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The Effect of Machining Coolant on the Integrity of CFRP Composites

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Abstract

It is well known that carbon fibre-reinforced polymer/plastic (CFRP) composites are sensitive to moisture, and so there is a reluctance to use cutting/machining fluids within the composites industry. In this work, the influence of a selection of machining fluids on the integrity of CFRP's and their final mechanical properties was studied. Six sets of CFRP specimens were exposed to air, water and four machining coolants at an elevated temperature of 60°C for 7 days. Swell tests were performed to observe the specimen weight gain due to moisture absorption during soaking. The specimens were subsequently bonded to produce lap shear test specimens. Bond strength test and short-beam shear test were performed to assess the degradation in mechanical properties due to exposure to the various lubricants. Out of the five fluid soaking media (water and four coolants), it was found that only one media (called Cindolube V30ML) did not cause the specimens to absorb moisture and it also had the lowest detrimental effect on the mechanical properties of composite.

Keywords

CFRP; Swell; Composite; Lap-shear; Short-beam; Strength

1. Introduction

The increasing use of composites in high end applications is placing a demand on fast and cheaper production of composite components. Consequently, the ability to quickly and effectively machine composite parts is generating a great deal of interest. When machining metals, it is standard practice to use a fluid coolant (typically oil or oil-water emulsion based) that quickly removes the heat from the tool and component as well as providing lubrication, enabling the cut to progress more quickly with less damage to the part and/or the tool.

It is well known that composites are detrimentally affected by moisture. This is reflected in industrial practice whereby it is commonplace to cut, machine and drill composites without the use of lubricants or cooling. The mechanisms which affect the way a composite can be machined are very different to those of other engineered materials which have been in use for much longer; metallics, for example. This is reflected again in the differing types of damage that is commonly presented when machining composites; break out, fibre pull out, delamination, etc.[1]. Because of these differences and the sensitivity of composites to heat and moisture, basic knowledge regarding the machining of more traditional materials cannot be directly transferred to composites and studying the effects of using coolants with composites is necessary.

Previous researchers have sought to address the effect of water absorption on adhesive bonding in particular[2-4], whilst others have focused on the mechanical properties and performance of composite after exposure to moisture[5,6]. The effect of moisture on mechanical properties was shown[5] to be heavily dependent on the material. Moisture has a limited effect on thermoplastics, but an epoxy matrix becomes softer and the fibre-matrix adhesion poorer. Furthermore, water absorption has been shown to only degrade the mechanical properties that are dominated by the matrix properties, or by the matrix/fibre interface properties[5], such as the impact resistance, fatigue, flexural strength[7], but not tensile strength for example[8]. These effects are usually reversible when the water is desorbed but prolonged or cyclic exposure to water at elevated temperatures can produce irreversible effects[9]. Wan et al.[7] investigated the influence of moisture uptake on flexural and shear properties (as well as characterising diffusion coefficients, absorption rates and maximum moisture content), and noted these mechanical properties to drop with exposure also.

To consider the effect of moisture on an adhesive bond is of particular importance in composite manufacture, yet there seemed to be relatively few publications dedicated to it. Previous work[3] had shown that joint strength is degraded by moisture, and this is confirmed by Parker[4,6]. Parker showed that joints lose strength with increased exposure to humid conditions, and concluded that the failure mode is a result of a complex balance between adhesive and composite properties and of the interface between the two. Parker observed the effects of moisture on both pre-bonded CFRP-CFRP joints[6], as well as subsequently bonded CFRP-CFRP joints[4,6]. In the latter case, evidence suggested that moisture diffused into the adhesive during the cure, causing plasticisation, which affected the failure mode. Laminates with higher moisture contents gave lower joint strengths, but the reduction in joint strength was adhesive dependent.

Cong et al.[10] was one of the few researchers that has extended these studies from water onto machining coolants. The authors compared the use of cutting fluid and cold air as a coolant on CFRP in rotary ultrasonic machining. This comparative study observed levels of cutting force, torque, surface roughness, burning of the machined surface, and tool wear whilst using the two cooling methods. They concluded that using a fluid was not always beneficial, because in some cases cutting forces and torque values were approximately the same irrespective of coolant media. However, using a cutting fluid did mostly lead to reduced torque and reduced cutting forces, as well as improving surface roughness, tool wear, and eliminating machined surface burning. In this reference[10] the benefits of using a coolant were apparent presented, but the consequences of doing so to the composite (i.e., effects on mechanical or adhesive properties) were not addressed.

In this work, typical aerospace CFRP test specimens were exposed to 5 preselected coolant candidates; water and 4 synthetic coolants (including 1 minimal quantity lubricant – MQL) over a period of 7 days at 60°C. Further identical specimens remained dry during this time (but were exposed to the same temperature) and were used by comparison as a control for this experiment. The specimens were monitored after the soak for weight changes. At the end of the 7 day period the specimens were bonded and tested to establish the bond strength and shear strength. As soon as possible after exposure, bond strength tests and short-beam shear tests were performed. These tests were used to give an indication of the reduction in matrix properties as a result of exposure to the coolant.

2. Experimental work

2.1. Materials

UD (Unidirectional) MTM44-1/HTC-12k-145gsm/33%RC thermoset prepreg (0.15mm thick) was sourced from ACG, UK. MTM44-1 is a high performance material and toughened epoxy resin formulated for aerospace structures and applications. MTM44-1 can be cured / processed at 180^{o}C via low pressure vacuum bag out-of-autoclave or autoclave moulding. Advantages of MTM44-1 include excellent T_g retention under wet conditions, low density and a high level of damage tolerance.

2.2. Composite laminate manufacturing

A composite panel of 500mm x 500mm was produced from UD MTM44-1 thermoset CFRP prepreg. The layup was tailored such that the outer most plies were at 0°, the nominal thickness was 2.5mm, and the panel was debulked after every fourth ply. The arrangement for such a layout is shown below in Table 1. A suitable caul plate and vacuum bag was applied, and the panel was cured in the autoclave using the cure cycle shown in Table 2**.**

The panel was accurately cut using the AMRC-5-axis CNC machine into 60-off (25mm x 100mm) specimens, and 18-off (15mm x 5mm) specimens. The length of each specimen was parallel to the panel's surface fibre direction (0^{o}). The remainder of the material was cut into specimens tabs of 25mm x 40mm. A total of 72 of these were obtained.

Table 1: Layup arrangement of MTM44-1/HTS 500mm X 500mm panel

Stack No.	Ply No.	Orientation angle
1	1	0
	2	+45
	3	90
	4	-45
Debulk		
2	5	0
	6	+45
	7	90
	8	-45
Debulk		
3	9	-45
	10	90
	11	+45
	12	0
Debulk		
4	13	-45
	14	90
	15	+45
	16	0

Table 2: Autoclave cycle description

Step	Instruction
1	Ramp to 130°C at 2°C/min
2	Dwell at 130°C for 2 hours
3	Ramp to 180°C at 2°C/min
4	Dwell at 180°C for 2 hours
5	Cool to ambient at maximum ramp rate

2.3. Short-beam shear specimens

Due to their small size, the short-beam shear specimens were unlikely to remain on the machine bed before the completion of the machine cycle. These specimens were therefore not completely machined from the panel, and manually removed from the panel after cutting through the remaining material with a Stanley knife. It was then necessary to manually grind along their edges to ensure a flat surface. Each specimen was then inspected for visual defects (such as splintering or delamination) and wiped clean with EnSolv.

2.4. Bond strength/lap shear specimens

It was noticed that the cured panel did not have uniform thickness, and as such the specimen thicknesses were not identical. This could potentially be problematic during bond strength testing, because the clamping may produce a pre-testing flexural load. Also, if the tab is not the same thickness as the specimen, this would cause the direction along which the load acts to be non-central. Figure 1.a shows a schematic diagram of such a case, whereby the loads are shown to act centrally with respect to the clamps of the machine, but due to the tabs being of a different thickness to the specimen, this load force does not act along the bond-line. In such circumstances, the applied loads would generate out-of-plane forces within the system that may affect the failure load and failure modes. Figure 1.b shows an example whereby the specimen halves are of differing thicknesses, but the matched specimen tabs ensure that the loading forces act along the bond-line, thus generating a fair test.

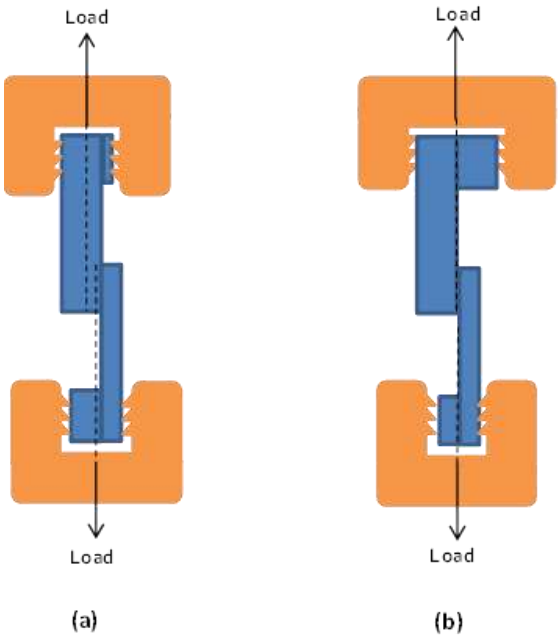

Figure 1: Lap shear specimens with halves of unequal thicknesses with a) unmatched specimen tab widths, and b) matched specimen tab widths.

The specimen tabs and specimen thicknesses were measured using Vernier calipers, and assorted into size order. The specimens and tabs were then assorted such that the difference between specimen and tab thicknesses was always less than 0.1mm.

Each specimen and tab was manually abraded at the interfaces using SiC (silicon-carbide) abrasive paper (P800 grade), and then further cleaned with EnSolv. The tab was bonded on using the adhesive Scotch-weld 9323 and using the surface table to ensure surfaces were flush. They were compressed together and held in position using a G-clamp, excess glue was wiped up, and then were left overnight for the adhesive to cure. Once cured, the clamp was removed and any excessive cured adhesive was manually ground away. Each specimen was then manually abraded at the lap interface using a sheet of P800 SiC paper affixed to the edge of a surface table. The sample surface that was to be bonded - which was to be 1 square inch (6.45cm^2) as per ASTM D5868- was then circled 5 times on the paper, and subsequently cleaned with EnSolv.

2.5. Soaking

The samples were split into six batches, such that there were three short-beam specimens per soaking media, and 10 bond strength specimens per soaking media (that would later provide

5 bond strength specimens once bonded). They were then given to the machine coolant manufacturer Houghton (www.houghtonglobal.com) for the soaking experiments and swell tests to be conducted. One batch of samples were left unexposed (i.e., in air), a further batch was soaked in demineralised water, and the remaining four were soaked in different machine fluids, namely Hocut 795B, Hocut GR3000, Cindolube V30ML, and Metalina B800. The samples were soaked for 7 days at a temperature of 60°C. Once soaking was complete, the samples were wiped dry with a paper towel and weighed. They were then placed into sealed sample bags, labeled with the media in which they were soaked, and returned to the AMRC for further preparation, bonding and testing.

2.6. Bond Strength Specimen Preparation and Bonding

The specimens were prepared into bond strength specimens as quickly as possible after their receipt at the AMRC to prevent any moisture desorption affecting the test results. Each sample was cleaned in the area to be adjoined using 3 passes of a fresh PF-SR solvent wipe (an aerospace industry sealant remover). A thin coverage of Scotch-weld 9323 was placed on both specimen halves in the overlap area, and a single layer of PK13-13gsm knitted polyester scrim (kindly provided by ACG) was applied to act as a spacer to ensure a bond-line thickness of 150µm. The samples were then placed within a custom made jig, shown below in Figure 2, to ensure that the specimen halves were positioned and aligned correctly, and that the overlap created when bonding the specimen halves together was 1 square inch, and reproducible from specimen to specimen. Figure 3 illustrates how the jig is used and where fixing clamps are located. Excess adhesive was removed. Clamps were used to hold the specimen halves in place until the adhesive had cured overnight. These final bond strength test specimens were removed from the jig when the adhesive had 24 hours to cure, and were immediately sent to the ASTC (the Advanced Structural Testing Centre, the AMRC's testing centre).

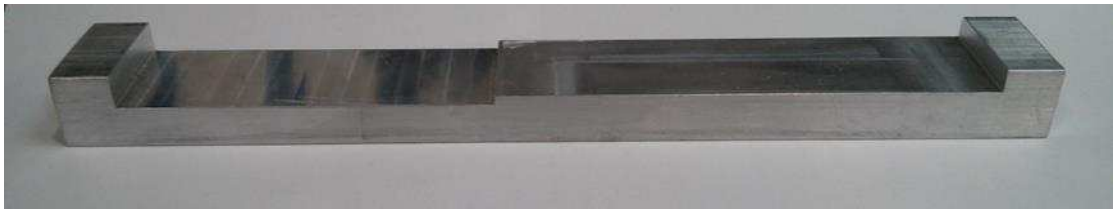

Figure 2: Custom made bonding jig for the bond strength specimens

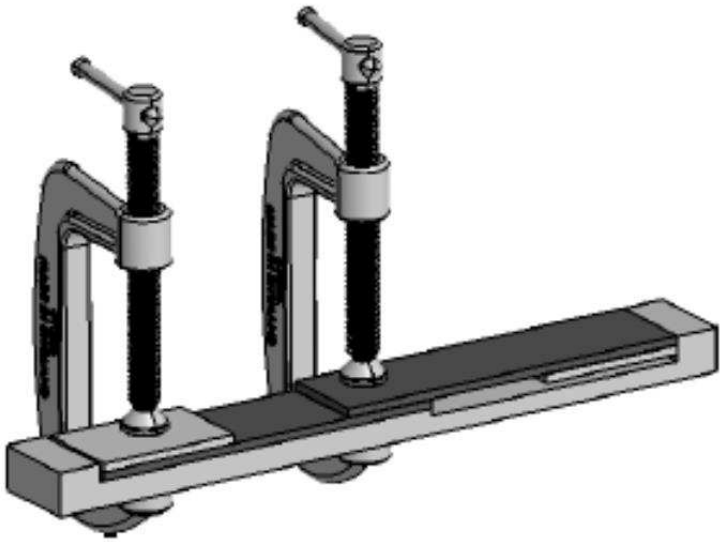

Figure 3: Illustration showing how the jig is used and where the clamps are located.

2.7. Mechanical testing

The short-beam shear and bond (lap shear) strength tests were performed by the ASTC in accordance with the standard methods; ASTM D2344[11] and ASTM D5868[12], respectively. Both sets of tests were performed on an Instron 50kN Universal Testing machine.

Short-beam and bond strengths were calculated using Equations 1[11] and 2[12], respectively.

$$\text{Short beam strength} = 0.75 \times \frac{P_m}{b \times h} \quad (1)$$

$$\text{Bond/lap shear strength} = \frac{P_m}{A} \quad (2)$$

Where P_m is the maximum flexure load in Newton, b is the specimen width in mm, h is the specimen thickness in mm and A is the overlap/bond area in mm^2.

3. Results

A total of 18 short-beam shear (3 per medium) and 60 bond strength specimen halves (10 per medium) were soaked. However, whilst the entire short-beam specimens went on to be tested, from the bond strength specimens only four specimens per media were taken forward

for final testing. In this section, the results are presented in tabular and graphical form for the swell tests, the short-beam shear tests and the bond strength tests.

The swell test results of bond strength samples are presented in Figure 4. The reason for omitting the swell results for the short-beam shear samples is because these samples, due to their size, are likely to absorb a larger proportion of water, which would yield larger percentage weight gain values. This is particularly noticeable in a few instances in the raw data, where the percentage weight-gain for the short-beam samples is significantly higher than those for the bond strength samples. The water and Metalina B800 data provide distinct examples of this, where a reading marked the weight gain at over 1%.

The samples that were exposed only to air showed a significant 0.15% weight loss, as can be seen in Figure 4. A weight loss when not exposed to fluid would seem intuitive, as the 60°C temperature would encourage moisture to desorb from the samples. The demineralized water, used as a control test within the experiment, produced a weight gain in the samples of 0.5%, over 3 times the magnitude of the weight loss in air. The three coolants Hocut 795B, Hocut GR3000 and Metalina B800 all generated a weight gain that was greater than but not dissimilar to that of water. However, when the statistical error is taken into account, it is not certain that these coolants caused more or less weight gain than that of the water. The Cindolube V30ML produced the most distinct effect in the samples than any of the other fluids used. The samples soaked in Cindolube V30ML clearly experienced the least effect regarding weight change than any other sample in fluid or air, and in fact they experienced a small weight loss instead of weight gain. However, when statistical error is taken into account, it is unclear as to whether these samples experienced a weight gain, loss or experienced no change at all, but the absolute measurements showed a weight loss to be more likely.

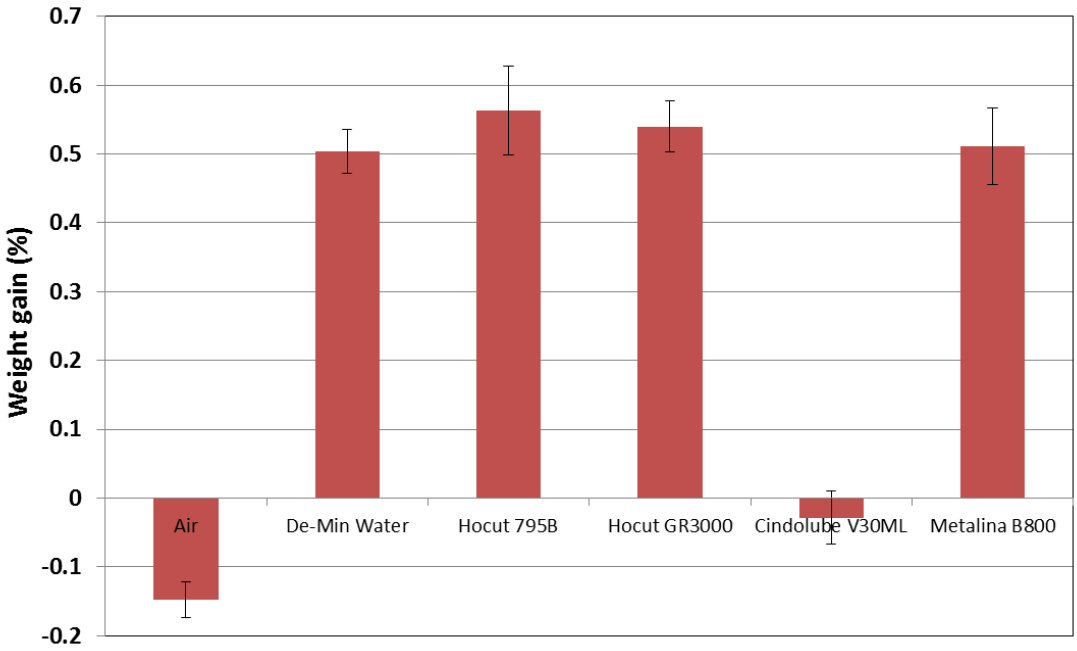

Figure 4 Swell test results for the bond strength half specimens only, samples exposed to air or fluid at 60°C for 7 days

The results for the short-beam shear and the adhesive-bond strength tests, for samples exposed to air or fluid at 60°C for 7 days, are summarized and presented in Figures 5 and 6, respectively. The short beam shear strength results (Fig. 5) show that exposure to water produced the largest decrease (9MPa) in this particular mechanical property. Out of the four selected coolants, the Metalina B800 produced the largest reduction (5MPa) in short beam shear strength, whilst the others (Hocut 795B, Hocut GR3000 and Cindolube V30ML) had approximately the same impact in this property, which was relatively little (2-3MPa). During the interlaminar shear strength test (ILSS), the tested samples were inspected to figure out the failure mode for each specimen, Table 3 gives the obtained failure mechanisms.

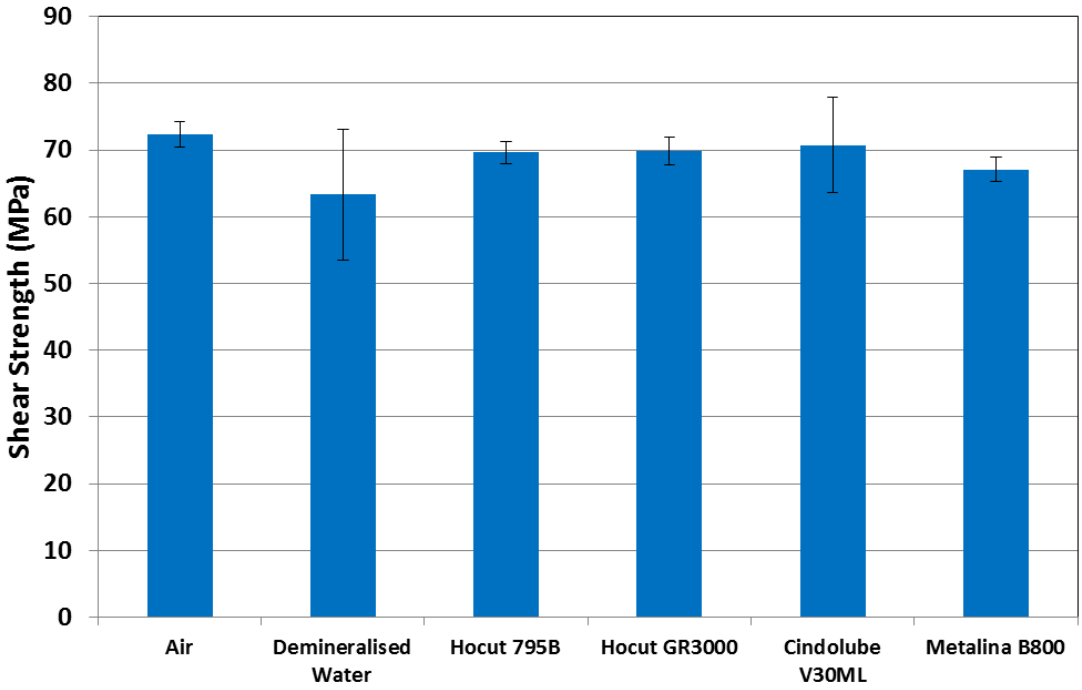

Figure 5 Short-beam shear strength results for samples exposed to air or fluid at 60°C for 7 days

In the case of the bond strength test results (Fig. 6), it is difficult to express by how much the mechanical property has degraded with exposure to each liquid media because the control specimens, those exposed to air, the results, do not have the greatest magnitude. Exposing the specimens to liquid is expected to degrade mechanical properties yet these seem to have improved, and as such the results for the air exposed samples are a cause for concern. This will be addressed in the discussion. Despite this, the comparative mechanical properties between the specimens soaked in the liquids shows similar trends to those of the short beam tests. More specifically, the samples soaked in Metalina B800 showed the worst mechanical properties, and were consequently the worst affected. The results for the Hocut 795B and Hocut GR3000 showed very similar degradation to each other, and the specimens soaked in Cindolube V30ML were the least affected.

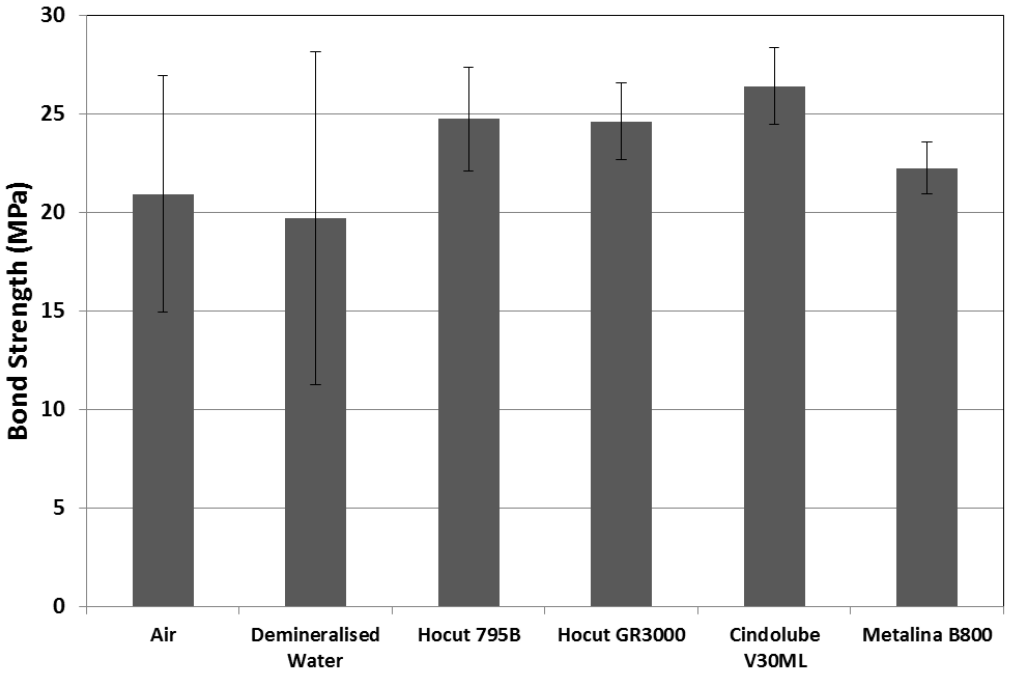

Figure 6 Bond strength results for samples exposed to air or fluid at 60°C for 7 days

Notably, the large statistical variations (particularly those associated with the demineralised water results and the bond strength of the specimens exposed to air) are cause for concern. In the bond strength results from the water soaked specimens, the four test results create an average of 19.7±8.4MPa (see Fig. 6). The large standard deviation suggests there may be an anomalous result within the data set, but on inspection there are two low values (12MPa and 14MPa) and two large values (25 MPa and 29MPa). This would make it statistically unfair to rule any of the results out as anomalous.

Table 3: ILSS results and failure modes

Coolant / Lubricant	Specimen	ILSS (MPa)	Failure mode
Air	1	71.75	Interlaminar shear
	2	70.85	Interlaminar shear
	3	74.56	Interlaminar shear / Flexure compression
De-Min Water	1	52.04	Interlaminar shear
	2	69.11	Interlaminar shear
	3	68.80	Interlaminar shear
Hocut 795B	1	68.29	Flexure compression

	2	71.47	Inelastic deformation
	3	69.15	Flexure compression
Hocut GR3000	1	67.87	Flexure compression
	2	69.52	Inelastic deformation
	3	72.12	Inelastic deformation
Cindolube V30ML	1	68.59	Interlaminar shear
	2	78.70	Interlaminar shear
	3	64.87	Interlaminar shear
Metalina B800	1	65.08	Interlaminar shear
	2	68.53	Flexure compression
	3	67.08	Flexure compression

4. Discussion

A weight loss from those samples exposed to air at elevated temperature was expected, and observed. It was also expected that the samples that would absorb the most moisture would be those exposed directly to water, but this was not seen to be the case. Statistical variation shows that it may be possible that the samples exposed to the synthetic fluids are actually less than or equal to the weight gain than those of those exposed to water, and consequently these results do not cause concern. Of particular interest though are the weight gain measurements of the samples exposed to Cindolube V30ML. These changed weight the least, which suggests not only that the transfer of moisture from the lubricant to the composite was minimal, but also the transfer of moisture from the composite to its surroundings were restricted or hindered in same transference mechanism. On inspection of the fluids composition, the Cindolube V30ML is a fully synthetic esther lubricant and as such does not contain water, whilst the other coolants are an emulsion, and do contain water. This suggests that the samples exposed to Hocut 795B, Hocut GR3000 and Metalina B800 are absorbing water from the emulsion, and that the Cindolube V30ML – being water insoluble – is not easily allowing moisture to transfer from the samples to their surroundings or vice versa. This would explain the minimal weight change observed in the Cindolube V30ML results. The Hocut 795B, Hocut GR3000 and the Metalina B800 are all known as 8% emulsion coolants,

i.e., they contain water in similar proportions to one another, explaining why these all absorbed moisture to similar levels.

There were features in the short beam shear and bond strength results that were anticipated, such as the worst properties being accredited to the samples that were soaked in water, and the mechanical properties of those soaked in other fluids being better than those of water soaked ones, and typically worse than those exposed to air that exhibit shear strength of 72.4MPa. The exception to this however was in the case of the bond strength results, whereby the specimens exposed to air demonstrated bond strength of 20.9MPa that were significantly worse than those exposed to the coolants. However, the large scatter associated with this value implies that some of the results in this category may have been erroneous. Inspecting the individual results, it was not sensible to isolate one result as an anomaly. In trying to identify possible alternative causes for the large scatter, the experiment should be considered in four sections, namely sample manufacture, sample soaking, sample preparation and sample testing.

Low ILSS compared to dry specimens was observed in case of the wet samples. Test samples that experienced weight loss are those with the highest ILSS results such as those exposed to hot air and to Cindolube V30ML. Previously[13] it is reported that during the development of tensile and compression technologies the "width-wise tapering to form a stress-focusing transition region usually leads to splitting failures in the tapered region long before a valid failure can be obtained in the gage region. This tendency appears to be related to excessively low shear strength of organic matrix composites in comparison with their tensile or compressive strength in the fibre direction". This suggests that the matrix might have been further weakened by coolant, leading to lower shear strength. The lap shear (bond strength) test results suggest that, with a basic cleaning cycle, the presence of coolant has not reduced lap shear. Since the failure mode happens on the substrate between the adhesive and the outer layer of the sample, a surface analysis would be ideal to fully understand the failure mechanisms and the reasons for the reduction in bond strength.

When comparing the swell test result with interlaminar shear strength and lap shear result respectively, it is interesting to note that samples exposed to air had opposite result in the two tests. In fact reduction in moisture content corresponded to higher shear strength, but lower bond strength than those which gained weight. This does not apply to Cindolube V30ML

when statistical errors are taken into account. Cindolube V30ML, which lost about 1/5th content of moisture than air, showed highest values for shear and bond strength (70.7MPa and 26.4MPa, respectively) than those which gained weight. This could be explained looking at the swell test result. Cindolube V30ML has demonstrated to be the only media which did not considerably changed, in positive or negative, the moisture content of the material after exposure. A significant lost or gain in moisture seems to have a detrimental effect on material properties in terms of shear strength.

During sample manufacture, all samples were accurately CMS machined from a single panel, with the exception of the short beam shear specimens; these specimens were partially machined out and then manually extracted using a Stanley knife. All specimens would later be placed into groups of "Air", "Water", "Hocut GR3000" etc. with no precedence as to where in the panel they came from. The high level of automation here suggests that it is very unlikely that the sample manufacture would produce specimens with such large dissimilarities that would later affect the results. However, possible internal defects could alter the materials capability to absorb water. For example, a sample with a high density of voids could take on significantly more water that a sample with a relatively low void content.

Prior to sample soaking, the samples were randomly selected into their groups, soaked, then cleaned of residue using paper towels and immediately bagged up. The only part of this process that would be subject to inconsistencies is the cleaning procedure of the specimens. The potentially erroneous results were however associated with the control samples, i.e., those exposed to air and water, and the air samples did not require cleaning. Hence the likelihood of an additional factor being introduced here is unlikely.

Sample preparation (only performed on bond strength specimens) involves abrasion, cleaning, alignment and clamping, all of which are done manually, and could therefore be subject to human inconsistency. Every care was taken to ensure that each sample was exposed to identical conditions. For example, sample cleaning was standardized to 3 passes of a solvent wipe, sample abrasions was (in a similar way) standardized by securing the abrasive on the bench and circling the specimens overlap area over it 5 times, and a jig was produced and used to ensure the specimen halves were aligned properly. During sample bonding, an excess of glue was produced around the edges of the bond interface. This was wiped clean where possible, but the bonding jig enclosed one edge whereby the adhesive

couldn't be removed. This excess of cured resin could cause variation in the adhesive strength results.

Sample testing is carried out by the University Advanced Structural Testing Centre. The tests themselves are automatic, controlled by tensile or compressive hydraulic systems, but the sample loading is a manual task, so whilst it is possible for inconsistencies to be introduced here, it is again unlikely.

The fact that the largest errors are associated with just one type of test (the bond strength tests) infers that the errors are introduced during an event/occurrence exclusive to those test pieces. This eliminates sample manufacture and sample soaking as possible sources for uncertainty. Hence, the large sources of error are likely to lie either with sample preparation or testing. Confidence within the remainder of the data is regained by the statistical trends within the two sets of results, for the investigation into the mechanical property of the samples. These trends primarily indicate that Metalina B800 causes the largest mechanical property degradation within the composite, and Cindolube V30ML causes the least. The effect of the Hocut GR3000 and the Hocut 795B are very similar.

5. Conclusion

Whilst large errors within the bond strength results provide a level of uncertainty, the trend repetition between these tests and the short-beam shear test results is reassuring, and the following conclusions can be drawn.

- All of machining synthetic coolants performed more favourably than water, because water created the greatest mechanical property degradation.
- The Metalina B800 was the poorest performing synthetic coolant by the same measure, i.e., the degradation in mechanical properties was the largest with the exception of water.
- The Hocut GR3000 and Hocut 795B affected the composite to very similar levels, and there was only one lubricant that appeared more favourable than these.
- The Cindolube V30ML seemed to be the best lubricant in terms of its suitability for use on composite materials. It effectively shielded the composite from water transfer, preventing moisture desorption as well as absorption. And the mechanical properties

of the composites exposed to this fluid showed the least degradation in material properties.

- The large variation in lap shear/bond strength results indicate that it might be an external factor affecting the results to a larger degree than the effect of soaking in coolant.

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