on thrust force: (**a**) with and (**b**) without adhesive tape layer.

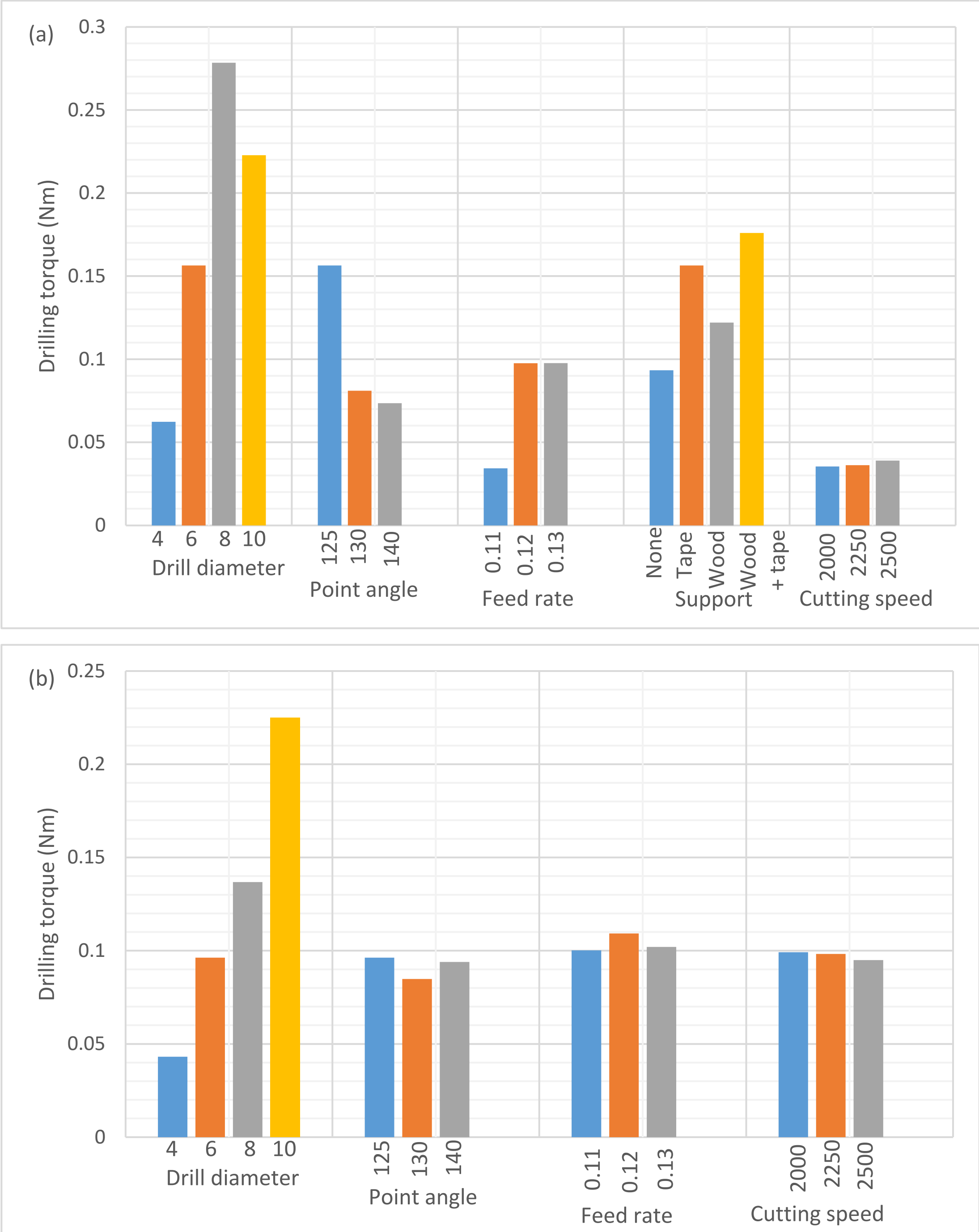

Figure 4. Effect of varying input parameters on torque: (**a**) with and (**b**) without adhesive tape layer.

Under constant cutting speed, point angle and drill diameter, the thrust forces and torque effectively increase with increased feed rate. The results revealed that average peak torque values increase significantly as the feed increases from 0.1 mm/min to 0.12 mm/min when the specimen was drilled with adhesive tape, followed by a slight increase in the values when the feed was altered from 0.12 mm/min to 0.13 mm/min. This was because, at higher feed rates, the undeformed chip thickness under the drill was largely translating into a higher material removal rate and thus, a higher thrust force induces higher drilling torque. For example, at 0.1 mm/min the torque was measured to be 0.034 Nm. At a similar drilling condition with adhesive tape layers, an increase in feed to 0.12 mm/min caused a 65% increase in the torque. Furthermore, the results attained for drilling condition without adhesive tape layers, it can be noticed that torque tends to remain more constant as the feed increases. This follows the similar trends that were mentioned in the literature [36], where feed rate has proven to be a major contributing factor for larger thrust forces and increased delamination. However, if the feed rate was too low, the cutting time at the exit would be prolonged which will cause delamination. The thrust force measured for the drilling with adhesive tape layers and point feed of 0.1 mm/min was 17.20 N. At the same feed of 0.1 mm/min and drilling without adhesive tape layers, the thrust force was measured as 17.8 N, thus reducing the thrust force by 3.4%. It can be said that maintaining a low feed rate is an ideal choice to minimize thrust forces and torque to achieve better quality holes.

The cutting speed has minimum effect on the thrust forces and torque under different drilling conditions and remain fairly constant. For example, average torque value of 0.098 Nm was measured for drilling condition without adhesive tape layers when spindle speed was altered from 2000 rpm to 2500 rpm. At similar speed combinations, the use of adhesive tape layers reduced the torque to 0.037 Nm. This suggests that, the use of adhesive tape as stacked layers on the specimen severely reduces the drilling induced torque by 62%. In addition to this, it could be said that spindle speed seems to have negligible impact when compared to other input parameters such as feed rate and drill diameter, which tend to be more influential as the torques measured were much higher for these parameters.

The effect of support plates under 0.12 mm/min feed rate with constant cutting speed, point angle and drill diameter of 2250 rpm, 125 degrees and 6 mm, thrust force increase with the presence of support layers. This was expected as the drill bit need to overcome the support stacks to go through the hole to complete the drilling.

3.2. Delamination Factor

The effect of varying input parameters on alternative delamination factor of the holes drilled into the composite specimen was shown in Figure 5 with (Figure 5a) or without (Figure 5b) the presence of support stacks. The delamination factor, measured at 1.32, was found to be minimum at a tool diameter of 4 mm, whilst the maximum was recorded to be approximately 1.48 at a tool diameter of 10 mm. In general, the trend of the plot indicates an increase in delamination factor with an increase in drill diameter. A sudden drop in the values could be noticed as the tool diameter increases from 6 to 8 mm. This was primarily due to the instability associated with the smaller drill bit diameter being operated at significantly high rotational speeds. Furthermore, when comparing and analysing the effect of adhesive tape layers, it can be clearly seen that values of delamination factors were relatively lower when the specimen was subjected to support stacks.

In regards to the effect of varying point angle on delamination factor, it could be said that the delamination factor at the hole exit decreases with increasing point angle. This fact was directly correlated to the decrement of the thrust forces with increasing point angle. A lowest delamination factor of 1.31 was determined for a drill point angle of 140°, whilst a 125° point angle observed the greatest delamination factor of 1.37.

In regards to the effect of varying spindle speed on delamination, with the presence of adhesive tape layers, it can be noticed that the damage increases with cutting parameters; which clearly means that the composite damage was larger for higher cutting speed. However, in saying that, comparison of these trends revealed delamination enveloping the hole exit periphery is greatly influence by feed rate, where the average delamination factor was measured was 1.40, as opposed to cutting speed, where the average delamination factor was measured as 1.37. Moreover, a cutting speed of 2750 rpm observed the greatest delamination factor of 1.38, whilst the lowest damage (1.35) around the hole was obtained when the drill bit was being operated at a spindle speed of 2000 rpm. Furthermore, it can be seen that the delamination factor significantly rises with an increase in spindle speed from 2000 to 2250 rpm, while it remains almost constant when the speed of the drill bit alters from 2250 to 2750 rpm. A spindle speed of 2000 rpm creates a feature of least delamination factor, while a spindle speed of 2750 rpm creates a feature of greatest delamination factor, where the values measured were 1.27 and 1.34, respectively.

The delamination factor at the hole exit seems to be significantly lower during supported drilling. For example, a delamination factor of 1.32 and 1.37 was calculated when the specimen was subjected to with and without adhesive tape layers, respectively. However, in saying that, the influence of supported drilling under the same feed of 0.1 mm/min has reduced the delamination factor to 1.25. Therefore, the use of support plates decreased delamination by approximately 6% and 8%, respectively. Thus, it could be said that combination of lower feed rate and supported drilling is always preferable in achieving the best quality of the holes with minimum amount of delamination damage.

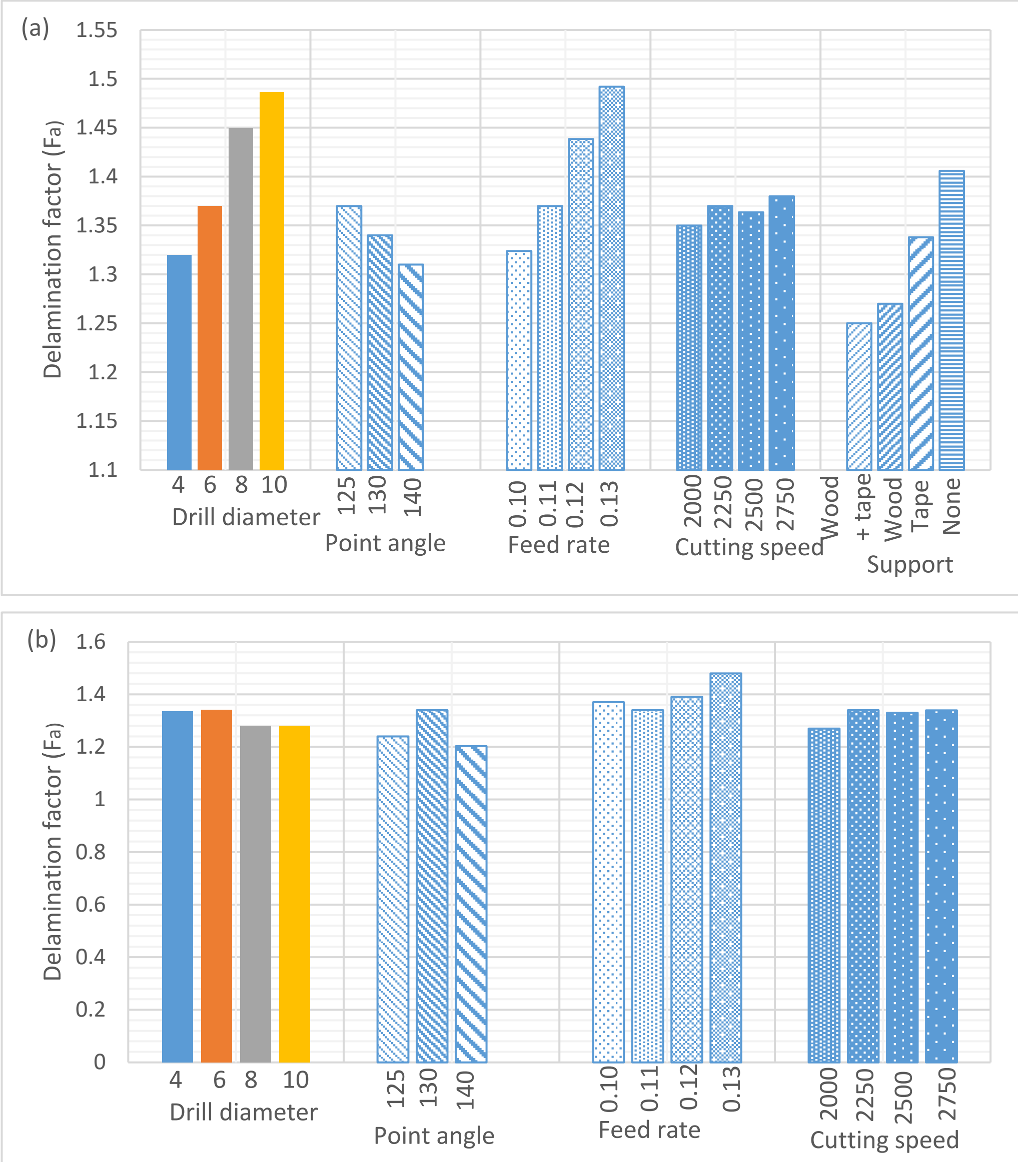

Figure 5. Effect of varying input parameters on delamination factor: (**a**) with and (**b**) without adhesive tape layer.

3.3. Fibre Pull-Out Factor

The effect of varying input parameters on fibre pull-out factor was shown in Figure 6a,b, respectively, with and without adhesive tape layers. In regards to the influence of adhesive tape layers, the fibre pull-out factor, measured at 0.074, was found to be minimum at a tool diameter of 6 mm, whilst the maximum was recorded to be approximately 0.259 at a tool diameter of 10 mm. In general, the results of fibre pull-out factor significantly fluctuates as the tool diameters were increasing, suggesting no real trend.

In regards to the effect of varying point angle, it could be said that, the fibre pull-out factor at the hole exit decreases with increasing point angle. This fact was directly correlated to the decrement of the thrust forces with increasing point angle, which was observed in Section 3.1. Furthermore, a lowest fibre pull-out factor of 0.068 was determined for a drill point angle of 140°, whilst a 125° point angle observed the greatest fibre pull-out factor of 0.074. The fibre pull-out factor significantly decreases (from 0.05 to 0.016) as point angle increases from 120° to 140°.

The values of fibre pull-out factor follow a trend of sudden decrease and increase as the feed rate alters from 0.1 mm/min to 0.13 mm/min. A maximum fibre pull-out factor, measured at 0.218, was calculated when the drill bit was being operated at a minimum feed rate of 0.1 mm/min. This was then followed by a sudden decrease in the degree of fibre pull-out as the feed increases to 0.12 mm/min, where the minimum fibre pull-out factor was calculated to be 0.045. However, in saying that, for experiments without adhesive tape layers and varying feed combinations, it was clear that the fibre pull-out factor progressively increases with increasing feed rate. This was primarily due to the increase in thrust forces exerted by the drill bit as it exits the hole. For example, the fibre pull-out factor at the hole exit for the drilling condition of 0.1 mm/min and a speed of 2250 rpm was calculated to be 0.03. At the same cutting speed of 2250 rpm, the hole drilled at 0.13 mm/min the fibre pull-outs were 0.131. The 0.03 mm/min difference in feed rate cause an 77% increase of fibre pull-outs on the hole at 0.13 mm/min when compared with the hole at 0.1 mm/min.

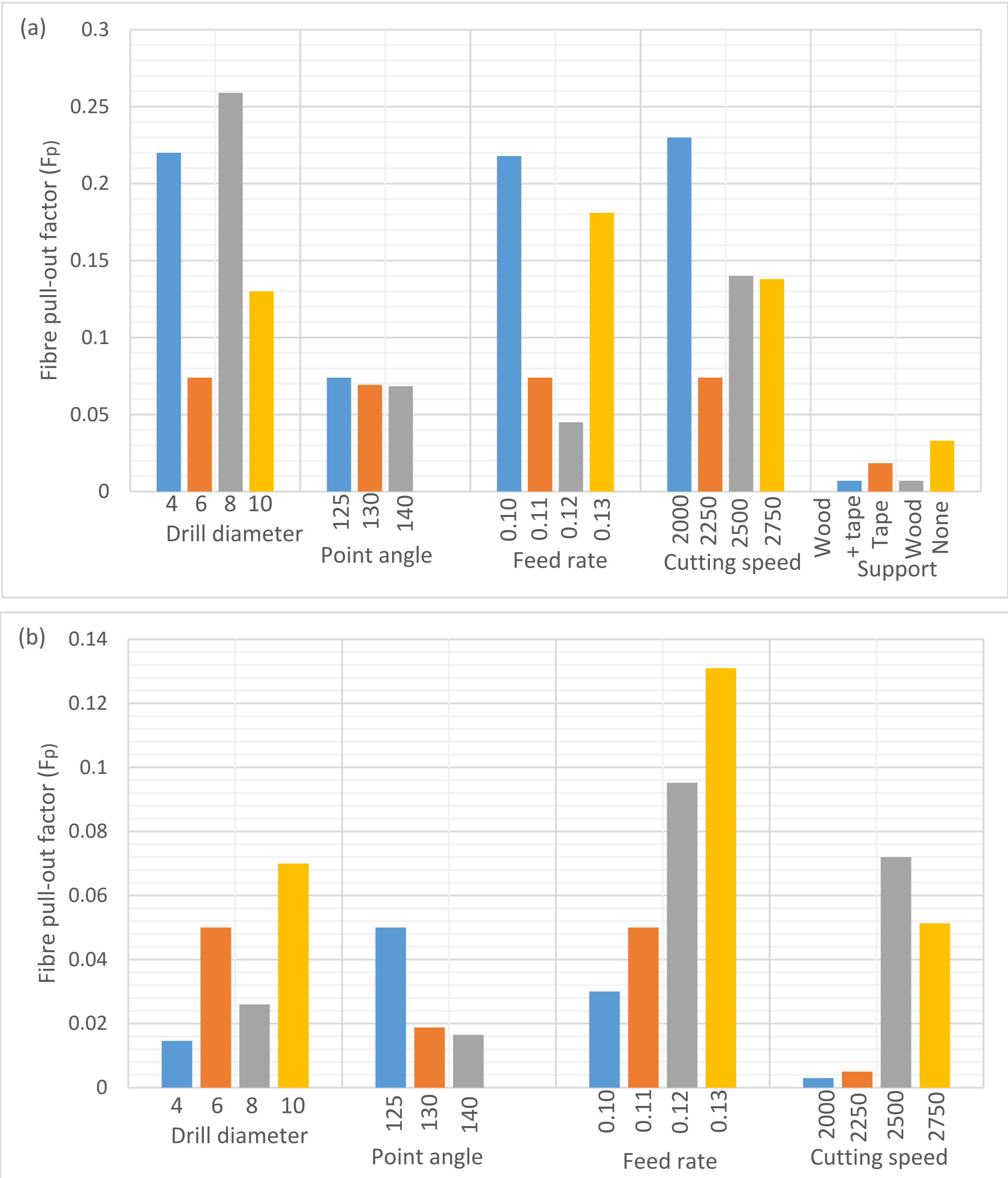

Figure 6. Effect of adhesive tape layers on fibre pull-out factor under varying input parameters: (**a**) with and (**b**) without adhesive tape layer.

In regards to the effect of varying cutting speed with the presence of adhesive tape layers, it could be said that the average fibre pull-out delamination factor decreases linearly with a factor of 0.021 with increasing speed of the drill. For instance, the maximum fibre pull-out factor for 0.11 mm/min and a speed of 2000 rpm was calculated as 0.23. At the same feed rate of 0.11 mm/min and a lower cutting speed of 2500 rpm the fibre pull-out factor was calculated as 0.14. The fibre pull-out factor significantly rises from 0.003 to a maximum of 0.072 as the spindle speed increases from 2000 to 2500 rpm. This increase in values was directly correlated to the increase in thrust forces at the exit of the hole. When increasing the speed, the undeformed chip thickness increases, resulting in increasing cutting force. This increased cutting force can extend the range of the angle between the fibre orientation and cutting direction, which ends up increasing the fibre pull-outs in a larger area.

The presence of support plates significantly reduces the fibre pull-out damage. For example, a fibre pull-out factor of 0.218 and 0.03 was evaluated when the CFRP plate was subjected to drilling, with and without adhesive tape layers, respectively, under drilling conditions of 0.1 mm/min feed rate. However, in saying that, the influence of supported drilling under the same feed of 0.1 mm/min has reduced the fibre pull-out factor to 0.007. Therefore, the use of support plates decreased the damage by approximately 96% and 77%, respectively. It could also be noticed that the degree of fibre pull-out seems to increase with increasing feed rate, as observed earlier in this section. Therefore, it could be said that combination of lower feed rate and supported drilling is always preferable in achieving the best quality of the holes with minimum amount of fibre pull-out damage.

Peel-up delamination at entrance of drill occurs due to the interaction of the laminate with the slope of the drill bit flutes. The subsequent uphill peeling force splits the toper plies from the undrilled plies which were pushed down by downward drilling force. This peeling force was influenced by the drill geometry and the frictional force between the drill and workpiece. Instead, push-out delamination at the exit of drill takes place when the drill force exceeds the threshold strength of inter-ply connection. The chance of push-out delamination reduces when the space between drill bit and bottommost ply of the CFRP decreases [2]. The adhesive tape and back support were introduced in this investigation to influence the above mechanism to minimize delamination.

3.4. Diameter Error

The effect of varying input parameters on diameter error was shown in Figure 7a,b, respectively, with and without adhesive tape layers. In regards to the influence of adhesive tape layers, it can be seen that the error in the diameter of the drilled holes remain fairly consistent and constant with an increase in tool diameter. However, in saying that, the results of diameter fluctuates as the tool diameters were increasing when the specimen was without adhesive tape layers.

In regards to the effect of point angle with the adhesive tape layers, the diameter error was measured at 0.006 mm which was found to be minimum, at a point angle of 130°, whilst the maximum was recorded as 0.019 mm at a higher point angle of 140°. The values of diameter error follows a trend of sudden decrease and increase as the point angles increases. Furthermore, it can be seen that the diameter error decreases with an increase in point angle from 125° to 130°, while it significantly increases to 0.044 mm when the point angle alters from 130° to 140°. Therefore, it could be said that the values of diameter error fluctuate with increasing point angle, regardless of the cutting conditions to which the workpiece was subjected to.

In regards to the effect of feed rate in the presence of adhesive tape layers, the values of diameter error remain fairly constant and consistent as feed rate increases from 0.1 mm/min to 0.13 mm/min. This value was determined to be approximately 0.011 mm. It was clear that a low feed rate of 0.1 mm/min creates a greater diameter error of 0.031 mm, whilst a feed rate of 0.12 mm/min results in least error of 0.006 mm. In addition to this, it could be observed that the errors in diameter for specimen without adhesive tape layers and feed rates of 0.12 and 0.13 mm/min were significantly smaller, as opposed to the presence of adhesive tape layers. Therefore, it could be understood that adhesive tape layers effectively increase the diameter error caused primarily due to fibre pull-out action.

In the presence of adhesive tape layers, the error in diameter increase with an increase in spindle speed. This is primarily due to the rotational stability of the drill bit being better at higher speeds, as opposed to lower cutting speeds. A spindle speed of 2750 rpm creates a feature of greater diameter, while a spindle speed of 2000 rpm creates a feature of least error in diameter, where the values measured were 0.02 mm 0.012 mm, respectively. A spindle speed of 2750 rpm creates a feature of greater diameter error, while a spindle speed of 2000 rpm creates a feature of least diameter error, where the values measured were 0.009 mm 0.005 mm, respectively. In general, greater diameter error values were obtained when the specimen was subjected to adhesive tape layers, as opposed without it.

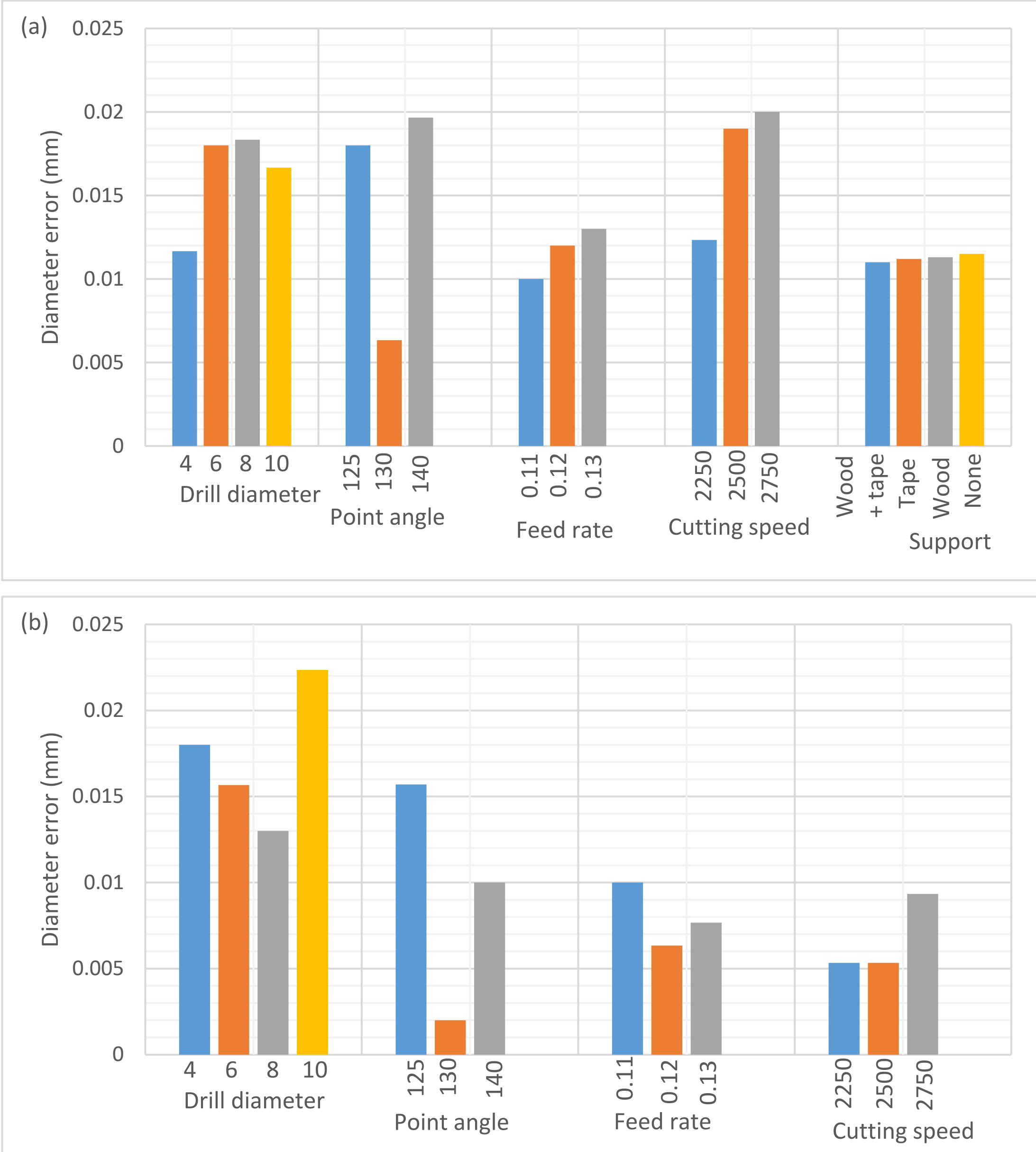

Figure 7. Effect of adhesive tape layers on diameter error under varying input parameters: (**a**) with and (**b**) without adhesive tape layer.

3.5. Circularity

Circularity can be described as a geometrical tolerance that permits how much a certain feature can deviate from a perfect circle. The effect of input parameters on circularity was shown in Figure 8. A low tool diameter of 4 mm creates lower circularity, whilst maximum deviation of the hole from a perfect circle was observed for a drill bit diameter of 10 mm, where the circularity was measured to be 0.053 mm. This may be primarily due to ploughing and friction induced by larger dimeter tools. An increase in the drill diameter of the drill bit increased the cross-sectional area of the unremoved chip and therefore resulting in greater circularity values.

In regards of point angle, a direct correlation between different point angles and circularity was noticed. Circularity was found as a minimum of 0.018 mm, at a higher point angle of 140°. In general, a decrease in circularity values with an increase in point angle was noticed. For experiments involving without adhesive tape layers, the circularity decreases with an increase in point angle from 125° to 130°, while it significantly increases to 0.086 mm when the point angle alters from 130° to 140°. Therefore, it could be said that the values of circularity fluctuate with increasing point angle, when the specimen was not influence by any layers of adhesive tape (Figure 8a).

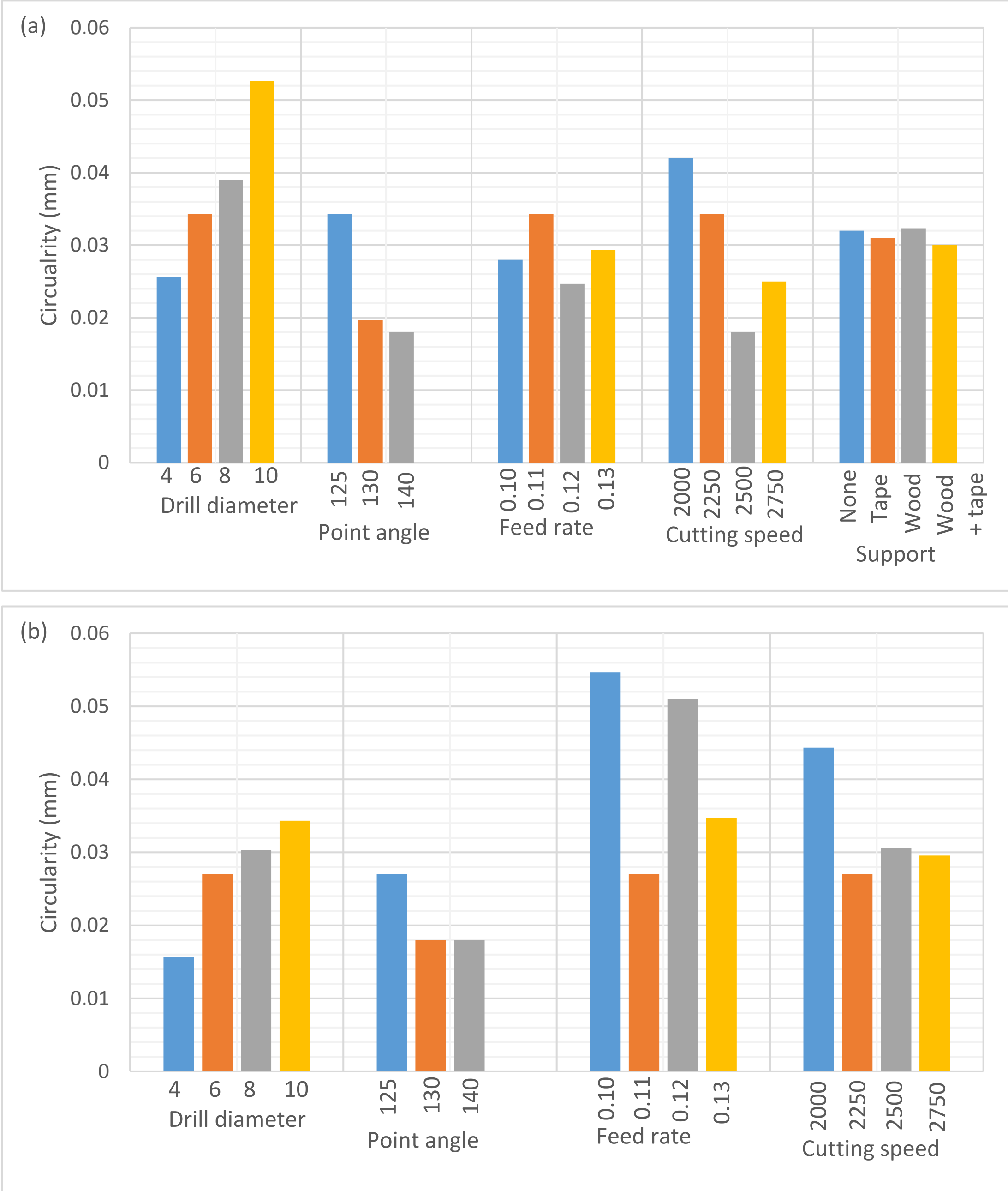

Figure 8. Effect of adhesive tape layers on circularity: (**a**) with and (**b**) without adhesive tape layer.

A low feed rate of 0.11 mm/min creates a greater circularity of 0.034 mm, whilst a feed rate of 0.12 mm/min results in least circularity of 0.025 mm. Therefore, it could be said that the results did not provide an adequate information to fully understand the effect of feed rate on circularity without the presence of adhesive tape layers (Figure 8b). The values of circularity fluctuate with an increase in feed rate. Therefore, it could be said that there is no clear trend observed for this relationship between circularity and feed rate.

In regards of the effect of spindle speed, the circularity decreases with an increase in spindle speed. This was primarily due to the rotational stability of the drill bit being better at higher speeds, as opposed to lower cutting speeds. A spindle speed of 2000 rpm creates a feature of greater circularity, while a spindle speed of 2500 rpm creates a feature of least circularity, where the values measured were 0.042, 0.018 mm, respectively. However, a slight increase in circularity could be observed as the spindle speed increases from 2500 to 2750 rpm, which was caused because of ploughing and frictional heating of the plate. It can be seen that the circularity decreases with an increase in spindle speed from 2000 to 2250 rpm, while it remains almost constant when the speed of the drill bit alters from 2250 to 2750 rpm. A spindle speed of 2000 rpm creates a feature of greater circularity, while a spindle speed of 2250 rpm creates a feature of least circularity, where the values measured were 0.0443, 0.027 mm, respectively.

In the presence of wooden support plate, the circularity values remain fairly constant with an increase in feed rate. Therefore, it could be concluded that the effect of feed rate is not dominant when compared to the effect induced by other parameters such as point angle and cutting speed. Furthermore, it can be seen that the influence of support stacks has a major effect on the circularity values, as opposed to other conditions, where the values fluctuate as feed rate increases.

In regards to the results attained for when the CFRP was drilled without the use of stacked layers, it was observed that the values of delamination factor almost remain constant for each varying input parameter, suggesting no real trends in the plot. However, in saying that, it could be concluded that feed rate was the most significant factor influencing delamination followed by drill diameter. As seen the damage increases with both cutting parameters; which means that the composite damage was bigger for higher feed rate and larger tool diameter. Therefore, for achieving minimum delamination, lower feed rates and smaller tool diameters were always preferred in the presence of support stacks. It can also be said that the use of higher point angle reduces delamination damages by better shearing of fibres. Furthermore, it could be noticed that the use of support plates effectively reduces drilling induced delamination. For example, the delamination factor when using support plates at the hole exit for drilling conditions of 0.13 mm/min and 2250 rpm was 1.406. At the same spindle speed of 2250 rpm, the hole drilled at 0.13 mm/min with no support plates has a delamination factor of 1.48. The use of support plates causes a 71% decrease of values.

The findings in relation to fibre pull-out factor was very similar and in close proximity with the results attained from evaluating the alternative delamination factor. It was observed that the use of both wooden support plates and adhesive tape layers on either side of the composite material significantly reduced the pull-out of fibres, as opposed to no use of either of the stacked materials. The reason for such low values of fibre pull-out factor were same as the ones previously mentioned, which was the use of supported drilling. Supported drilling reduces the imbalance and inflection of the material, therefore maintaining a steady feed rate and reduce the thrust forces when the drill starts to exit the work piece. This decrease in thrust forces significantly enhance the quality of the hole produced by reducing the degree of fibre pull-out damage. Point angle was the least factor affecting fibre pull-out after the use of support plates when compared to other cutting parameters such as, cutting speed, feed rate and drill diameter. On the other hand, drill diameter seems to be the most influential parameter affecting fibre pull-out damage followed by feed rate and cutting speed. Furthermore, the results reveal that the damage decreases as the values of these parameters were increased. Therefore, minimum damage of fibre pull-out was achieved when using larger values of tool diameter, feed rate and cutting speed along with the use of support plates. For example, the fibre pull-out factor when using support plates at the hole exit for drilling conditions 0.11 mm/min and 2250 rpm was 0.0184. At the same spindle speed of 2250 rpm, the hole drilled at 0.11 mm/min with no support plates had a fibre pull-out factor of 0.074. The use of support plates causes a 75% decrease of values. However, when analyzing the fibre pull-out factor for varying speed and feed combinations, it was often noticed that the values fluctuated significantly as each of these parameters were increased. In saying that, it could be deduced that the least amount of damage in regards to fibre pull-out at the hole exit was observed for drilling conditions of 0.11 mm/min and 2250 rpm, where the factor was evaluated to be 0.074. Feed rate was the most influential parameter causing maximum amount of fibre pull-out damage, followed by cutting speed, tool diameter and point angle which seems to have the least impact on damage relating to fibre pull-out. When increasing the feed, the undeformed chip thickness increases, resulting in increasing cutting force. Increased cutting force can extend the range of the angle between the fibre orientation and cutting direction, which ends up increasing the fibre pull-outs in larger area. However, in saying that, the least amount of damage was noticed when the material was being operated with drill conditions of 2250 rpm, 0.11 mm/min, drill diameter of 6 mm and a drill point angle of 125, where the measured fibre pull-out factor was 0.005. However, the delamination factor evaluated at these drilling conditions was 1.34, as opposed to a lower delamination factor of 1.27 attained for similar drilling condition but with the use of support plates. The use of support plates reduces the delamination induced by 5.5% suggesting that although no use of adhesive tape layer may result in minimal damage of fibre pull-out, the damage induced as delamination was significantly higher at the hole exit. Therefore, it could be suggested that in order to attain the best quality hole i.e., least amount of damage in regards to delamination and fibre pull-out, the use of support plates and adhesive tape layers as stacked materials on either side of the CFRP composite laminate were always preferable.

The cutting speed of the drill bit seems to be the most influential factor affecting the circularity. The circularity error decreases with increase in spindle speed, while it effectively increases with an increase in tool diameter. This could be because of ploughing and frictional heating caused due to larger drill diameter when drilling stacks of adhesive tape as the chisel cutting edge exits the workpiece. However, in saying that, the results of circularity almost remained constant for increase in feeds, as seen in the use of support plates where the feed was altered from 0.1 mm/min to 0.13 mm/min. This was because of the rotational stability of the drill was better at higher cutting speeds and feed rates. Furthermore, it could be noticed that the use of higher point angle reduces the circularity error of the drilled holes. Therefore, for achieving minimum circularity errors on the CFRP holes, higher point angles with lower tool diameter and a higher cutting speed were always preferred. Based on the above discussion, the optimized input parameters to drill quality holes in CFRP are as follows:

- Drill diameter—4, 6, 8 and 10 mm from worst to best, respectively.
- Point angle—125°, 130° and 140° from worst to best, respectively.
- Feed rate—0.1, 0.11, 0.12 and 0.13 mm/min from worst to best, respectively.
- Spindle speed—2000, 2250, 2500 and 2750 rpm from worst to best, respectively
- Support stacks with combination of as mentioned parameters in the same trend.

Based on the above discussion, the drilling mechanism can be schematically presented as shown in Figure 9. The profile in Figure 9 can be divided into 7 stages at various depths of the CFRP composite stack. At the first stage of the machining process, the chisel edge of the drill bit starts to penetrate into the 1st layer of the stacks i.e., the adhesive tape layers which indicated a steep increase in the thrust force and gradual increment of torque. As the cutting edges of the drill bit pass through the 1st layer of adhesive tape and into the 2nd stage, the amount of thrust force and torque increases more rapidly. This phase was then followed by the drill penetration into the CFRP composite plate at the 3rd stage, which indicates a rapid increase in the thrust force and torque values. This phenomenon was due to the sudden change in material hardness of the CFRP compared to adhesive tape layers.

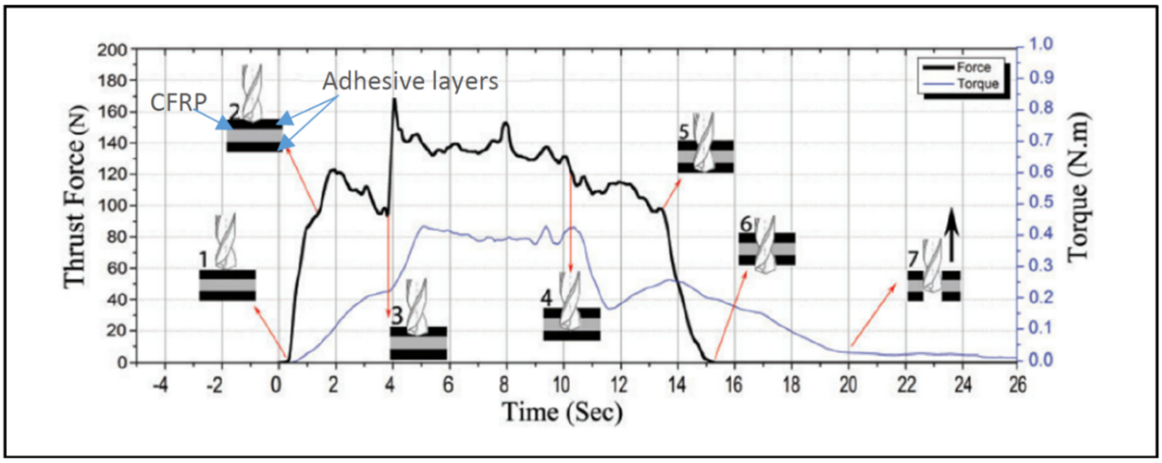

Figure 9. Schematic representation of drilling mechanism in terms of thrust force and torque generation with drilling depth.

After the 3rd stage the amount of drilling induced thrust force and torque decreases gradually. At the 4th stage of the machining process, it could be said that while cutting the last layer of the CFRP plate, the drill experience the highest amount of thrust force and torque. The 5th stage is when the drill bit begins to penetrate the 2nd layers of adhesive tape layers at the bottom of the CFRP plate. Subsequently, this was followed by the 6th stage where a rapid decrease in thrust force values down to zero was recorded by the dynamometer. This clearly indicated that the drill has fully penetrated into the stacked composite plate. In saying this, it was interesting to notice that, although the drill has passed through the 2nd layer of adhesive tape layers, the amount of drilling induced torque still remained constant throughout the process until the drill started to retract, 7th stage, where the torque recorded decreased gradually to zero.

4. Conclusions

This manuscript investigates the effect of drill bit diameter, point angle, cutting speed, feed rate, adhesive tape layers and back support, on the delamination of CFRP and dimensional accuracy of holes during. The study could be concluded as follows:

(a) Feed rate and drill bit diameter seem to be the most influential parameter affecting delamination, irrespective of the drilling geometry. The support plates and adhesive tape layers effectively reduces drilling-induced delamination by 71% by providing additional resistance to peeling forces at the entry and exit of the drilled holes. The support plates and scotch tape layers significantly reduced fibre pull-out. The reason for such low values of fibre pull-out factor was the use of supported drilling which reduces the imbalance and inflection of the material. This decrease in thrust forces significantly enhance the quality of the hole produced by reducing the degree of fibre pull-out damage. For example, the fibre pull-out factor, in the presence of support plates at hole exit for 0.11 mm/min feed rate and 2250 rpm cutting speed was 0.0184. At the same feed rate and cutting speed, without support plates, it was 0.074. Thus, the use of support plates causes a 75% decrease of pull-out factor.

(b) Feed rate was the most influential parameter affecting the thrust forces, followed by drill diameter and the use of support plates. In addition to this, it was found that the use of adhesive tape layers did not affect significantly the thrust force for each input parameter that was varied, as opposed to without any adhesive tape layers. Nearly similar trends were noticed for torque when the input parameters were varied.

(c) The circularity with and without adhesive tape layers were found to be very similar. The diameter of the drill seems to be the most influential parameter followed by cutting speed and point angle. Circularity error decreases with increasing spindle speed and effectively increases with increasing tool diameter Therefore, circularity of the holes was better achieved when operated at higher cutting speed and lower tool diameter, irrespective of the drilling condition. The use of adhesive tape layers was found to make no significant difference. Similarly, the use of support plates reduced the diameter error by 20% and 5% for varying feed and spindle speeds, respectively. Therefore, lower feed rates and cutting speeds are always preferable when subjected to adhesive tape layers to achieve the best hole quality with minimum diameter error.

(d) Scotch tape layers seem to increase the diameter error of the holes for each input parameters. This suggests that, scotch tape layers were not an ideal solution in limiting the induced diameter error. Having saying that, feed rate and cutting speed were the most influential parameters when the specimen was subjected to 12 layers of scotch tape. Therefore, lower feed rates and cutting speeds were preferable when subjected to scotch tape layers to achieve the best hole quality with minimum diameter error.

Further research is required to improve the quality of drilled holes in CFRP. The optimization of adhesive tape properties and customized back support have the potential in producing delamination free drilling.

Author Contributions

A.K.B.: conceptualization and methodology, writing—reviewing and editing; A.P.: supervision, conceptualization and methodology data curation, writing—original draft preparation; S.S.: writing—reviewing and editing; T. M.: writing—reviewing and editing; C.P.: writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

Data is available on request.

Conflicts of Interest

The authors declare no conflict of interest.

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