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Wet vs dry CFRP drilling: Influence of cutting fluid on tool performance

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Abstract

Carbon fibre reinforced polymer (CFRP) cutting operations have core features which include; i) chip types consisting of sub 50 micron particles and ii) aggressive abrasion-dominated tool wear. The workpieces used in this investigation were manufactured in a single batch from aerospace-grade, out-of-autoclave, quasi-isotropic, thermoset prepreg materials. Initially, a number of conventional tests were performed to assess the performance of isolated cutting fluid chemicals. The fluid-to-fluid variance was shown to be less significant in these tests when compared against dry conditions. A 6 percent basic micro-emulsion concentrate produced the best results with dry setup produced lower torque results than any cutting fluid tested. Production-style drilling trials were undertaken to investigate the tool life under varying fluid conditions from basic to commercially available. These trials indicated that dry, tip-extracted conditions enabled an extended tool life prior to coating failure against the best cutting fluid with identical parameters, machine tool, cutting tool and workpiece material manufacture conditions. The hypothesis for this reduction in tool performance under general wet conditions is that heat introduced by the drilling process changes the CFRP polymer's visco-elastic properties thus reducing the abrasive interaction between tool and workpiece during material removal processes. The best cutting fluid, a 5 percent semi-synthetic, commercially available chemistry, produced approximately 60 holes more than the poorest performing chemistry.

Keywords: *CFRP; cutting fluid; drilling; cost*

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1. Introduction

With amplified focus on global targets to minimise carbon emission levels, lightweight engineered composite materials, such as CFRP, are experiencing rapidly increasing demand within sectors including aerospace, automotive, rail, renewables and marine. This has resulted in a drive towards high rate, sustainable composite manufacturing processes that achieve design intent. The aerospace sector, in particular, recognises mechanically fastened joints as a key current process for cost / cycle time reductions.

In a typical machining operation, Merchant suggested that lubricating cutting fluid influences the process when drawn into the tool-chip interface by capillary action of the interlocking network of surface asperities [1]. The effects of removing the cutting fluid from a metal cutting process are an

Nomenclature

ANOVA	Analysis of variance
CFRP	Carbon fibre reinforced polymer
CVD	Chemical vapour deposition
DLC	Diamond-like coating
LSL	Lower specification limit
PCD	Poly crystalline diamond
UD	Unidirectional
USL	Upper specification limit
ILSS	Interlaminar shear strength

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increase in friction at the tool-chip interface, an increased shear angle and shear strain with thicker chip and the potential for a built-up edge. In CFRP cutting operations, the process initiates with a similar increase in friction at the tool-chip interface. However, due to low polymer thermal conductivity, heat build-up from increased friction leads to a localised softened zone of material at the cutting edge (CE). This has been shown to cause smearing and, in extreme circumstances, burning [2]. It is hypothesised that the softening of the matrix subsequently allows for abrasive carbon fibres to shift orientation before fracture during CE engagement. This, in turn, may cause reduced abrasion upon the tool during contact resulting in better tool life. An additional by-product of such softening is the lowered modulus. Though the tool experiences lower loads, matrix adhesion to the tool may affect the quality of cut. The goal of this research is to investigate this hypothesis and quantify the differences in dry and wet CFRP drilling process.

1.1. Drilling CFRP composites with and without cutting fluid

Best practice when generating holes within composite materials must be considered in the context of component/system design intent. Valid, scenario-specific reasons exist for cutting both with and without cutting fluids. Whilst recent trends have extended the term *cutting fluids* to include gas-based and sub-zero substances, this research will classify cutting fluids as either oil- or water-based single-phase, ambient fluids. Benefits of using such cutting fluids include:

- Provision of an effective environment for capture and removal of inhalable dust-like CFRP chip without exposure to operator and nearby electronics.
- Enhanced heat removal from the cutting zone, increasing thermal control over a heat-sensitive polymers process.
- Additional cleaning properties for preparation in future processes, e.g. painting.
- No need for additional extraction equipment and appropriate ATEX zone classifications and precautions due to the presence of carbon / polymer dust clouds.

Conversely, the drawbacks of using cutting fluids include:

- Reductions in bond strength in multi-stack assemblies due to cutting fluid use may occur. Although previous research has shown that exposure of well consolidated CFRP to cutting fluids does not cause reduction in ILSS [3] of part.
- Additional costs of equipment and fluid maintenance ultimately mean that the process sustainability is reduced.
- Further part drying processes may be required.
- Potential for micro-chips generated during drilling to form an abrasive past that ultimately reduces tool life.

1.2. Tool wear assessment methods for CFRP composites

Works such as [4] have established that, for metal cutting investigations, cutting force provides a much better repeatability and resolution of cutting fluid performance. As such investigations have yet to be performed for composite materials, this research includes tool wear as a metric for study. Previous CFRP machining works have indicated that the most suitable metric for tracking the wear profile of CFRP-specific cutting tools is the edge flattening (Δr) and/or edge radius (ER) value [5]. It is known from previous CFRP trials that the primary zone of edge wear on the drill is at the outer corner of the primary CE. Previous literature [6] has indicated that the presence of a coating can change the wear process on the CE. Using a 3D measurement allowed for this sudden loss of coating to be captured that would otherwise be challenging to quantify with 2D optical microscopy.

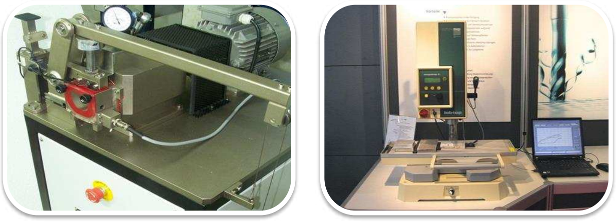
2. Lab-based cutting fluid investigations

2.1. Workpiece manufacture

The workpiece material was Cycom 5320-1 resin with T650 high strength carbon fibre. This CFRP composite prepreg material includes fibres in 3k tow bundles woven into a 2 x 2 twill weave immersed in an epoxy matrix resin system. The resin system is designed to facilitate out-of-autoclave cure cycles for structural grade aerospace applications. The prepreg laminae were laid up in a quasi-isotropic, balanced, symmetric configuration. This incorporated 32 plies configured as $[(0/45/90/-45)_4]_S$ for drilling plates and 60 plies as $[0/45\ [(90/-45/0/45)_7]_S\ 45/0]$ for lab-based analyses with each ply being of approximately 0.192mm thickness. After being laid up, a bagging process was used which incorporated caul plates prior to oven curing. The oven heating cycle initiated with heating to 121 °C at a rate of 2 °C / min, followed by post-cure at 177 °C for 2 hours before being removed from the oven and allowed to cooling in a free standing state.

2.2. Test method down-selection

The test methods initially screened in this research [7] included the tests as shown in Fig. 1. This screening exercise indicated that the most appropriate test to determine cutting capability, and particularly relevant to the drilling process, was the Tapping torque test (TTT). This was due to superior consistency of results and relevance to the tribological aspects associated with abrasive tool wear in CFRP cutting operations.



Reichert test **Tapping torque test**

Wettability test **Corrosion test**

Fig. 1. Lab-based test methods reviewed by [7].

2.3. Multi-lab tapping torque test (TTT) methodology

Three European cutting fluid development laboratories were invited to perform standardised trials on water-based, straight mineral oil and vegetable oils to identify an appropriate cutting fluid chemistry to use in on-machine drilling life trials.

The Labtap TTT machine is commonly used to assess cutting fluids and tools for metallic machinability studies when assessing cutting fluids including soluble oils, semi-synthetics and synthetic fluids. This machine provides information to allow assessment of cutting fluids, tool life, tap outline and machinability utilising the ASTM D 5619 standard. TTTs assess lubricity by either cutting or forming a thread inside a pre-drilled hole and measuring the required torque. All trials were conducted using standardised CFRP workpieces and CVD coated tap geometry. Petroleum Ether (40/60), acetone and paper tissue of reagent grade were used to rinse and clean the equipment after each use to remove all traces of swarf. The test conditions employed by all labs performing TTTs are shown in Table 1.

Table 1. Settings used for tapping torque tests.

Parameter	*Setting Value*
Speed (rpm)	800
Depth (mm)	11.5
Force (Fz)	5
Rotation	Right
Reverse (%)	100

Following initial internal investigations, all labs down-selected to a semi-synthetic variant as described below.

- Laboratory 1 cutting fluid: A micro emulsion type package containing mineral oil. It is a basic chemistry, which contains 40% of a mixture of Amine borate (Corrosion Inhibitor), water, naphthenic oil, distilled tall oil, glycols and biocides. This mixture was diluted with 60% water to make the final concentrated product and was mixed at 5 % dilution with soft water.
- Laboratory 2 cutting fluid: A water-soluble emulsion formulation incorporating 5% cutting fluid dilution with hard water. It includes anti-foam chemicals, corrosion inhibitors and tramp oil rejection characteristics. The chemistry is designed odourless and free of sodium nitrite, phenols and chlorinated additives.
- Laboratory 3 cutting fluid: A micro-emulsion formulation incorporating 8% cutting fluid dilution with moderately hard water as with cutting fluid type 2.

2.4. TTT results

The results from each laboratory represent the maximum and mean torque measured for a series of tapped holes with each cutting condition. Each site performed a fluid-free trial to establish a baseline. Fig. 2 provides an overall summary of the average and maximum torque values obtained from all tap torque tests.

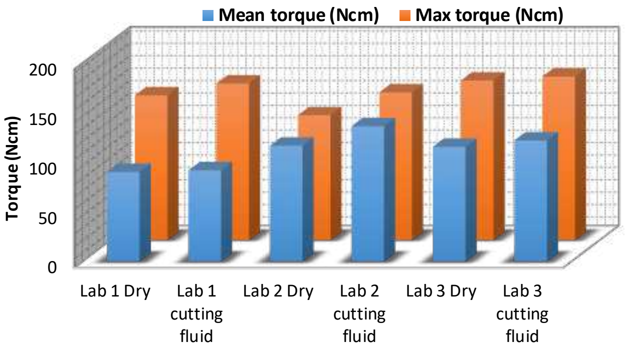


Fig. 2. Multi-site TTT results for cutting fluids.

An analysis of variance (ANOVA) indicated with 95% confidence that run-to-run variation between tests did not contribute a significant effect to the experimental result, with a p-value for the mean torque data of 0.468 and a p-value for max torque of 0.602. Changing the cutting condition from lab-to-lab and dry to wet showed a significant effect, generating p-values of less than 0.000 for both mean and max torque data for both scenarios.

Performing a specific examination on the dry versus cutting fluid torque results, similar ANOVA tests indicated that torque values achieved using each labs cutting fluid were not statistically significantly higher than mean torque values from the final dry trial. Therefore, the deduction was made that the primary source of variance in torque results is due to the variation between lab results for both dry and wet conditions.

3. Case Study: CNC drilling investigations

3.1. Experimental setup and measurement methods

Machining trials were performed on the DMU Monoblock 60 5-axis CNC machine tool due to its ability to operate under both

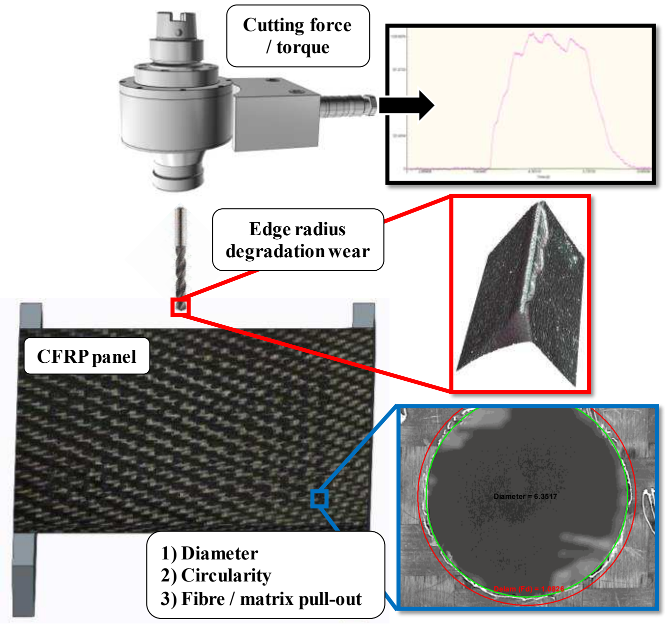


Fig. 3. Experimental setup with CFRP panel, drill and measurements taken during tool life experiments.

full external flood and dry, extracted machining conditions whilst having appropriate ingress protection against carbon-based composite particulate. The CFRP workpiece material was manufactured as described in § 2.1 to generate panels of dimension 300 x 300 x ~6.2 mm into which 900 holes were drilled at 30 hole intervals. Measurements were taken at discrete intervals of the cutting tool edge radius throughout experiments via an Alicona InfiniteFocus G4 three-dimensional, focus-variation-based, optical measurement system. Geometric features of diameter and circularity were measured using a Mitutoyo Crysta Apex CMM, calibrated to ISO10360-2 2001 using traceable artefacts. Delamination in the form of fibre/matrix hole exit pull-out was measured via a combination of optical microscopy and image processing. Thrust forces and torque were measured using a rotating cutting dynamometer as illustrated in Fig. 3. Holes were generated using a 6.35 mm diameter diamond-like coated (DLC) carbide drill geometry with a 4-facet drill point and a 120°cutting angle. The quality and content of cutting fluid was assessed at regular intervals throughout the wet life trials using a calibrated refractometer.

3.2. Design of experiments

The core focus for this experiment was to understand the effects of the presence of cutting fluid upon a number of responses measured including tool thrust force, CE wear, hole delamination and geometry. The primary DOE was therefore restricted as shown in Table 2, with two repeats. A key part of the experimental design was in identifying industrially relevant constraints across a wide range of potential factors identified as important to minimise to remove hidden systematic errors in results.

Table 2. DOE factors and levels for drilling trials.

Factor	***Levels***			
	Level 1	Level 2	Level 3	Level 4
Cutting Condition	Dry	Cutting fluid type 1	Cutting fluid type 2	Cutting fluid type 3

The dwell time between holes drilled was set to *no dwell* and instead a rapid G00 line was used. The depth of cut was set to the caul plated composite panel thickness of 6.2 mm. The feed was set to 0.06 mm / rev and the cutting speed was set at 100 m/min.

3.3. On-machine results

The primary failure criteria used to determine end of life of tools was the formation of a section of exposed carbide as the DLC coating of the cutting tool chipped due to the abrasive interaction with the CFRP workpiece. The results, shown in Table 3 indicated a significant difference between dry and all fluid environments in terms of the level of abrasion caused to the CE, ultimately resulting in the onset of tool coating falure.

Table 3. Tool failure limits for different dry and wet cutting conditions

Cutting Condition	**Tool Life (No. Holes)**
Dry - Tool 1	810
Dry - Tool 1	805
Cutting fluid type 1 - Tool 1	375
Cutting fluid type 1 - Tool 2	340
Cutting fluid type 2 - Tool 1	420
Cutting fluid type 2 - Tool 2	390
Cutting fluid type 3 - Tool 1	390
Cutting fluid type 3 - Tool 2	360

3.3.1. Thrust forces

The ANOVA investigation indicated that the percentage contribution to the variance in the system was dominated by the cutting condition even more so than the tool wear, while variation between tools appears to contribute minimally to the variance. The significance of the contribution of cutting condition to 80% of the process variance is clarified when comparing against the 16% contribution of CE tool wear. The thrust force is known to be dominated by wear of the chisel edge of the tool. The abrasive nature of the process is known to have a significant effect on the thrust force and a catastrophic effect on the tool wear. Thus, cutting condition has an major effect on the abrasive nature of the process.

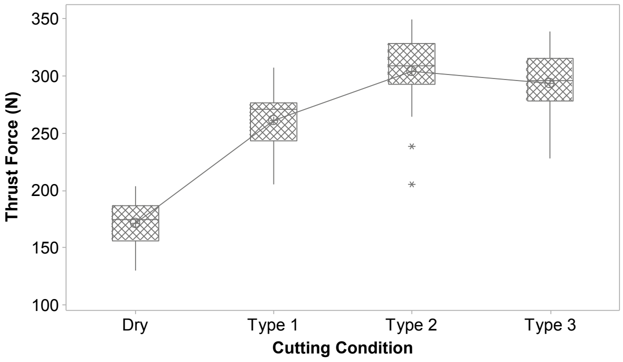


Fig. 4. Box plot showing the effect of cutting condition on thrust force.

Viewing the data in a boxplot form, as in Fig. 4, a uniform distribution with similar variances between cutting condition types is observed apart from cutting fluid type 2 which indicates two significantly low outlier data points.

3.3.2. Hole surface delamination

- An ANOVA test showed the variation due to tool wear prooved to be significant. The change of cutting conditions shows an even greater effect than the tool wear, represented by the hole-to-hole variation, although both were shown to be statistically significant with 95% confidence. The presence of outliers suggests some opportunity for improvement in measurement metric perhaps considering area or volume. The mean delamination of the dry process was approximately 10% lower than any other condition. While results indicated the presence of an increasing trend in the delamination experienced, this can only loosely be correlated to the cutting condition, thrust force and too wear.

3.3.3. Tool edge wear

The quantity of edge degradation was noticeably more rapid when the cutting condition involves the use of cutting fluid. This observation agrees with the visual indication of tool coating failure, shown in Fig. 5, wherein the edge degradation exceeds the coating thickness of approximately 12 µm on average throughout tool life.

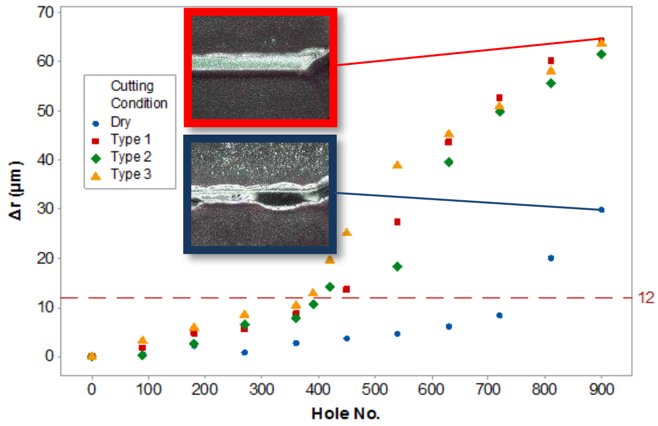


Fig. 5. Plot of radius degradation (Δr) tracking tool wear through 900 holes.

In this figure, the data for CE 1 of the first tool in each condition was plotted to illustrate the effect, showing rapid increase in tool wear rate beyond coating thickness.

3.3.4. Hole diameter and circularity

Fig. 6 clearly shows that only the dry condition provided a consistently capable process over the 900 holes sampled for the given hole diameter requirements.

Hole circularity results indicated a similar trend to diameter results with dry conditions producing superior mean results across the tool life with a mean circularity of 30 µm and cutting fluid 3 producing the least effective circularity result of 42 µm.

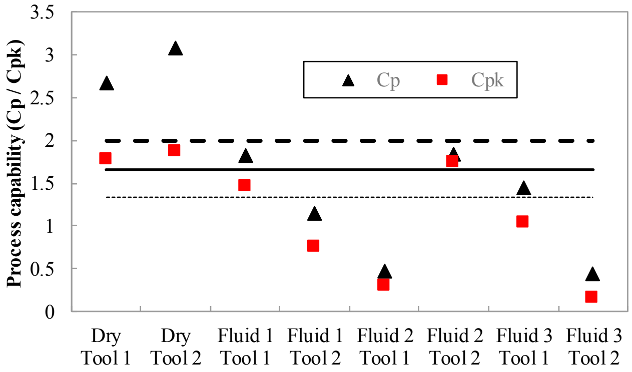


Fig. 6. Plot of capability results for Cp and Cpk of hole diameter with USL = 6.41 and LSL = 6.35. Cp > 2 & Cpk > 1.6 represent quality required.

4. Conclusions

During initial investigations into the effect of cutting fluids in tool-CFRP interactions using standardised lab-style equipment, the following conclusions were drawn:

- The TTT resulted in the most reliable information on the cutting fluid performance.
- All investigations using the TTT indicated that the dry conditions generated a lower torque than all fluids tested.
- All cutting fluid labs identified a type of semi-synthetic emulsion fluid as most CFRP-appropriate.

The tool life trials for the CFRP drilling process revealed the following conclusions:

- Changing between the dry and wet conditions contributed approximately 80% of the variance for tool wear response. Dry drilling with extraction generated approximately twice as many holes prior to tool coating failure compared to all flood cutting fluid supply conditions for parameters used.
- The hole diameter / roundness capability of the dry process presented in-specification results, whereas the results for Cp for all cutting fluids were more variable and generally presented capability values below the Cp and Cpk limits.
- Hypothesis of reduced matrix stiffness causing fibre movement prior to fracture appears intact with further investigation required to fully verify. This intimates that, with increasing production rates and more energetic parameters, future drilling processes will require greater thermal control through heat removal techniques to achieve a specific thermal energy window.

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References

[1] P. N. Rao, *Manufacturing Technology*: McGraw Hill Education, 2013.

[2] K. Kerrigan and G. E. O'Donnell, On the Relationship between Cutting Temperature and Workpiece Polymer Degradation During CFRP Edge Trimming, *Procedia CIRP,* vol. 55, pp. 170-175, 2016/01/01/ 2016.

[3] J. Turner, R. J. Scaife, and H. M. El-Dessouky, Effect of machining coolant on integrity of CFRP composites, *Advanced manufacturing: Polymer & Composites Science,* vol. 1, pp. 54-60, 2015.

[4] L. De Chiffre and W. Belluco, Comparison of Methods for Cutting Fluid Performance Testing, *CIRP Annals,* vol. 49, pp. 57-60, 2000/01/01/ 2000.

[5] A. Faraz, D. Biermann, and K. Weinert, Cutting edge rounding: An innovative tool wear criterion in drilling CFRP composite laminates, *International Journal of Machine Tools and Manufacture,* vol. 49, pp. 1185-1196, 12// 2009.

[6] J. Y. Sheikh-Ahmad, *Machining of Polymer Composites*. New York: Springer, 2009.

[7] A. G. M. Ismail, Development of performance tests for CFRP-specific cutting fluids, M.Sc., Department of Mechanical Engineering, University of Sheffield, 2014.