Proceedings Paper:

Merino-Pérez, J.L., Hayes, T.O., Melis, D. et al. (2 more authors) (2019) Wet vs dry CFRP drilling : comparison of cutting fluid delivery methods. In: Kerrigan, K., Mativenga, P. and El-Dessouky, H., (eds.) Procedia CIRP. 2nd CIRP Conference on Composite Material Parts Manufacturing, 10-11 Oct 2019, Sheffield, UK. Elsevier , pp. 335-340.

https://doi.org/10.1016/j.procir.2019.10.009

Available online at www.sciencedirect.com

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Procedia CIRP 85 (2019) 332–337

www.elsevier.com/locate/procedia

2nd CIRP Conference on Composite Material Parts Manufacturing (CIRP-CCMPM 2019)

Wet vs dry CFRP drilling: Comparison of cutting fluid delivery methods

Julián L Merino-Pérez[a], Thomas O Hayes [a], Davide Melis [a], Richard Scaife [a], Kevin Kerrigan [a]*

[a]Advanced Manufacturing Research Centre, The University of Sheffield, Advanced Manufacturing Park, Wallis Way, S60 5TZ Catcliffe, Rotherham, UK

* Corresponding author. Tel.: +44 114 215 8056; *E-mail address:* k.kerrigan@amrc.co.uk

Abstract

This work studied the impact of flood and through-tool cutting fluid delivery methods during the drilling of carbon fibre reinforced polymer (CFRP) composite panels against a dry baseline condition. The cutting fluid considered was a water-based, composite-specific fluid, and the cutting tool was a Ø6.35 mm diamond-coated drill bit. After an initial design of experiments (DOE) approach enabled the establishment of appropriate cutting parameters to minimise delamination, both delivery methods and dry baseline drilling were compared in terms of tool wear and hole quality. The increased heat removal efficiency of through-tool delivery method is theorized to have prevented the localised softening of the resin and consequently maintained high abrasiveness of the composite workpiece, ultimately developing the highest tool wear for the given parameters. After drilling 600 holes, dry drilling exhibited the best results and lowest variation of hole quality metrics, i.e. the most stable process. However, after drilling 300 holes, flood delivery produced a better performance for cylindricity and perpendicularity and similar exit delamination factor (F_d) than dry drilling. Interestingly, through-tool delivery exhibited a slightly better performance than dry drilling when the analysis and comparison is conducted after the first 100 holes drilled only. These results indicate that hole diameter is highly dependent on tool wear and demonstrates that heat evacuation helps to produce holes with better cylindricity and perpendicularity, since hole distortion is highly affected by heat up and cool down cycles and the different coefficient of thermal expansion (CTE) across the laminate.

Keywords: Drilling; Composite; Fluid

1. Introduction

The interest in the use of cutting fluids by aerospace and automotive original equipment manufacturers (OEMs) in carbon fibre reinforced polymer (CFRP) composites machining has increased in recent years with diverse purposes, such as increasing the performance of the machining process, seeking for an increased throughput or for health and safety purposes, such as dust suppression, and cleanliness of both part and machine tool [1]. According to Airbus' Global Market Forecast and Boeing's Current Market Outlook [2, 3], the demand for new commercial and freight aircrafts over the next 20 years will exceed 37,000 units, which means that the world fleet will be double its current size.

This increasing demand will require more aggressive cutting parameters to achieve higher material removal rates. This will increase the heat generated during the operations. In this scenario, the use of cutting fluids has the potential to prevent thermal damage caused to the composite's matrix material, by dissipating the excess of heat generated in high-throughput machining operations. This is paramount and specially interesting in hard-to-cool operations such as drilling.

Hole generation in composite aerospace structures, mostly CFRP, is the most extensive machining operation in the manufacturing of newly designed aircrafts, such as Boeing's 787 Dreamliner and Airbus' A350 XWB, due to the thousands of riveted and bolted connections carried out in its assembly, therefore accounting for a considerable amount of the entire aircraft's machining cycle time [2]. Recent research by Kerrigan and Scaife [4] indicated a potential effect due to changes in visco-elastic properties of the resin in a CFRP workpiece on tool coating failure and general wear via a

10.1016/j.procir.2019.10.009

comparison between dry extracted and external full-flood wet drilling conditions. Composite machining operations, which generate extensive heat due to the abrasiveness of the fibres and the friction between the clearance face of the cutting edges and the machined workpiece, are traditionally conducted in dry conditions, increasing the risk of thermal damage to the polymer [5].

In recent studies on CFRP drilling in dry conditions, increasing the cutting speed to achieve higher removal rates generate excessive heat and high temperature gradients concentrated in the heat affected zone (HAZ) that can cause hole distortion and further induced damage if the glass transition temperature (T_g) is exceeded [6, 7], thus limiting the cutting parameters in such conditions. In this scenario, cutting fluids present a potential solution to achieve greater throughputs without inducing thermal damage to the composite.

Specifically on monolithic CFRP composite parts, recent studies by Helmy et al. [8] investigated the impact of MQL and flood cutting fluid delivery on ultrasonic assisted machining (UAM) of multidirectional CFRP laminates using diamond abrasive tools at different cutting conditions. Despite the researchers reportedly finding similar results in terms of cutting forces, spring-back effect and surface integrity, results for flood delivery were found to be slightly better than MQL due to the higher heat removal. In contrast, Iskander *et al.* [9] utilised PIV and PDA flow visualization to optimise MQL spray for slotting of CFRP parts. The authors found that, through precise placement of the MQL nozzle, significant improvements in process performance, specifically tool wear, could be achieved over both flood and dry conditions. The improvement was indicated to be due to effective atomisation, a large number of small droplets travelling at high velocity and better penetration into the cutting zone. This was reinforced to a degree by Wang *et al.* [10].

2. Cutting fluid-assisted drilling of CFRP composites

2.1. Materials and equipment

In order to investigate the impact of cutting fluids in the drilling operation, this research considered a series of drilling experiments comparing dry drilling, flood only and through-tool plus flood fluid delivery methods. The drilling processes were compared for: hole quality, via hole diameter, cylindricity, perpendicularity and exit F_d metrics; tool wear, via edge rounding, ER and edge retraction, Δr, metrics; and cutting forces, via thrust force and torque metrics, F_z and M_z.

The machine tool considered was a Hermle C42 U MT 5-axis mill turn with a Heidenhain TNC 640 controller. The cutting fluid used was a new, commercially available water-based composite fluid utilising the latest developments in cutting fluid chemistry. The fluid was prepared with tap water for a 5% concentration using a Dosatron. The machine tool sump was filled with the fluid and circulated through the fluid delivery piping for 12 hours and samples of fluid, collected at the delivery point, were tested to verify the concentration, colour and pH.

The quasi-isotropic, symmetric and balanced composite panels were made of Solvay's CYCOM 5320-1 T650 prepreg plies (~V_f = 0.64) following hand lay-up method. These out-of-autoclave (OoA) CYCOM5320-1 resin-based panels were cured and post-cured to develop full mechanical properties and a maximum glass transition temperature (T_g) of approximately 177 °C [11, 12]. This was verified via a dynamic mechanical analysis (DMA) of a specimen taken from the cured panel.

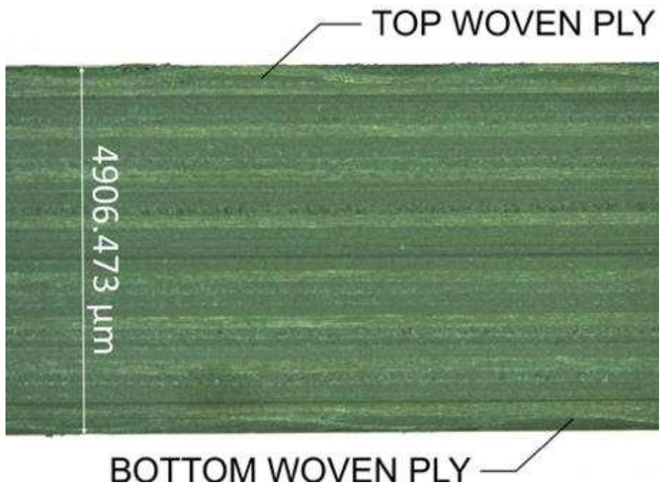


Fig. 1. Cross-section of the 32 plies CFRP panels utilised.

In this laminate, 30 UD plies formed the structural core, having a lay-up sequence $[(0/45/90/-45)_3/(0/45/90)]_s$). Top and bottom woven plies were added to reduce delamination as shown in Fig. 1. Each panel was assembled on a bespoke aluminium drilling fixture with pilot holes, so as not to hinder the formation of exit delamination as the tool wore, using four M12 bolts applying a 10 N·m torque. Each panel could accommodate up to 300 holes with a pitch of 9 mm.

The drill bit geometry utilised was an Ø6.35 mm double helix Kennametal SPF drill with coolant channels and a 9 µm thick CVD diamond coating (KCC10 grade) deposited on the carbide substrate via chemical vapour deposition (CVD). This drill bit features a 90º point angle, an Ø8 mm shank diameter and a maximum clamping length of 36 mm.

The thrust force and torque were directly recorded using a tool holder-integrated, Kistler 9170A type, rotating cutting force dynamometer (RCD). The spindle interface connection of this device is a HSK63A and the cutting tool is assembled via an ER32 collet system. In order to successfully deliver cutting fluid through the tool with optimal performance, the clamping system was sealed using an Ø8 mm sealing disc and a ERC32 clamping nut. In order to apply an optimal clamping torque and keep it consistent across tests, a torque wrench fitted with a ER32 key was utilised. For an Ø8 mm tool shank, the recommended clamping torque of 136 N·m was used.

2.2. Tool wear assessment

Tool wear was assessed by measuring the edge rounding (ER), retraction of the cutting edge nose (Δr, Fig. 2a) and measuring the chipped length (l_c, Fig. 2b) using an Alicona InfiniteFocus G5 and a bespoke 3D printed fixture to avoid removing the tool from the tool holder for the edge inspection. The region of interest inspected corresponded to the outer corner of the cutting edge.

The results for each tool were calculated averaging the wear measured on each cutting edge and the results for each condition were presented as the average of the two tools inspected per condition.

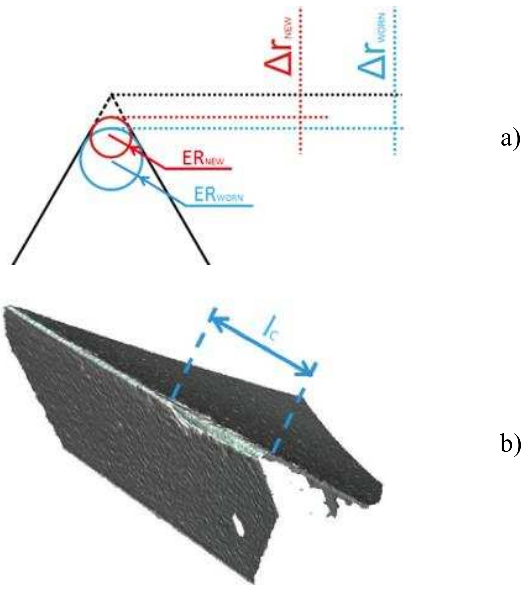


Fig. 2. Tool wear metrics measured during drilling experiments, showing a) edge regression and radius and b) chipped length along cutting edge.

2.3. Hole quality assessment

Exit delamination was assessed by measuring the delamination factor (F_d). The delamination factor is defined as the ratio of the diameter of the circle containing the maximum delamination (D_{MAX}) to the nominal hole diameter (D), as defined by Chen [13].

Digital images of the holes exit were obtained using an optical microscope. Each plate was inspected for 1 in 10 holes until the 600th hole, adding a total of 61 holes inspected per tool (e.g. holes 1, 10, 20, 30...600). The images were then exported and F_d was measured using a bespoke MATLAB code. The values of F_d were plotted against hole number and the drilling conditions were compared considering this criteria. Hole geometry was assessed using an identical inspection interval as in the assessment of delamination. The holes were inspected using a Metris LK Evolution 251512 CMM. The metrics evaluated were: 1) hole diameter, 2) cylindricity and 3) perpendicularity. Each hole was divided in three planes at three axial depths, at each plane the hole wall was probed at 7 points and the diameter of the best-fitted circumference taken as the diameter. At each plane, the circularity was evaluated by calculating the distance between the minimum and maximum points measured in the hole. Finally, a cylinder was constructed from the circumferences fitted at each level plane.

2.4. Acquisition of cutting forces and torque

Thrust force and torque measurement chain consisted of a Kistler rotating cutting dynamometer kit (rotor type 9170A131, stator type 5236B, signal conditioner type 5238B and data cable type 1500A95), a Kistler DAQ type 5697A and a laptop with DynoWare 2.6.5.16 software. Piezoelectric sensors are highly sensitive to changes in temperature and the signal collected can show linear and non-linear temperature-dependent drift, which needs to be compensated with post-processing using a MATLAB script. In order to minimise this drift, the CAM program established a time of 3 minutes where the spindle was left turning at the required rate and, in the trials with cutting fluid, with the fluid method enabled so that the dynamometer could reach a stable temperature prior to acquiring the data.

2.5. Drilling experiment procedure

Prior to conducting the tool life trials, a functionality test was used to select appropriate cutting parameters aiming at minimum F_d at the hole exit (method to assess F_d is described further below). As wet drilling trials will be compared to the dry drilling, the functionality test was conducted in dry conditions. The design of experiments approach considered three levels of cutting speed (v_c) and three levels of feed rate (f_n) for the functionality test. An industrially recommended cutting speed (v_c) of 120 m/min and a feed rate (f_n) of 0.05 mm/rev was used to construct the three-level full factorial design (3^2) by varying the suggested parameters by ±25%.

Table 1. Summary of test conditions, cutting forces, tool wear and tool life inspection cadence.

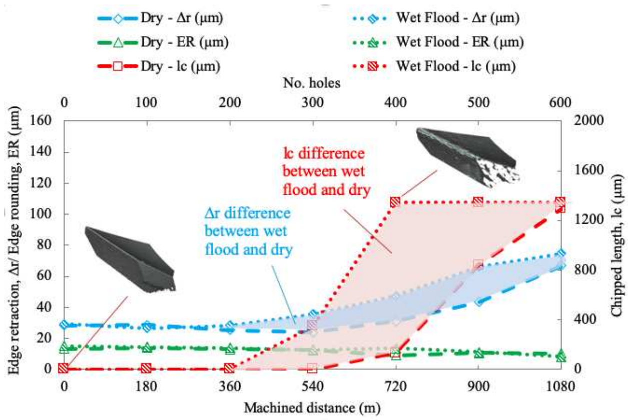
<table>
<tr><th>Condition</th><th>Forces analysis interval</th><th>Hole geometry inspection interval</th><th>Tool wear inspection interval</th></tr>
<tr><td>Dry (2 tools, 1,200 holes/tool)</td><td colspan="2" rowspan="3">1st hole + 1 in 10 holes</td><td rowspan="3">New condition + 100 holes</td></tr>
<tr><td>Wet flood (2 tools, 1,200 holes/tool)</td></tr>
<tr><td>Wet TT + flood (2 tools, 1,200 holes/tool)</td></tr>
</table>

In order to account for wear effects, 33 blocks, from block 1 to 33, were drilled consecutively. Each block consisted of the 9 levels, where odd-numbered blocks drilled holes from level 1 to level 9 and even-numbered blocks followed the reverse order (i.e. from level 9 to level 1). In total 297 holes were drilled in this functionality test. The hole exit analysis indicated that level 5 (v_c 120 m/min and f_n 0.05 mm/rev) developed the lowest exit F_d. Tool life tests were conducted in dry and wet conditions. Wet drilling tests considered two cutting fluid delivery methods, flood delivery and through-tool plus flood delivery. In the latter case, an industrially appropriate fluid delivery pressure of 50 bar was utilised. Two tools per condition and 600 holes per tool were considered, resulting in a total of 1,200 holes drilled per condition. The holes were drilled following a serpentine path allocating 300 holes per CFRP plate (i.e. using 2 CFRP plates per tool). Test conditions, cutting forces analysis, tool wear and tool life inspection intervals are summarised in Table 1.

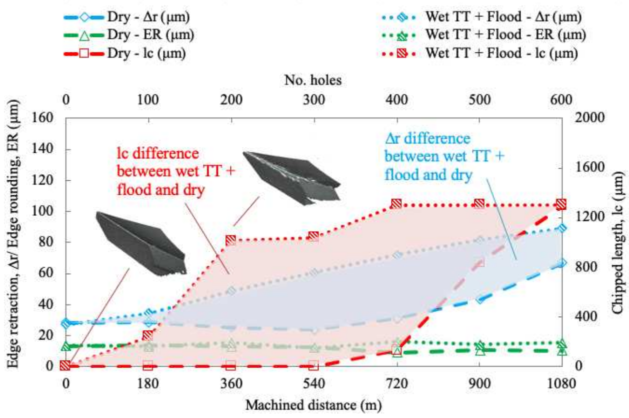
3. Results and discussion

3.1. Tool wear

Fig. 3 shows the overall results for dry and wet drilling using the two delivery methods considered.



a)



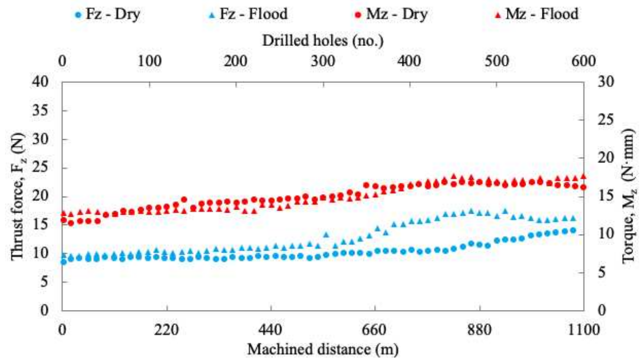
b)

Fig. 3. Tool wear comparison between dry and wet CFRP drilling: a) dry vs flood and b) dry and vs through-tool + flood delivery. Images of chipping at different stages are superimposed for comparison.

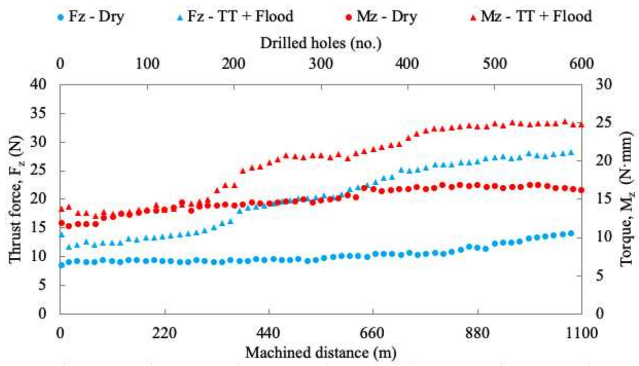
Comparing dry drilling against wet drilling, tools used for dry drilling started to develop coating chipping after 300 holes (540 m machined), reaching the full chipping of the scanned area at the end of the drilling tests (600 holes, 1,080 m).

On the other hand, for flood delivery (Fig. 3a), chipping onset was observed after 200 holes (360 m) and full chipping happened after 400 holes (720 m) in both cases. In the case of through-tool & flood (Fig. 3b), chipping of the cutting edge started to develop from the start of the trials, achieving the full chipping of the inspected area after 400 holes. The chipping of the diamond coating had an effect on Δr. In dry drilling, Δr showed little variation until 300 holes drilled (540 m) and then steadily increased until it reached ~67 µm. Similarly, wet drilling with flood delivery presented a small variation until 200 holes drilled. From this point, this experienced a sharper increase and reached ~74 µm after 600 holes.

Adding through-tool fluid delivery increased the tool wear developed, especially with the premature chipping of the coating. After 600 holes drilled, through-tool + flood delivery with reached ~90 µm (~34% higher than dry and ~22% higher than flood delivery only). The wear process described above resulted in a changing geometry with little impact on the ER metric. Edge rounding presented limited variation around the nominal value across tests, for all the media and delivery methods considered.



a)



b)

Fig. 4. Comparison of forces in dry vs wet (cutting fluid 1): a) flood and b) through-tool & flood.

This can be attributed to a series of edge wear and re-sharpening iterations caused by an uneven wear of the flank and the rake faces, much higher in the former case due to the composite spring-back and the limited chip formation on the rake face. Therefore, Δr stands as a better suitable metric than ER to assess the wear progress in the drilling of CFRP composites.

When comparing the process after 300 holes, the quality of the data improves considerably, especially for flood delivery only. Over this range, wet drilling with flood delivery and dry drilling performed very similarly, especially for hole cylindricity and perpendicularity, where the gradients are almost identical (Fig. 4b and c).

The progress of forces in wet drilling when through-tool fluid delivery was enabled developed considerably higher forces than drilling dry or flood delivery only, shown in Fig. 4b. In this scenario, F_Z and M_Z increased from the beginning of the operation, with an abrupt increase before reaching 200 holes drilled. The points where the gradient in forces changes, for both flood and through-tool plus flood, are coincident with cutting edge chipping onset. This indicates potential for tool health monitoring and could aid in preventing catastrophic tool failure and extended delamination requiring rework.

3.2. Hole diameter, cylindricity and circularity

The hole geometry features obtained in the drilling scenarios and fluid delivery methods considered showed interesting results, which depend on the number of holes machined in dry or wet conditions.

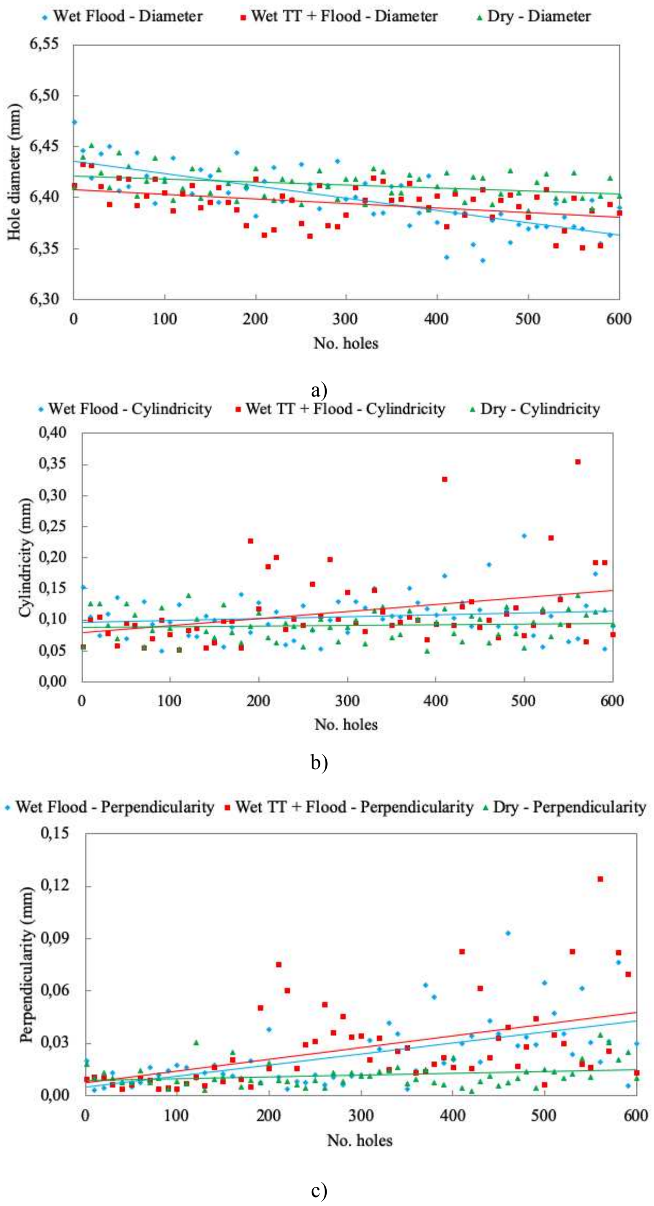


Fig. 5. Comparison of CFRP hole a) diameter, b) cylindricity and c) perpendicularity in dry vs both wet drilling conditions.

Comparing dry drilling against wet drilling over the entire tool life trials (e.g. 600 holes, Fig. 5), dry drilling shows the lowest variability (i.e. lowest gradient and scatter of data over the range considered) for hole diameter, cylindricity and circularity. The variability in the data for the metrics studied increased from the chipping onset onwards and reached noticeable levels of scatter once the cutting edge is completely chipped, ~400 holes using flood delivery and ~400 holes when through-tool delivery is also enabled.

When comparing the process after 300 holes, the quality of the data improves considerably, especially for flood delivery only. Over this range, wet drilling with flood delivery and dry drilling performed very similarly, especially for hole cylindricity and perpendicularity, where the gradients are almost identical. After 100 holes, the differences observed in hole diameter, cylindricity and perpendicularity between dry drilling and wet drilling with flood only and through-tool & flood delivery were marginal. It is interesting to observe the low variability achieved when through-tool delivery was enabled, especially in hole cylindricity, which suggests that the geometry of the hole generated is mostly affected by the state of the tool (i.e. tool wear).

This behaviour repeated for the two tools tested; therefore this cannot be attributed to variability in the CFRP panels and further research is necessary to clarify the reasons behind this behaviour, such as behaviour of the fluid at the delivery pressure (50 bar), possible cavitation or interaction between the fluid chemistry and the workpiece.

3.3. Delamination

Results for visible exit delamination, evaluated through the delamination factor (F_d), presented values below a threshold of $F_d = 1.4$ for every cutting condition considered shown in Fig. 6.

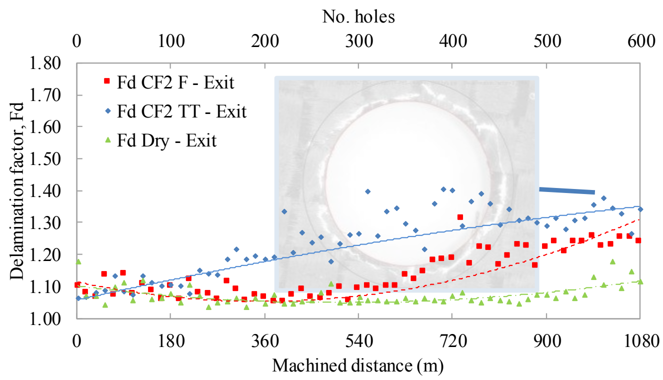
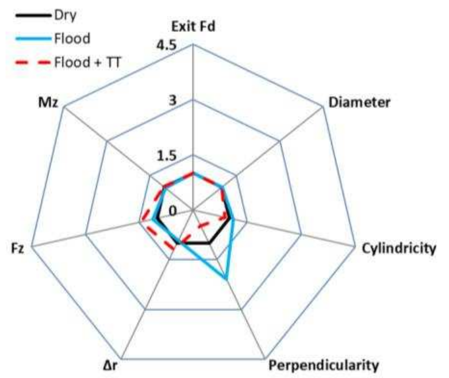


Fig. 6. Exit delamination factor (F_d) in dry and wet CFRP drilling.

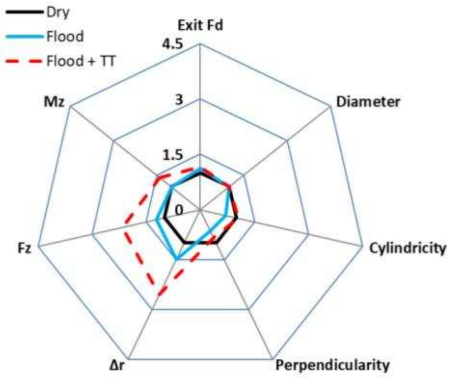
Exit delamination shows a similar behaviour to that observed for hole geometry features, where dry drilling produced the results with the lowest variability after drilling 600 holes. After drilling 200 holes, flood delivery and dry drilling yielded very similar results. When only the first 100 holes are considered for comparison, dry drilling and wet drilling with both delivery options developed similar values of F_d. Hence, as observed earlier in the assessment of hole geometry features, delamination showed to be considerably dependent on the wear and chipping of the tool, as the variability as the data increases with propagation of cutting edge chipping.

4. Conclusions and future work

Fig. 7 summarises the results obtained in this research, where the normalised results have been calculated by dividing each individual condition result by the dry condition result, which was the baseline condition. The performance of the drilling operation under the conditions studied changes depending on the number of holes drilled. For the first 100 holes, where edge chipping did not occur, through-tool plus flood fluid delivery produced holes with tighter hole cylindricity and perpendicularity metrics than flood delivery.



a)



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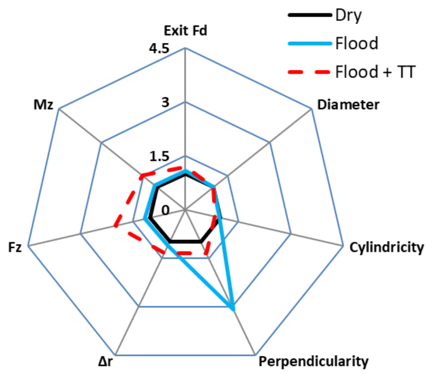

c)

Fig. 7. Comparison of the CFRP drilling methods considered for a) 100, b) 300 and c) 600 holes normalised against dry drilling.

Considering 300 holes, advanced edge chipping using through-tool plus flood delivery produced higher tool wear (increased edge retraction), which also increased the cutting forces. After drilling 600 holes, through-tool plus flood fluid delivery still developed the best results for hole cylindricity, despite tool wear (Δr) and thrust force being the highest among the conditions investigated. The performance of the drilling operation under the conditions studied changes depending on the number of holes drilled. For the first 100 holes, where edge chipping did not occur, through-tool plus flood fluid delivery produced holes with tighter hole cylindricity and perpendicularity metrics than increased the cutting forces.

After drilling 600 holes, through-tool plus flood fluid delivery still developed the best results for hole cylindricity, despite tool wear (Δr) and thrust force being the highest among the conditions investigated. The state of the cutting edge seems to play a key role in the quality of the holes drilled.

Drilling wet, especially with through-tool delivery enabled, maintains the composite's temperature below its T_g, making the operation more abrasive and increasing tool wear. However, before tool wear becomes significant, wet machining offers better results in terms of hole geometry than dry drilling and shows good potential to maintain hole quality in the drilling of thick parts. Further research must be undertaken to establish how the current results compare to scenarios deploying advanced MQL and gas-based technologies.

Acknowledgements

The authors would like to thank AMRC and its partners, especially Fuchs Lubricants UK and Kennametal UK, for the resources provided for the completion of this piece of research.

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