Drilling Strategy for Thick Carbon Fiber Reinforced Polymer Composites (CFRP): A Preliminary Assessment

Sharizal Ahmad Sobri*[1,2], Robert Heinemann[1], David Whitehead[1] & Norshah Afizi Shuaib[1,3]

[1]School of Mechanical, Aerospace and Civil Engineering, University of Manchester,
Pariser Building, Sackville Street, Manchester M13 9PL, United Kingdom
[2]Advanced Material Research Cluster, Faculty of Bioengineering and Technology,
Universiti Malaysia Kelantan, Jeli Campus, 17600 Jeli, Kelantan, Malaysia
[3]School of Manufacturing Engineering, Universiti Malaysia Perlis,
Pauh Putra Campus, 02600 Arau, Perlis, Malaysia
*E-mail: sharizal.s@umk.edu.my

Abstract. Carbon fiber reinforced polymer or CFRP composites are the epitome of high-performance materials in lightweight design. However, their machinability can be problematic due to non-homogenous and anisotropic material properties. This preliminary assessment emphasizes drilling strategy by using mechanical drilling and laser machining on 25.4 mm thick CFRP, which has not been investigated so far. In mechanical drilling, three drilling strategies were applied with the same parameters in order to assess the feasibility of drilling thick CFRP. The laser machining experiments were conducted to identify the potential of fiber laser machines to cut thick CFRP due to their superior laser beam quality. The results showed that choosing the appropriate drilling strategy in mechanical drilling is essential for reducing damage when drilling thick CFRP. Significant damage occurred in all experiments. The results are useful to define the relationships between machining parameters related to mechanical/laser drilling and hole/cut quality.

Keywords*: delamination; drilling; heat-affected zone (HAZ); laser machining; thick carbon fiber reinforced polymer composites (CFRP).*

1 Introduction

The use of highly advanced composite materials has knock-on effects for the way aircraft are built and assembled and it is pertinent to note that, according to Kalpakjian, *et al.* (1999) [1], almost 50% of the total airframe production cost is in airframe assembly. For components made of CFRP, certain difficulties, such as fiber pull-out, delamination and decomposition of the matrix material, are the most frequent problems that occur during the machining processes, all of which affect the quality of the machined surfaces and the material properties [2-4]. The work conducted on machining of CFRP so far has almost exclusively focused on CFRP thicknesses of less than 25 mm [5-12], which has resulted in

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only a small number of references on drilling thick, i.e. approximately one inch or 25 mm, CFRP material. Next to works on conventional machining, the amount of research conducted on unconventional machining of composites is increasing gradually.

Machining composites by laser technology appears to be a viable approach since one of the composite phases is often a type of polymer and polymers in general exhibit a very high absorption coefficient for infrared radiation as well as low thermal conductivity, which causes the thermal energy to remain highly localized [10,11]. An ideal cut for laser machining would be very narrow, completely straight and vertical, perfectly clean, and the cut faces would be smooth [5]. However, a typical laser cut is characterized by striations (regular straight lines on the cutting surface caused by the laser beam axis), splatter on the top surface, kerf width, edge roundness, microstructure defects due to HAZ, dross at the bottom surface, and unwanted tapering [7-12].

The present paper emphasizes the application of different drilling strategies on thick CFRP composites (provided by Airbus UK) in the mechanical drilling experiments in order to determine whether the tools can actually drill through an entire stack in a single stroke or whether the hole chip evacuation poses a serious problem and can ultimately fracture the tool. For the laser drilling experiments, the objective was to identify the potential of a 1-kW fiber laser to penetrate thick CFRP composites due to its superior laser beam quality (i.e. $M^2 = 1.1\text{-}1.2$), high degree of energy conversion (i.e. 20-30%), power stability, small focal spot, small physical size, high brightness and highly-resilient laser beam delivery with optical fiber [12,13]. Four machining parameters were selected in the assessment, i.e. feed rate and cutting speed for mechanical drilling, and laser power and scanning speed for laser cutting. The influence of these parameters on key output measures, such as hole depth, delamination and other damages, were investigated. Evaluation of the delamination factor (F_{da}) was also conducted by adapting the method of Davim *et al.* (2007) [14]. In addition, other damage was observed using a digital microscope. The results were used for qualitative analysis to define the relationships between machining parameters related to mechanical/laser drilling and hole/cut quality.

2 Experimental Conditions

The mechanical drilling experiments were conducted on 25.4 mm thick CFRP composites (see Figure 1) in order to drill a Ø 8mm hole (material sample size 50 (length) x 20 (width) x 25.4 (thick/height) mm) by using a 2-flute tungsten carbide drill bit (WC-uncoated Ø 8 mm with a point angle and helix angle of 118° and 35° respectively) on a Takisawa MAC-V3 Machining Center (maximum spindle speed and power of 6,000 rpm and 5.6 kW, respectively) in a dry cutting operation conducted at the Pariser Building of the University of Manchester. The experimental work used a 3 by 3 matrix as the process parameter window; the levels of cutting speed (i.e. *Vs*: 64, 80, 120 m/min) and feed rate (i.e. *F*: 0.096, 0.12, 0.18 mm/rev) were selected based on the literature. It was decided to run the experiments using a 2-flute uncoated tungsten carbide drill with three different drilling strategies while it was not clear at that stage whether the tool could actually drill through the entire stack in a single stroke or whether the chip evacuation would pose a serious problem and could ultimately fracture the tool. The drilling strategies chosen were: a) single-step drilling, i.e. the entire hole is drilled in one uninterrupted motion; b) peck drilling using 2 steps, where the drill was withdrawn once before reaching the hole exit, as it reached a depth of 15 mm; and c) peck drilling using 4 steps, where the drill was withdrawn 3 times, i.e. at depths of 7, 12, and 17 mm. Each strategy produced 9 holes and this resulted in a total of 27 drilling tests, which were conducted in a sequential manner, i.e. starting with the combination of the lowest parameters and ending with the combination of the highest parameters.

Figure 1 CFRP specimen.

Table 1 shows the drilling sequence for all strategies. Each strategy used one new drill bit to drill 9 holes. Additional tests done in a random manner were also conducted, resulting in 18 holes. All experiments were replicated three times. Table 2 shows the drilling tests done in a random manner, whereby for each strategy a new tool was used. These additional tests were conducted to identify the damage mainly caused either by the operating parameters or the progression of tool wear.

Table 1 Matrix table of speed and feed rate in a sequential manner for all strategies.

Vs [m/min]	**F [mm/rev]**		
	0.096	**0.12**	**0.18**
120	H3	H6	H9
80	H2	H5	H8
64	H1	H4	H7

Table 2 Matrix table of speed and feed rate in a random manner (indicated as 'R'): Single-step (1st, 4th and 7th column); 2-step (2nd, 5th and 8th column); and 4-step (3rd, 6th and 9th column) peck drilling.

Vs [m/min]	**F [mm/rev]**								
	0.096			**0.12**			**0.18**		
120	R3		R3	R5, R6	R3	R5, R6		R1	
80		R5					R2	R2	R2
64	R1		R1		R6		R4	R4	R4

Airbus UK was reluctant to disclose full details about the material used, which required the author to conduct limited examinations to determine the material's specifications. However, they did provide a few pertinent details about the material, i.e. that it is a toughened epoxy matrix/resin incorporating high strength, polyacrylonitrile (PAN) based carbon fibers typically used for aircraft structures.

The yield strength and density of this material are 835 MPa and 2.06 g/cm^3, respectively. Visual inspection using a digital microscope (Keyence VHX-500X) at Laser Processing Research Centre (LPRC), University of Manchester revealed that the stacking sequence of the lamina was arranged as [0°/90°/-45°/90°/45°/90°/-45°/90°/45°/90°/-45°/90°/0°], recurring up to 25.4mm thickness, where the thickness of each ply is 0.22 mm and 114 layers are laid up with this fiber orientation arrangement.

Figure 2 shows the layers at both the hole entry and the hole exit. As can be seen, the top layer has a glass-cloth coating, which looks glossy and smooth. In the final layer, apart from the hole damage area, the weave pattern was clearly visible. Both layers had similar appearances in accordance with observations from other references [15,16]. The initial thickness of the peel ply layer as well as the final layer was 0.14 mm.

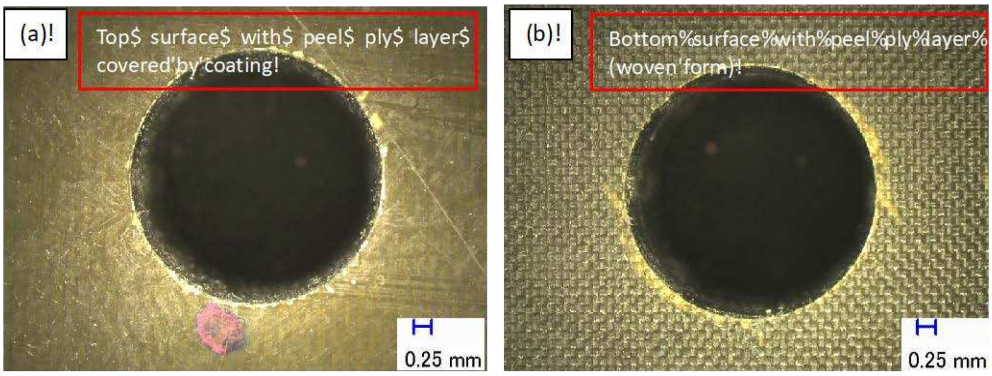

Figure 2 Hole results by mechanical drilling with back-up/support material applied to both sides: (a) entry side; and (b) exit side

A microscope was also used to assess the defects from mechanical/laser drilling. Figure 3 shows how to quantify the delamination zone. An adjusted delamination factor equation (F_{da}) was used, adapted from Davim, *et al.* (2007) [14], which is a two-dimensional delamination factor equation. Equation (1) consists of two parts. The first one is the ratio of delamination damage, where D_{max} is the maximum diameter of the observed delamination zone and D_0 is the nominal diameter of the drilled hole, i.e. the overall size of the crack contribution, and the second part is the damage area contribution.

$$F_{da} = \alpha \frac{D_{max}}{D_0} + \beta \frac{A_{max}}{A_0} \qquad (1)$$

where A_{max} is the area related to the maximum diameter of the delamination zone D_{max} (the area indicated by a yellow indicator), and A_o is the nominal area of the drilled hole (the area in the red circle). The parameters α and β were used as weights in these parts; further details can be found in Davim, *et al.* (2007) [14].

The laser drilling experiments were conducted on the same material as used in the mechanical drilling experiments, using a continuous-wave (CW) fiber laser (IPG YLR- 1000-SM, single-mode emitting at near infrared (wavelength, λ = 1070 nm; laser power P = 1 kW, ytterbium doped) at LPRC. The focusing lens diameter was 38 mm with a focal length of 190 mm. The focusing position can be coaxially adjusted (view window range -20 to +10 mm). Based on the literature, laser power, scanning speed and laser control mode appear to exhibit the most dominant effects on cut quality. However, for this assessment it was decided to focus only on laser power (P: 500, 600, 900 W) and scanning speed

(speed: 5, 7, 10 mm/sec) to determine the processing window for drilling thick CFRP (8 mm hole diameter) with single-pass settings.

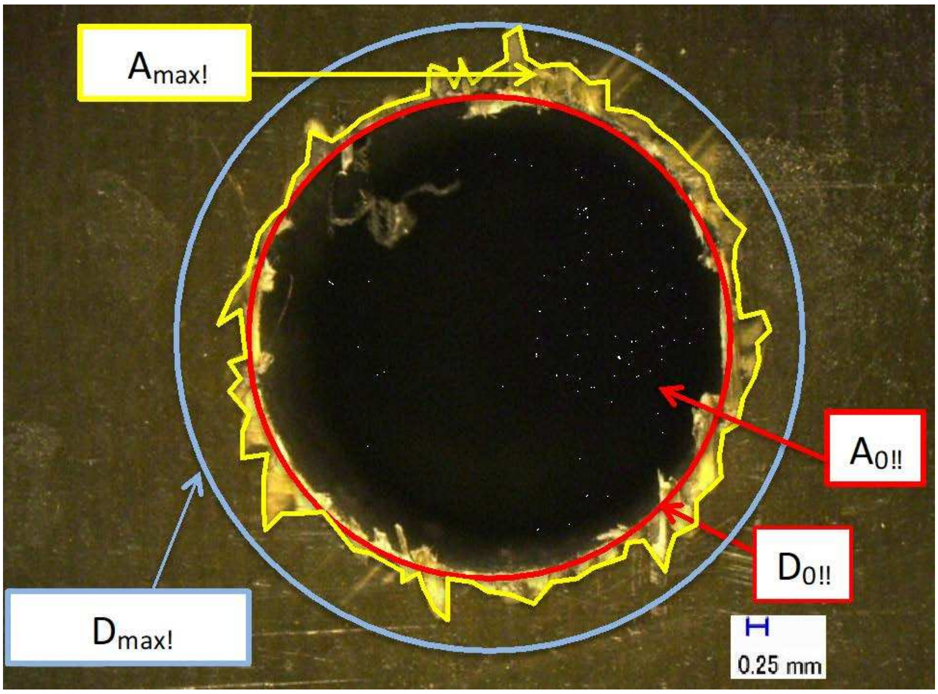

Figure 3 Measuring the delamination zone using the F_{da} method.

Table 3 shows the matrix table of laser power and scanning speed for single-pass drilling thick CFRP, while Table 4 shows the fixed parameters. The same as the mechanical drilling, it was conducted sequentially, going from the lowest combined parameters to the highest. The selection of these variables was based on the range of common parameters used and the maximum limit of laser power settings in the literature. The initial experiment was conducted before doing the drilling experiments in order to ascertain the maximum hole depth that can be achieved with the laser system identified for this part of the research. The purpose was to establish if the 1 kW fiber laser machining system feasibly penetrates 25.4 mm thick CFRP completely or not, since this was the first attempt at machining CFRP of more than 7 mm thick and it has never been done by other researchers [5-12]. Narrow slots were machined (i.e. cut) into some CFRP blocks (see Figure 4), and laser power at 900 W and scanning speed at 5 mm/sec were fixed parameters, including other parameters as mentioned in Table 4. Each slot was cut to various targeted depths and conducted in multiple passes as well. Starting with a depth of 4 mm, the laser machine cut in single-pass and then the remaining slots were cut in multi-pass. The multi-pass arrangement was varied at 2, 3, 4 and 5 passes for producing depths of 8, 12, 16 and 20 mm, respectively. All experiments were replicated three times.

Table 3 Variable parameters for laser drilling.

Scanning Speed (mm/s)	**Laser Power (W)**		
	500	**600**	**900**
10	H3	H6	H9
7	H2	H5	H8
5	H1	H4	H7

Table 4 Fixed parameters for laser drilling.

Processing Parameter	**Experimental unit value/selection**
Laser mode operation	CW
Type of assist gas	Nitrogen
Gas pressure	8 bar
Nozzle diameter	1mm
Stand-off distance	1mm
Focal plane position (FPP)	- 12mm
Focal length	7.5"
Focal lens diameter	1.5"
Beam spot diameter	70 µm (at reference point, FPP = -12mm)

3 Results and Discussion

3.1 Feasibility of Three Mechanical Drilling Strategies

At this stage, the evaluation was only focused on the delamination factor without tool wear observation and to decide which drilling strategy achieved the best hole quality. Figure 5 shows samples of the hole entry (left image) and exit (right image) after drilling with three drilling strategies, i.e. peck drilling with 2 and 4 steps, as well as single-step. The holes depicted in Figure 5 were drilled in sequence, which means that the first hole was drilled with the lowest feed and the lowest speed, while the last hole was drilled with the highest feed and highest speed. In contrast, Figure 6 (the left image is the hole entry and the right image is the hole exit) shows the combination of feeds and cutting speeds where each hole was drilled in a random manner in order to establish if the hole quality is affected either by the cutting parameters solely or both from the cutting parameters and tool wear progression.

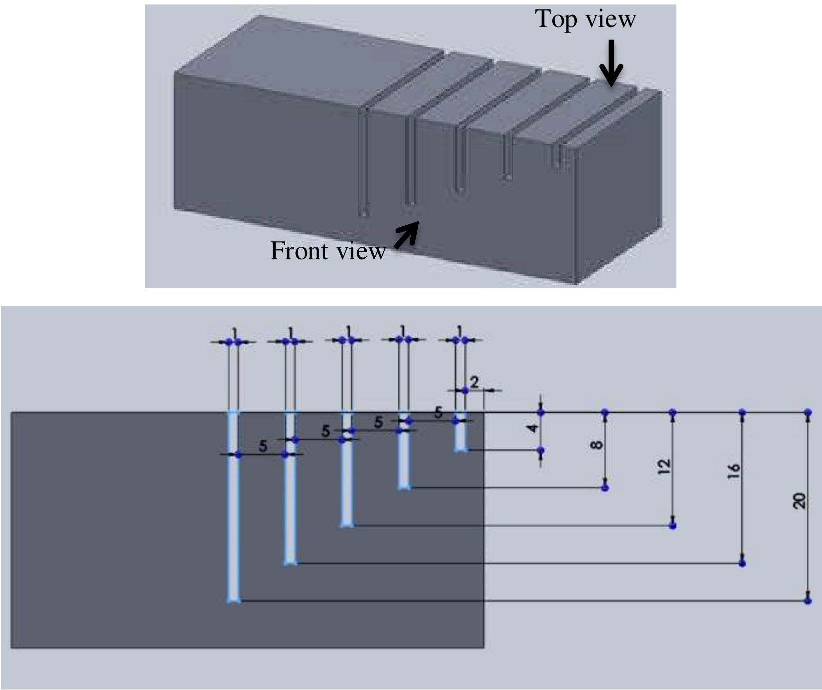

Figure 4 Schematic of illustrations for laser machining effects: isometric and front views of a sample with five different depths of trenches (all units in mm).

Visible damage was observed to all holes produced, particularly peel-up and push-down delamination. The hole defects became more serious as the number of steps of peck drilling increased, with most damage visible after 4-step peck drilling. The quality concern was confirmed when comparing two strategies, i.e. single-step and 2-step peck drilling. It is apparent from the pictures shown in Figures 5 and 6 that the most significant damage occurred at the hole entries. In these tables, the left hole is the entry side while the right one is the exit side. All damage and the adjusted delamination factor (F_{da}) ratios are shown in both tables. Although the delamination at the hole entry generally appeared to be more severe compared to the damage produced at the hole exit, a closer inspection of the defects of the hole exit, such as delamination and overhanging/uncut fibers, in Figures 5 and 6 show that there was a similar trend there, i.e. damage along a certain quadrant area in most cases. In addition, the regular lines stretching out radially at these quadrant areas (as annotated in the table) is believed to be part of the heat affected zone, where the thermal conductivity of the carbon fibers is high compared to the surrounding matrix, thus encouraging the heat generated during the cutting process to spread out along the fibers.

Some damage also occurred at angles opposite the quadrant with the angle between 180° and 90° degrees, such as in the case of H6 and H8 (2-step peck drilling) in Figure 5. In addition, certain combinations of cutting speed and feed rate, such as in the case of H19 and H27 (4-step peck driling) in Figure 5 and H10 and H15 (4-step peck drilling) in Figure 6, resulted in the bottom of the workpiece showing large areas of the bottom attached to the workpiece. This behavior is the same as in another research attempt [3], where the critical cutting angles occurred between 180° and 90° degrees where delamination and overhanging/uncut fibers occurred. All holes shown in both tables are from the perspective of the initial and final layer, whereby both layers possessed a woven-ply structure with no specific fiber orientation due to the bidirectional form. During the drilling process, the fibers were actually bent by the cutting edges and it was obvious that cutting perpendicular to the fiber direction caused significant damage.

This may have been caused by softening of the matrix, which allowed the fibers to elastically deflect during the cutting process and therefore not being fully cut by the tool. In addition to that, generation of drilling heat softened the matrix, which can compromise its shear modulus and relieve the radial stresses exerted over the fibers. Consequently, 2-step and 4-step peck drilling generated a large amount of heat as the tool was required to be taken in and out two or four times, while single-step drilling involves less interaction time between the tool and the workpiece. Furthermore, the matrix was unable to transfer the local strain perturbations efficiently to the fibers and failed to provide sufficient stability to the fibers against the cutting action of the twisting drill, the same as in other researches [5,6,17] on premature fiber debonding, slipping and fracture, dependent on the relative orientation of the fiber with respect to the cutting edge of the drill. This is supported by the evidence of the softened matrix on the hole boundaries. Thus, the drilling strategy affected the hole quality.

The delamination factor (i.e. F_{da} ratios) results confirmed the relationships between the speed-feed combinations and the amount of damage to both hole entry and exit hole. These are not really new contributions towards the mechanical drilling of CFRP composites due to the abundance of investigation attempts by other researchers. However, the three mechanical drilling strategies should be highlighted, since such experiments were never done or specifically mentioned in previous research attempts.

Single-step drilling was able to drill 25.4 mm thick CFRP with minimum damage occurring (i.e. delamination and overhanging/uncut fibers) and it was discovered as the most favorable strategy to achieve good results in terms of hole quality compared to 2- and 4-step peck drilling strategies, where serious delamination and uncut fibers occurred. No suggestions were made by other researchers in terms of drilling strategies, specifically for drilling of thick CFRP. Obtaining these results helps to clarify the uncertainty of drilling thick composites about whether the tool can actually cut a thick workpiece or not.

Achieving a minimum amount of damage is a key issue for drilling CFRP composites and previous researchers [1-6,15-17] mostly agree that mechanical drilling requires the selection of optimum cutting operation parameters, i.e. cutting speed (spindle speed) and feed rate, in order to avoid excessive forces affecting the surface integrity of CFRP composites. By identifying the drilling strategy, having expensive drill bits (i.e. diamond tipped core drill bit, 3-flute diamond coated drill bit, etc.) is not necessary due to the positive effects of single-step drilling. In addition, it is not practical to manipulate the cutting parameters in peck drilling strategies. This can be explained by observing the hole quality of a tool drilled to a certain depth inside the hole at various speed-feed combinations.

The next series of experiments was conducted to establish whether the hole quality depends solely on one cutting parameter or not. The experiments were done the same way as the previous experiments, however, this time they were conducted in a random sequence. Based on the results in Figure 6, the hole damage was reduced compared to the results shown in Figure 5. In the meantime, the 4-step peck drilling still achieved the least good result compared to the other strategies. These results were confirmed by the values of the delamination factor as provided at the bottom of each hole image. Furthermore, the results indicate that hole quality does not depend solely on one cutting parameter.

Peck drilling strategies were discarded for the next experiments due to the positive results of the single-step strategy. That the hole defects were significantly reduced by changing the sequence means that the change in hole quality could not be associated with the alteration of one single process parameter (i.e. increase/decrease of speed or feed rate). Hence, it is likely that the hole quality was also affected by the progression of tool wear.

A subsequent experiment was conducted to identify the progression of tool wear affecting hole quality by drilling 50 holes with a fixed set of cutting parameters (i.e. cutting speed, Vs: 80m/min; feed rate, F:120 mm/rev) using a single-step strategy only. This test was also replicated, resulting in a total of 100 holes. Each tool drilled 50 holes.

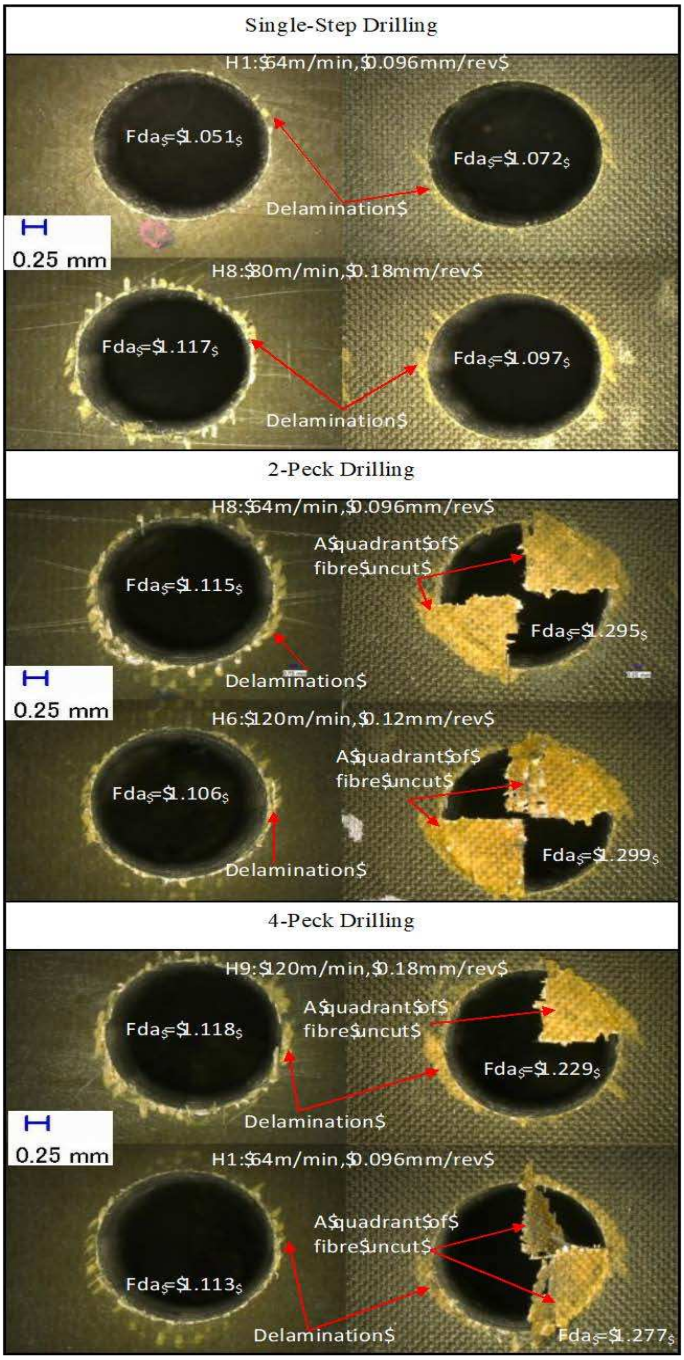

Figure 5 Image results of drilling strategies in sequential manner.

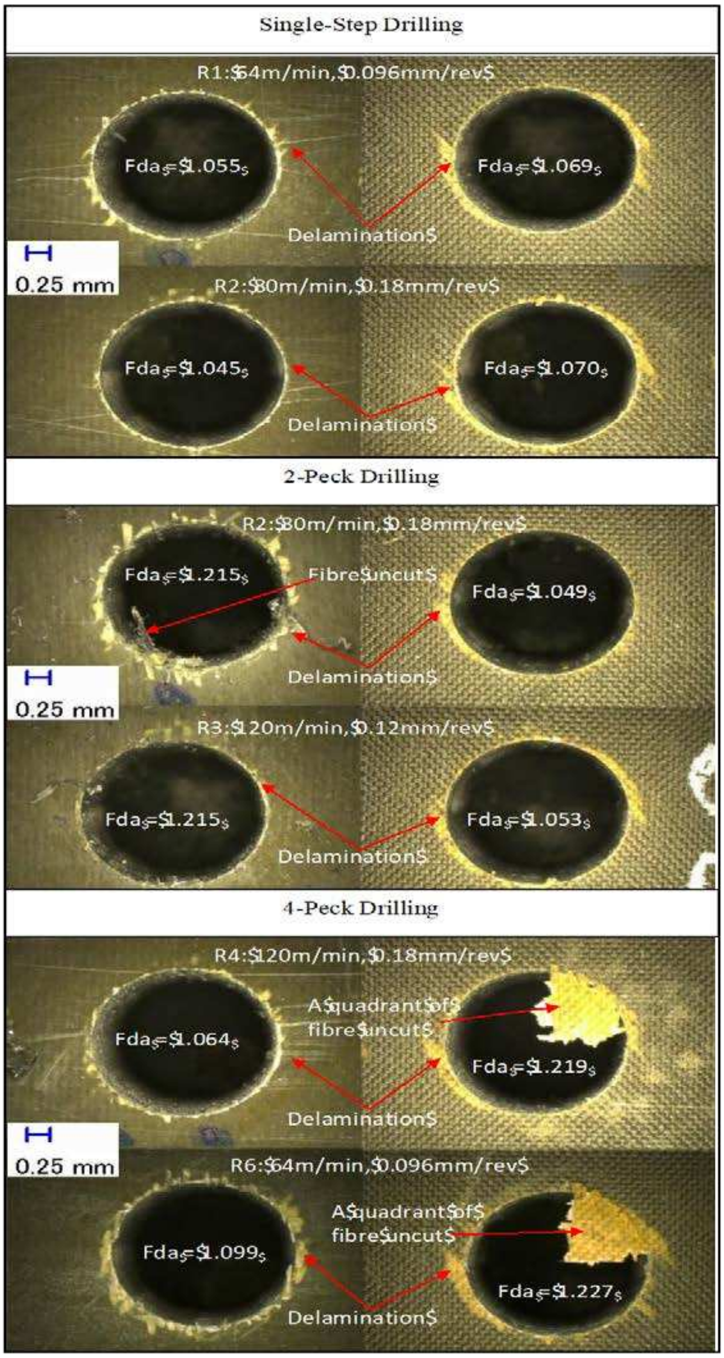

Figure 6 Image results of drilling strategies in random manner.

Both the hole entries and exits, as shown in Figure 7, indicate an increasing deterioration with the growing number of holes that the tool produced, which exhibited the same damage as previously described after drilling only 37 holes. Consequently, the damages further increased as the tool drilled another 13 holes. In contrast, the first 30 holes appeared to be of similar quality with regard to their hole entries and exits. This test confirmed that in order to limit the effects of tool wear progression on hole quality, and thus to identify the impact of different process parameters on hole quality in isolation, the number of holes drilled per tool had to be heavily restricted. Based on what was observed in this experiment, a tool life up to 30 holes seems to be reasonable according to the F_{da} results, with optimum hole quality after drilling around 5 to 6 holes. This may not be acceptable in a production environment, but the effect of tool wear was among the main interests of this research.

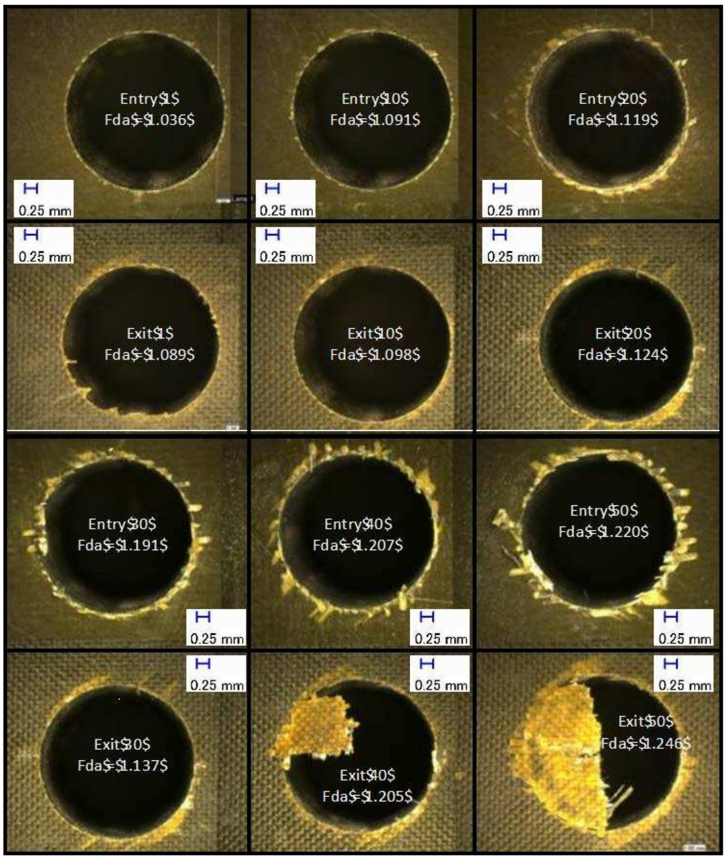

Figure 7 Image results of tool wear progression (scale unit in mm).

3.2 Laser Machining of Thick CFRP by using 1 kW Fiber Laser

Initially, it was decided to focus only on laser power and scanning speed to determine the processing window for single-pass cutting. Figure 8 shows the attempt of laser drilling, which was unsuccessful in penetrating the workpiece, even though the experiments were conducted with variation of laser power and scanning speed. A significant amount of HAZ appeared at the outer region of the hole circumference. Then, another experiment was conducted to investigate how far the laser could penetrate the 25.4 mm thick CFRP workpiece in multiple passes at different depths, since the earlier tests were unsuccessful in cutting through the entire block in a single pass.

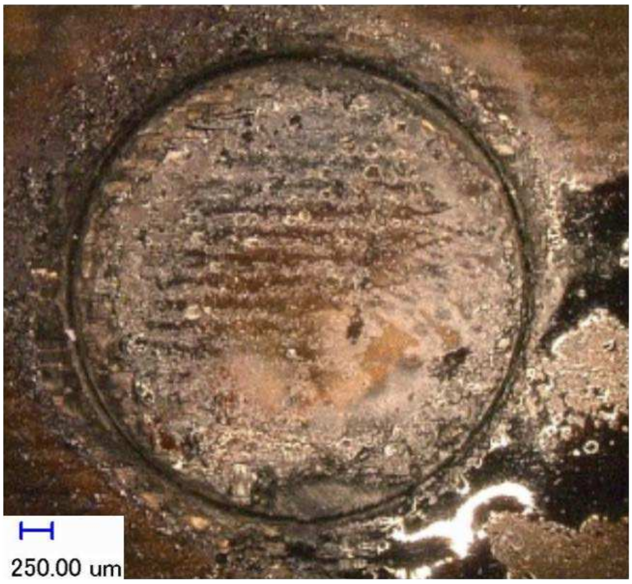

Figure 8 Initial laser drilling result (power: 900 W; speed: 10 mm/sec; single pass).

As shown in Figure 9, kerf depths in excess of 4 to 5 mm were impossible to achieve, although the kerf depth appeared to be significantly deeper as suggested by the vertical cuts underneath the trench. Actually, these were the only surface cuts that did not have any significant depth into the material. The trenches exhibited strong matrix recession around both the entrance and top surfaces of the workpiece, including HAZ with matrix recession and disoriented fiber layers.

The multi-pass tests were unsuccessful, where the laser could only penetrate the material up to 5 mm deep, even though the laser cutting was done in 5 passes.

The next attempt was explored by doubling the number of passes from 5 to 10 as well as the scanning speed from 5 to 10 mm/s in the hope of penetrating deeper and reducing damage due to the length of the interaction time between the laser beam and the workpiece. Hence, Figure 9 shows the sample with a trench depth of 5 mm and the remaining samples did not need to be shown because these did not achieve more than 5 mm depth. Other experiments were conducted to produce non-straight cut paths into the CFRP material, thereby progressively changing the cut path from a straight line to a curve, resembling a section of a hole. The idea behind this was to understand the damage that occurs when the laser moves in a non-straight path.

Figure 10 shows a section of a hole (90° degrees) located at the edge of the workpiece with a depth of 5 mm (4 passes). Due to the curved cut path, the cut-off could easily be removed, providing access to the cut surface without further damaging the workpiece. These images of the damage to the workpiece clearly show splatter on the top surface and the extent of HAZ.

When the laser pulse was finished, the gas flow ceased and the melt would fall back as splatter around the edges of the cutting path, or even drop into the kerf as the assist-gas was not be able to effectively blow away the dust and vapors generated during the cutting/drilling process. Another possible explanation for this restriction could be found in the design of the nozzle tip, which makes it difficult for the nozzle to lower down towards the workpiece, as it is not designed to be a thread nozzle, which restricts the setting of the stand-off distance. Moreover, stand-off distance must be set to 1 mm between the nozzle and the workpiece in order to make certain a significant amount of inert gas go inside the material to aid the removal process and boost cutting efficiency as recommended by Hernandez, *et al.* (2011) [13]. During the experiments, some of the samples were burnt at the top surface, which could be because a low gas pressure setting was used at that time (i.e. less than 3 bar) and the initial layer of a sample (i.e. the peel-ply layer) is also prone to burning.

It is essential that the gas pressure should be set to a high level so that the gas can cool down the surface effectively as well as assist the removal process efficiently. A major obstacle in laser drilling is non-escaped vaporized materials, which can act as blockage for the laser beam to go further towards the bottom of the hole because not all fibers are ejected completely. Therefore, the crucial concern is to fine-tune the laser beam energy (i.e. higher laser power) and assist gas pressure (i.e. higher bar pressure) for developing the laser drilling parameters in order to avoid severe HAZ and penetrate thick CFRP material (i.e. 25.4 mm thick) completely.

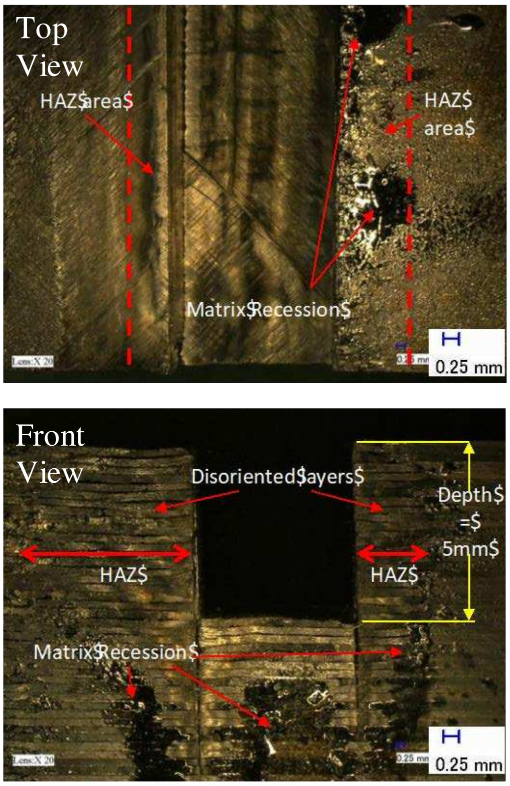

Figure 9 Typical example of trench produced by fiber laser machine (power: 600 W; speed: 5 mm/sec).

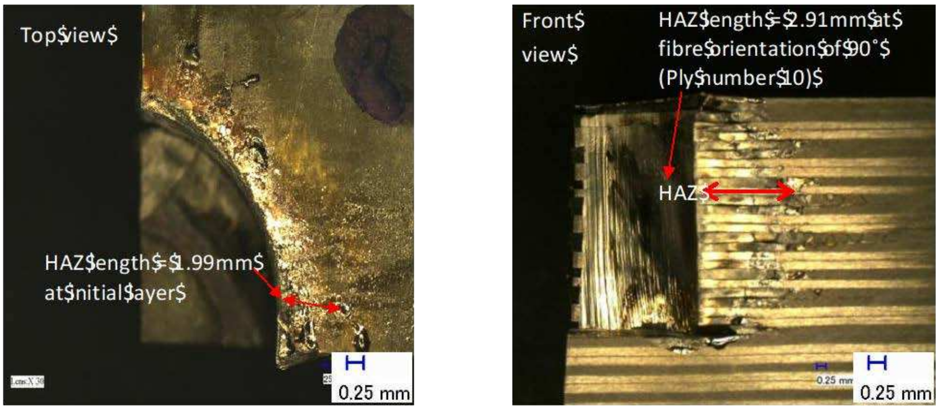

Figure 10 Typical example of 90° degree hole (power: 900 W; speed: 5 mm/sec).

4 Conclusions

This research was devoted to assessing the capabilities of different drilling strategies on 25.4 mm thick carbon fiber reinforced polymer (CFRP) composites by using mechanical and laser drilling. This was performed by investigating each machining technology with the proposed strategies in order to determine whether the tool could actually drill through the entire stack in a single stroke or not for mechanical drilling and to identify the potential of a 1-kW fiber laser to penetrate thick CFRP composites for laser drilling.

The results for mechanical drilling indicated that all strategies were able to drill the entire sample completely. However, only single-step drilling was capable of drilling 25.4 mm thick CFRP with minimum damage (i.e. delamination and overhanging/uncut fibers). This strategy is also practical to manipulate the machining parameters for reducing hole damage in future work. The first and final layer of the CFRP were covered by an additional surface or coating layer (i.e. peel-ply layer) that acts as surface protection. Possibly, this was affected due to a higher fiber density/concentration in the woven-ply structure compared to unidirectional configurations and led to increased interaction between abrasive fibers and the drill bit during drilling, resulting in significant delamination. Furthermore, single-step drilling was proven to be more feasible than peck drilling. Drilling was successful by using a standard 2-flute uncoated tungsten carbide/WC, thus, the use of an advanced tool design is not essential for drilling thick CFRP. In contrast, the laser drilling experiments were unsuccessful in penetrating 25.4 mm thick CFRP, even though the experiments were conducted with various machining parameters. The major obstacle was the removal of dust/by-products inside the hole, which obstructed the laser beam to drill further inside the hole. It should be noted that the nozzle tip and assist gas pressure are crucial elements for enabling the laser beam to penetrate inside the hole. As a consequence, the nozzle tip must be set to a distance of 1 mm from the workpiece in order to cut/drill effectively, and lower gas pressure bar levels encourage significant HAZ during the machining process.

Overall, the presented results are useful to define the relationships between machining parameters related to mechanical/laser drilling and hole/cut quality for future considerations. This work revealed that the 2-flute uncoated WC drill bit produced the best holes so far and it is suggested that further research on different types of tool materials as well as assessing tool life and performance over tool life could be conducted in the future. Additional cutting tests, covering a wider range of cutting speeds and feed rates, should be carried out in order to determine the cutting speed and feed rate combination that results in the best hole quality and maximum tool life. Further investigation should also focus on fine-tuning the laser machining parameters by identifying the effects of focal plane position, assist gas pressure and pulse mode on hole depth, HAZ and other potential damage in order to find a feasible drilling strategy.

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