THERMALLY ASSISTED PIERCING; MANUFACTURE AND PROPERTIES OF MULTIPLY-PIERCED COMPOSITES

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ABSTRACT

Drilling is one of the most widely employed techniques to make holes in composite materials. However, this technique can reduce the structural integrity of the composites by cutting the load-bearing fibres.

This paper has investigated the mechanical properties of a multiply-pierced composite by the thermally assisted piercing (TAP) technique. This is a material displacement process and previously has shown superior mechanical properties in comparison to drilling.

The results of the open hole tensile tests for the multiply-pierced and drilled composites indicated that the pierced composites have higher strength than the drilled composites. This data was then compared to the microscopy images obtained from the microstructure of the perforated specimens. The preliminary results have shown that TAP has the potential to be used instead of the current methods of machining for composite materials.

1 INTRODUCTION

Fibre-reinforced polymers (FRPs) have the ability to be tailored for a specific purpose by the combination of reinforcements, together with their alignment and fibre fraction. Composite parts can be manufactured to near-net-shape with minimum wastage of material; however, there is almost always a need for further machining. The most common post-manufacture machining operation for composite materials is to create holes for assembly. Producing holes amounts to approximately 90% of the aerospace industry's requirements for composites machining [1]. The holes are primarily for joining applications, but they may also be used for acoustic damping (e.g. in gas turbine engine nacelles or landing gear), leading edge de-icing, and hybrid laminar flow control.

Drilling composites is heavily used in industry as it is a relatively inexpensive method of machining holes (in comparison to laser or water-jet cutting) and can be used on large, non-flat structures without significant complications. However, if drilling parameters are not carefully selected and controlled, then delamination can result from the drilling process, leading to a reduction in the mechanical performance of the composite material. Difficulties in accuracy and repeatability of the drilling can also lead to expensive part rejections. For example, Airbus delayed the entry-to-service date of the A350 XWB by three months due to difficulties in implementing the automated drilling process [2], which highlights the major complexity of drilling composites.

As an alternative to a material removal process such as drilling, material displacement processes including molding-in holes can be employed, where significant increases in tensile strength have been found [3,4] when compared with material removal techniques. This technique is often used for thermoset composites, however, it can be introduced during the manufacturing process of thermoplastic composites as well (prior to resin infusion). However, the process requires placing individual inserts, is labour intensive and, due to their high melt viscosity, has proven to be difficult for thermoplastics that are not easily resin infused.

Previously, an alternative material displacement process – the single-hole thermally assisted piercing (TAP) technique [5,6] – was used to create a 6 mm diameter hole in Carbon fibre/ Polyetheretherketone (PEEK). Mechanical tests indicated open-hole tension and compression strength improvements of up to 11% and 21% respectively for pierced specimens when compared with drilled specimens. In this paper, the TAP technique is extended to multiply pierced FRP coupons and the mechanisms for the improved performance over equivalent drilled samples are explored through expanded mechanical testing and microscopy.

2 EXPERIMENTAL METHODS

2.1 Specimen Manufacture

Sixteen-ply laminates of carbon fibre-reinforced polyamide-12 (PA12) (Suprem T55% AS4/PA12-2150 with a nominal fibre volume fraction of 0.55) pre-impregnated unidirectional tape were used with the configuration [(0/90)S/0]S. The laminates were pressed at 214°C (at a rate of 5°C/min) under a consolidation pressure of 9kN (0.5 kN/min). After reaching the desired pressure and temperature, the conditions were maintained for a further 25 minutes. Subsequently, the laminate was cooled down under consolidation pressure to room temperature, at an approximate cooling rate of 5°C/min. This produced a laminate with a nominal thickness of 3.0 mm (measured after manufacture).

Specimens were divided into three different groups: unperforated; with drilled holes; and with pierced holes. The dimensions of the individual coupons were the same for each group and are given in Table 1.

Table 1: Coupon dimensions

Length, mm	Width, mm	Thickness, mm
300	36	3

For both drilled and pierced coupons, the diameter, spacing, and number of the holes were the same: 2.0 mm diameter; 15.0 mm centre to centre spacing; and four holes aligned with the direction of the applied loading. Three different techniques for drilling holes in the composite were previously tested and drilled holes made using an interpolation technique were shown to produce less damage to the composite (Table 2). Consequently, the interpolation technique was exclusively used to create the 2.0 mm diameter holes in the drilled coupon group.

Table 2: Three different techniques tested for making holes in the drilled group of test coupons

Drilling Method	**Hole finish**
Using two different sizes of drill bits, 2.7 mm and 3.0 mm diameter	
Interpolation technique: creating a small hole using a 1.0 mm diameter drill bit and then using a 1.0 mm diameter end mill in a circular motion in order to achieve 3.0 mm diameter hole.	

Creating a hole with a 2.7 mm diameter drill bit and then employing a 3.0 mm end mill to achieve the desired hole diameter.	

For the multiply TAP specimens, the laminates were pierced in advance of machining the coupons to their final dimensions. The multiply TAP coupons were produced by a piercing rig that was designed as a part of this project. The rig (Figure 1), has the potential to pierce one hundred holes with a diameter of 2.0 mm simultaneously.

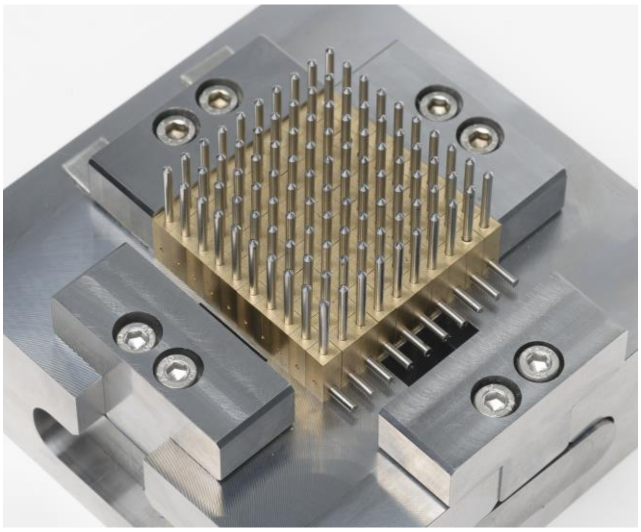

Figure 1: Multiple thermally assisted piercing rig

A clamping system was also made from two aluminium plates that have the desired pattern of the perforations drilled onto them (Figure 2). This clamping system is necessary to prevent the laminate from deconsolidation while it is being heated. Therefore, the pierced coupon process itself relies on five key stages:

i. composite is clamped between the aluminium plates;
ii. composite and the clamping system are heated to the melting point of the matrix;
iii. piercing rig pressing through the hot laminate;
iv. cooling of the laminate and the clamps;
v. cutting of the laminate into coupons.

A pierced coupon that has been prepared for mechanical testing is shown in Figure 3.

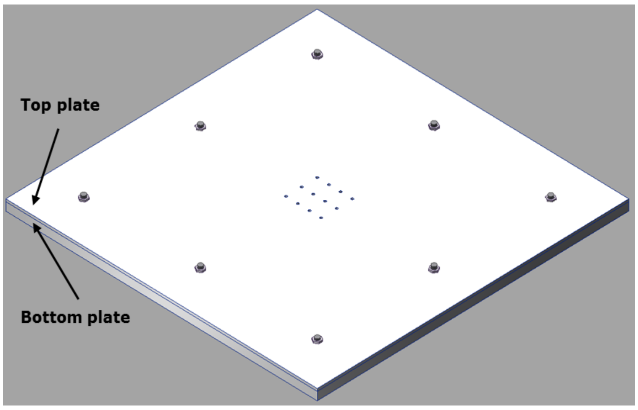

Figure 2: Aluminum clamping plates used to prevent deconsolidation of the laminate

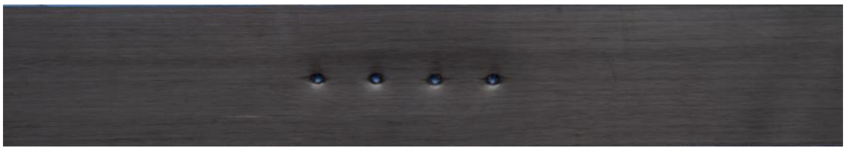

Figure 3: Pierced coupon prior to mechanical testing

2.2 Test Methods

Testing was conducted to confirm the hypothesis that pierced coupons have better mechanical properties than the drilled coupons. Test methods including mechanical testing, Digital Image Correlation (DIC), optical microscopy, and infinite focus microscopy were employed. The specimens were mechanically loaded while DIC was used to measure the resultant surface strains in all perforated coupons. The purpose of using the DIC was to measure the strain around the holes for both drilled and pierced specimens.

2.2.1 Mechanical Testing

The open hole tensile (OHT) test was conducted on thirty coupons in total with ten each from the unperforated, drilled and TAP groups. The purpose of the test was to compare the mechanical properties of the different groups. Tensile testing followed ASTM D5766/D5766M-11 [7]. A 250kN screw driven Instron 8802 with parallel hydraulic grips was employed for this test. During the test, a constant displacement rate of 1 mm/min was applied until ultimate failure occurred.

2.2.2 Digital Image Correlation

Three-dimensional DIC measurements were conducted during the mechanical testing. The GOM-ARAMIS three-dimensional DIC system used consisted of two cameras (controlled by ARAMIS software) and was set to calculate the strain data at 1 Hz. The analysis of the DIC was conducted using facet settings of 19×19 pixels with 3 pixels overlap. The settings are within the mid-values of the system and allow for good accuracy and fast computation [8]. For all the specimens with holes, DIC was carried out using computational masking in order to minimise the errors around the holes.

2.2.3 Microstructural Analysis

Two different types of microscope were used in order to understand the differences between the microstructure of the drilled and pierced coupons. The first tests were conducted using an inverted geometry optical microscope with a Colorview III camera (Olympus GX71). The specimen preparation for this technique included sectioning, grinding, and polishing of the drilled and pierced coupons.

A 3D surface profilometer (Alicona InfiniteFocus SL) was used to understand the fibre distribution around the holes. Analysis was performed using the associated IF Measure Suite software. Surface information in this technique was gathered by moving the optics relative to the sample while continuously imaging the surface. Height information was then determined from the regions of the images that were in focus, with 3D maps generated by stitching focussed regions together.

3 RESULTS AND DISCUSSION

3.1 Mechanical Testing and DIC Results

Figure 4 compares the ultimate tensile strength of the unperforated, pierced and drilled groups of coupons for the OHT test. The pierced coupons have the largest mean ultimate tensile strength of the three groups. While this would suggest that in certain situations the TAP process could make the coupons stronger, using the Student's t-test to compare the unperforated and pierced groups shows that this finding is not statistically significant ($p = 0.769$). However, the Approximate Student's t-test does show that the superior ultimate tensile strength for both unperforated and TAP groups in comparison to the drilled group is statistically significant ($p = 0.005$ and $p = 0.003$ respectively).

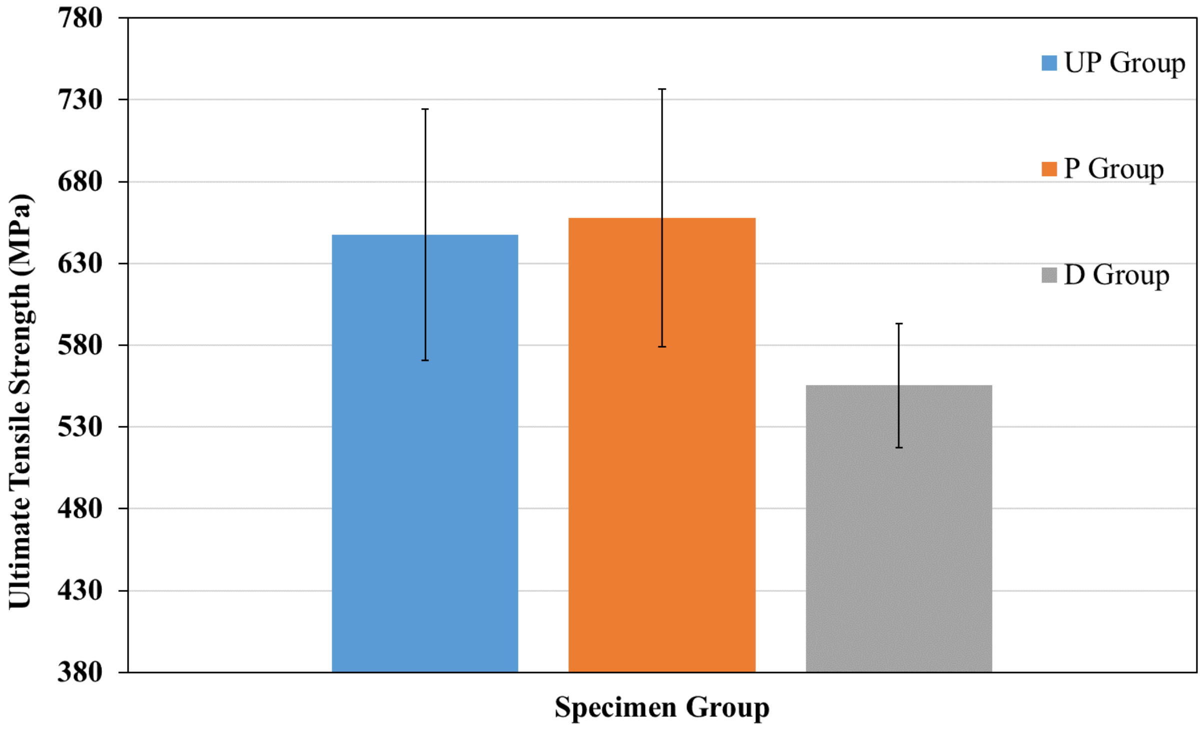

Figure 4: Ultimate tensile strength of unperforated (UP), pierced (P) and drilled (D) coupons. The error bars indicate the standard deviation

To compare the more general mechanical response during OHT, three virtual sections were constructed at the same position on all the DIC images. These sections ensured that the strain measurements were obtained from equivalent locations on all of the coupons. Figure 5 indicates the positions of the planes for the drilled and pierced coupons. It was assumed that strain was uniform in the unperforated group. Bi-axial strain gauges, also seen in Figure 5a, were employed to validate the DIC results. As the drilled coupons failed at a lower load, the strain measurements along the virtual sections for the perforated groups were taken at 30%, 60%, and 90% of the mean failure load of the drilled coupon. Table 3 provides the applied loads equivalent to the percentage of this mean failure load, which were then used to compare DIC results from the TAP and drilled processes.

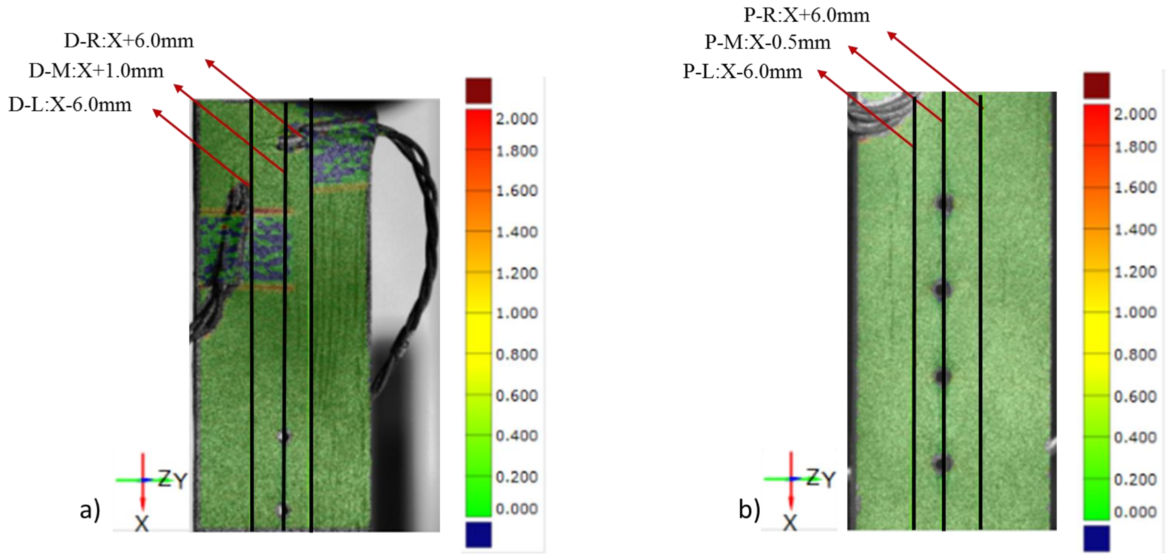

Figure 5: DIC image of the a) drilled and b) pierced coupon. The three lines indicate the constructed virtual sections for strain measurements. The scale bar shows the percentage strain. The strain gauges are used for validation purposes.

Table 3: Loads used for measurements of strain along the virtual sections of drilled coupons

	30%	**60%**	**90%**
Drilled coupon, Force, kN	15.2	30.1	45.1
Pierced coupon, Force, kN	15.1	30.4	45.3

Figure 6, Figure 7, and Figure 8 show the strain measurements in the *X*-direction for the drilled and pierced coupon, at the three different sections and reference loads. The data indicated that for both drilled and pierced coupons, as expected, the sections away from the holes have a very similar strain. In these areas both coupons have very similar properties as the fibre structure has not been disrupted in any way by cuts or displacements. However, the mid-section which passes through the holes, indicated that the strain between the holes for the pierced coupon is slightly higher than the drilled coupon. This can be explained by the pierced coupon still having continuous fibres running around and between the holes that are carrying load. In the case of the drilled coupon, the fibres have been cut and become discontinuous, hence the load they are carrying is reduced.

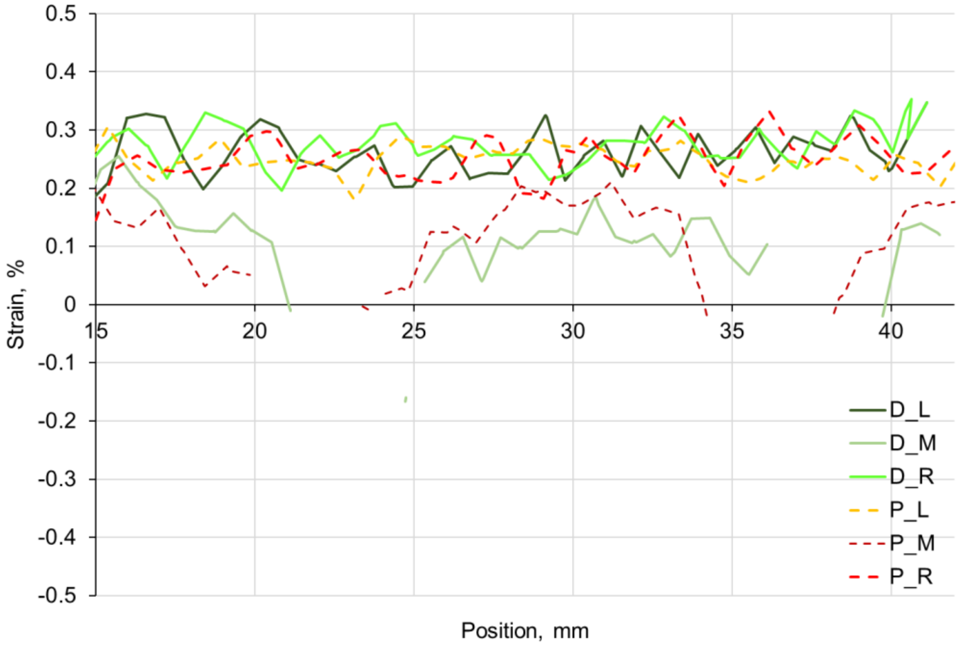

Figure 6: DIC results for drilled and pierced coupon at 30% of the drilled coupon's failure load. D and P represent the Drilled and Pierced coupons respectively, while L, M, and R represent the Left, Middle and Right virtual sections. Breaks in the data indicate holes in the specimen.

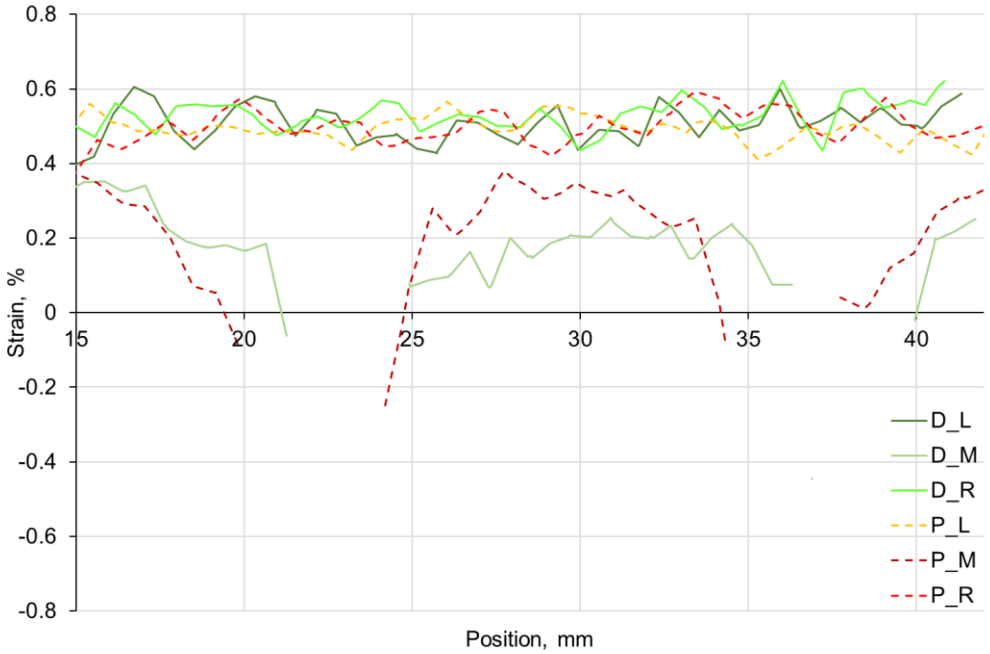

Figure 7: DIC results for drilled and pierced coupon at 60% of the drilled coupon's failure load. D and P represent the Drilled and Pierced coupons respectively, while L, M, and R represent the Left, Middle and Right virtual sections. Breaks in the data indicate holes in the specimen.

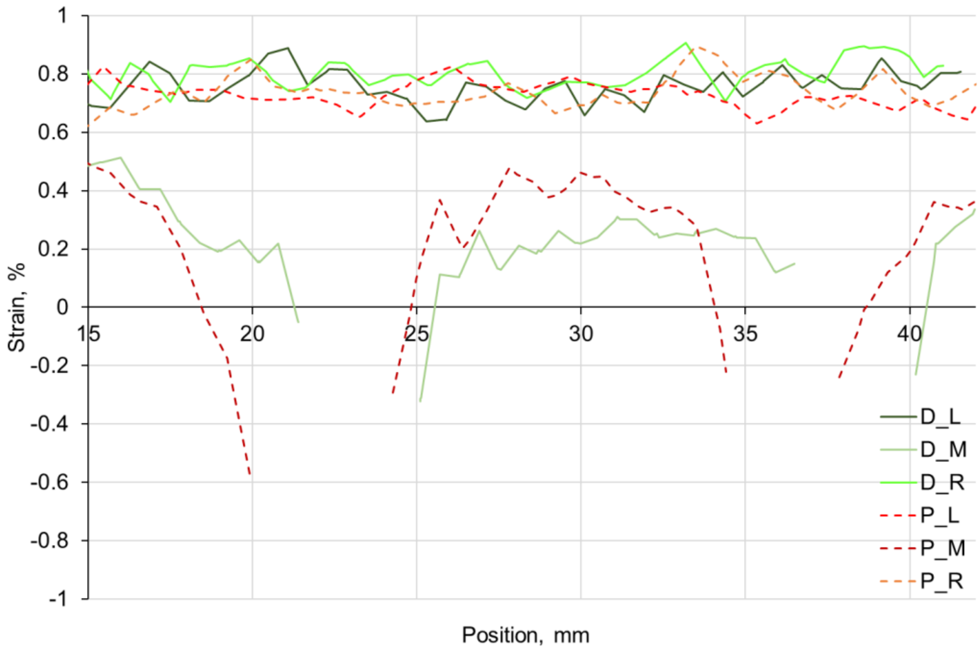

Figure 8: DIC results for drilled and pierced coupon at 90% of the drilled coupon's failure load. D and P represent the Drilled and Pierced coupons respectively, while L, M, and R represent the Left, Middle and Right virtual sections. Breaks in the data indicate holes in the specimen.

3.2 Microstructural Analysis Results

When drilling a hole in a composite laminate, the resulting fibre distribution surrounding the hole remains unchanged. Fibres will remain in their 0° and 90° orientations for the laminates used in the current investigation (Figure 9.a). The drilling process tends to cut the fibres rather than deform them. When piercing a coupon, the fibres are deformed and displaced, which modifies the local material microstructure surrounding the hole, as shown schematically in Figure 9.b. Both the fibre volume fraction and fibre orientations are altered with fewer fibres broken in comparison with the drilling process.

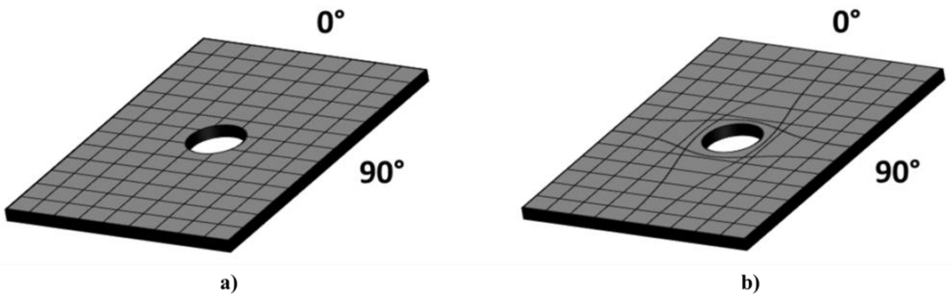

Figure 9: Schematic diagram of resultant fibre architecture in composite laminates for a) drilled specimens; and b) pierced specimens (Brown, 2016)

The resultant microstructure observed within a pierced specimen, sectioned through a hole and along 0°, is shown in Figure 10. Significant 0° and 90° ply distortions are evident around the hole. The plies have also been deformed in the *Z*-axis (through thickness) of the laminate, as the piercing pin drags them and the molten matrix during insertion. The resultant effect of the TAP process is a fibre architecture that has accommodated the deformation and displacement of material as the pin travels through the laminate. When sectioned along the 0° fibre orientation, the plies were shown to significantly reduce in thickness towards the hole's edge. Voids are also created due to the flow of the molten matrix in conjunction with the fibre movement.

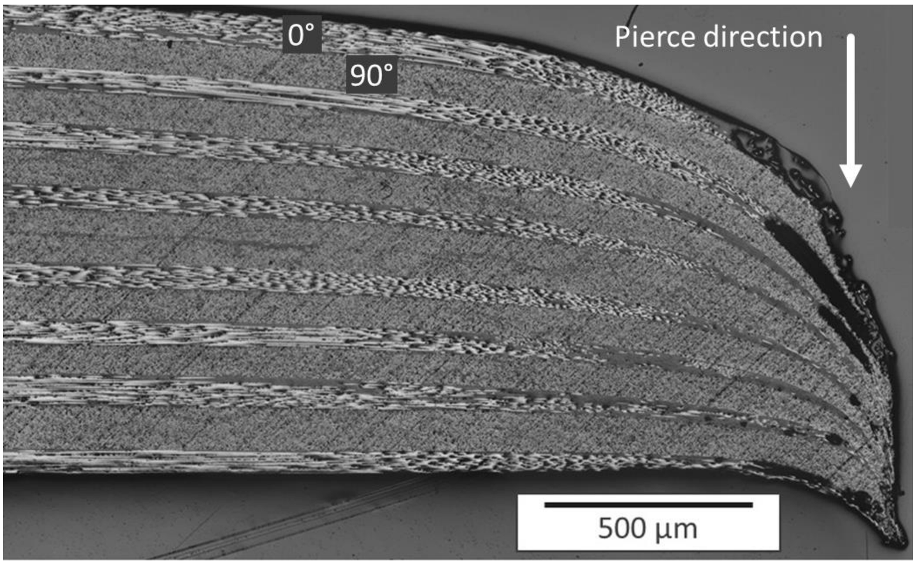

Figure 10: Optical microscopy image of the pierced specimen showing the 0° section cut following the TAP process. The white arrow shows the direction of the piercing pin.

Two mechanisms caused the resulting fibre structure around the piercing (Figure 10). Firstly, the 0° fibres were displaced from their original position at the centre of the hole (location 1 on Figure 11). These fibres were bunched and compressed against the edge of the pin and gather in volume as the pin displaces more material (location 2 on Figure 11). The increased volume of fibres built up at the edge of the pin at location 2 was reciprocated with a reduction in fibre volume fraction at location 3. The second mechanism that changes the material structure is the fibres and matrix being displaced and deformed in the *Z* direction. In the plies with fibres orientated at 90°, the same respective behaviour is seen but rotated through 90° to align with equivalent fibre direction in those layers.

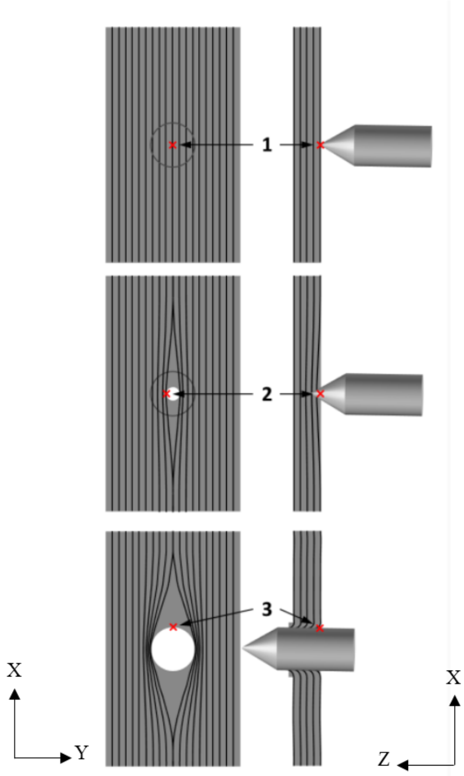

Figure 11: Schematic diagram of piercing process, with indicated locations 1, 2, and 3, looking at the *X*-*Y* plane and *Z*-*X* plane

Infinite focus microscopy images showed clear differences between the perforated regions of the pierced and drilled coupons (Figure 12). For the TAP specimen, the fibres have created a path around the hole, to which the better tensile strength of these specimens can be attributed. A greater proportion of the load bearing fibres are only deformed rather than cut during the TAP process. This effect can also be seen between the two holes (Figure 12.a) where the deformed fibres are not fully able to return to their original position. This effect can be contrasted with the undeformed and cut fibres between the drilled holes in Figure 12.b. The nature of the fibres' ability to displace and orientate around a piercing as well as the molten matrix flow in these regions will be the subject of further investigation. In particular, the effect of altering the number of holes and distance between them will be the subject of further experiments using the multiple TAP rig seen in Figure 1.

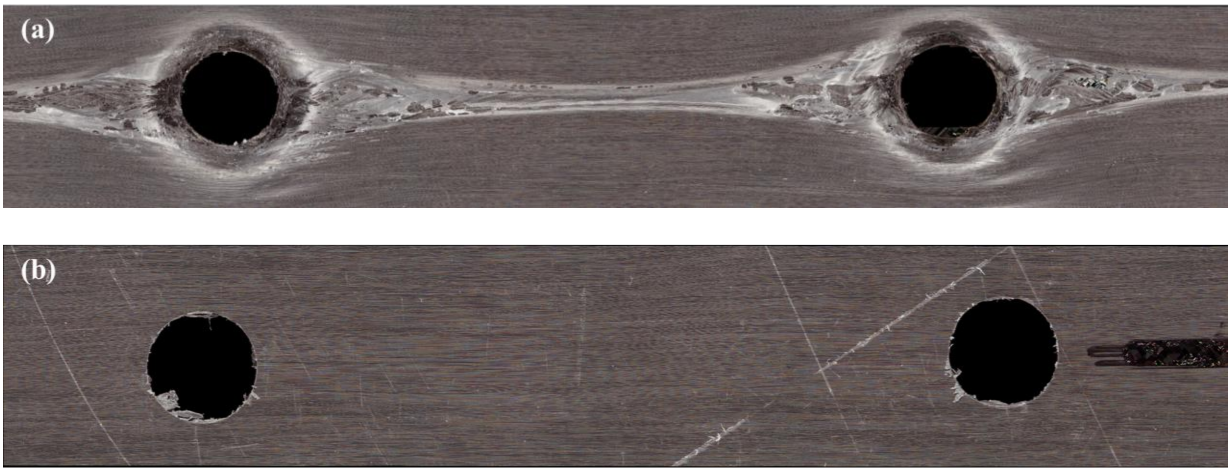

Figure 12: Infinite focus microscopy of a) pierced coupon and b) drilled coupon (50x magnification)

4 CONCLUDING REMARKS

The multiple TAP process was used to form holes in thermoplastic composites to establish the effectiveness of this technique in comparison to the conventional drilling. Preliminary mechanical tests and microstructural analysis have indicated that the pierced composite coupons have superior mechanical properties in comparison with the drilled composite coupons. The microstructural analysis of the pierced coupons showed that the carbon fibres have created a path around the holes. The displacement rather than cutting of the load-bearing fibres around the holes has caused the strength of the pierced composite to be higher than the drilled composite.

Future work for this project includes conducting further mechanical testing including Open Hole Compression tests and in-plain shear tests to compare further the mechanical properties of the pierced and drilled specimens. The spacing between the holes will also be altered in order to find out the effect of the distance between the holes on the mechanical properties. Non-destructive techniques including Computed Tomography x-ray will also be employed to understand the effect of the hole spacing on the orientation of the fibres.

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