BENEFITS OF CO$_2$ COOLING AS A COOLING TECHNOLOGY FOR DRILLING OF STACKUP COMPOSITE STRUCTURES

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ABSTRACT

The use of composite materials and composite stackups in aerospace and automotive applications has been and will continue to grow at a very high rate due to the high strength and low weight of the materials. One key problem manufacturers have using this material is the ability to efficiently drill holes through the layers to install fasteners and other components. This is especially true in stackups of Carbon Fiber Reinforced Plastic (CFRP) and titanium (Ti) due to the desire of drilling dry for the CFRP layer and the need for cooling when drilling the high strength Ti layer. By using carbon dioxide (CO$_2$) through tool cooling agent, it is possible to protect both layers. Previous studies have shown significant benefits of CO$_2$ Cooling in CFRP-Ti stackups including: 30% productivity increases, 10% tool life improvements, and substantial energy savings [1, 2, 3].

This study extends the earlier work by comparing the performance of polycrystalline diamond (PCD) tooling in drilling of CFRP-Ti stackups with three types of coolant conditions: CO$_2$ coolant only, Minimum Quantity Lubrication (MQL) only, and CO$_2$ with MQL. Furthermore, these tests were conducted using portable Automatic Drilling Unit (ADU) which are common in many aerospace assembly processes. Parameters evaluated include roundness of composite and Ti, composite erosion, Ti surface finish, delamination of composite, PCD tooling chipping, and tool wear. Based on the results of a comparison of MQL drilling vs. MQL+CO$_2$ and CO$_2$ alone, the addition of CO$_2$ coolant does not alter the average hole diameter in the Ti layer. However the addition of CO$_2$ cooling generally results in a slightly small hole diameter in the CFRP material. Furthermore, CO$_2$+MQL is expected to increase productivity by 3X without creating observed delamination issues within the CFRP layer.

INTRODUCTION

Heat is the key issue in nearly every machining operation, causing wear, reduced tool life, reduced processing speed, and limiting throughput. The balancing act between productivity, tool life, surface finish, and part quality is optimized by the ability to reduce or eliminate heat generation. CO$_2$ cooling has the ability to significantly reduce the heat in the cut zone, while maintaining a dry machining environment. This paper will explain benefits of using CO$_2$ cooling systems applied to through the tooling for drilling composite assemblies or “stackups”. In addition, these results can be used as new machine tool cooling ideas in industries where these high tech materials are utilized. Many results in this paper were generated projects supported by
the National Science Foundation (NSF), Department of Energy (DOE), and Environmental Protection Agency [1, 2, 3]. This paper also presents new data on the effect of using CO₂ cooling technology on the effectiveness of drilling composite structures.

1.1 Background

The automotive and aerospace industries use CFRP because it is more durable and lighter than other materials. CFRP is used in components such as aircraft fuselages, wing skins, door panels, automotive body panels, and many other areas that are trickling down to mainstream production vehicles from racing applications. Multiple layers of CFRP and another material, such as Ti, are called a “stackup”.

The use of composite materials for applications demanding strength, flexibility, elimination of corrosion, at minimal weight is well documented. A key machining/drilling challenge for CFRP applications is that traditional liquid coolants, particularly petroleum-based coolants, are not often used for cooling and lubrication during machining operations as their use can lead to melting of the matrix material and induce chemical reactions [4]. For this reason, nearly all composite manufacturing operations are performed completely dry. However, dry machining can induce thermal damage due to low thermal of CFRP materials and high cutting temperatures. Some researchers have used MQL to improve the performance CFRP stackup machining.

1.2 Drilling of CFRP-Ti Stackups

There are many types of composites used in the automotive and aerospace industries; a primary example is CFRP. In areas where concentrated loads have to be introduced into the composite structure, metallic reinforcements are frequently used such as Titanium or Aluminum. These reinforcements may be located on just one outer side, both outer sides, or interspersed within the composite material layers. When material is stacked-up and bonded together, heat from drilling a Titanium layer can thermally damage the resin matrix in the CFRP layer(s).

CFRP drilling operations require consideration of three primary issues:

1. CFRPs have very low heat conductive and storage properties – To accommodate this issue, slow cutting speeds to maintain an acceptable equilibrium between heat generation and heat disposal are required.

2. CFRPs are very abrasive - This issue makes diamond reinforced tools desirable. However these tools are heat sensitive.

3. CFRP stackups can easily delaminate on the exit side of a drilled hole - This issue must be handled in part by maintaining low matrix material temperatures. Other additional measures can include sacrificial backing material, the addition of an outer scrim cloth layer, and controlling drill exit forces.

When drilling a CFRP-Ti stackup a frequent challenge for airframe manufacturers is to hold a consistent hole size in the softer composite. Usually the composite is the top layer and is drilled first, then the Titanium is drilled with the Titanium chips passing through the composite. Coolants such as water and oil, or misting of oil are often used with stackup structures. These conventional coolant approaches do not provide optimal cooling for machining of these stackup
materials, which often results in poor hole surface quality or holes out of dimensional tolerance. CFRP-Ti stackup is utilized in the fuselage of most new aircraft.

As this operation is frequently performed on aircraft frame assemblies, it is not feasible to clean liquid coolants or oils from them during manufacturing. Therefore, the drilling operations performed to secure fuselage panels to the frame are typically done dry. Drilling through the Ti layer without any coolant is a difficult and time consuming process. The feed rate of the drill bit through the Ti layer must be kept very slow in order to keep the created chips light, fluffy and relatively cool, so they do not damage the CFRP layer.

1.3 CO₂ Cooling Technology

The CO₂ based Environmentally Friendly Coolant System (EFCS) used for these tests delivers a cooling fluid consisting of CO₂ ice particles, CO₂ gas, and air, directly to the cut zone where cooling is required. The EFCS tool, shown in Figure 1 was used for these tests to deliver the CO₂ – based cooling fluid. The solid CO₂ particles in this fluid are formed from the expansion of liquid CO₂ to form a mixture of solid and gaseous CO₂. This expansion is capable of absorbing significant amounts of heat, approximately 127-207 kJ/kg. The EFCS delivers the CO₂ cooling fluid with solid particles of CO₂ dry ice at a temperature of -79°C into the heat zone of the tool/work piece interface. This dry ice in solid form penetrates the vapor heat barrier to optimize heat transfer and thus the cooling effect. No other coolant technology is delivered in solid form; hence no other competing technology has the equivalent mass and momentum to impinge the heat barrier. Furthermore, small quantities of lubricant can be added to this cooling fluid to provide additional lubrication benefits.

![Figure 1. EFCS used to generate the CO2 cooling fluid for these tests.](image)
The end result is:

- Solid CO\textsubscript{2} particles blasted into the heat zone to deliver significant cooling.
- Solid CO\textsubscript{2} particles have mass that can be forced through vapor barriers and heat zones.
- Cutting tool stays cool from the solid CO\textsubscript{2}, keeping the cutting edge sharper to extend tool life significantly greater than conventional processes.
- CO\textsubscript{2} EFCS process is dry and can be used on materials that cannot use conventional liquid flood coolant, such as composites.

1.4 Methods of delivering CO\textsubscript{2}-Coolant

The EFCS system is capable of delivering CO\textsubscript{2} coolant to the tool-work piece interface in two methods. The first method, shown in Figure 2, is used for drilling and delivers CO\textsubscript{2} coolant through coolant ports in the tool. The second method, which delivers CO\textsubscript{2} through an external nozzle, is used for turning applications, not presented in this paper.

![Figure 2. Through-Tool CO\textsubscript{2} Cooling.](image)
EFCS through tool cooling uses both gas and liquid CO\textsubscript{2}. Both phases are delivered through a single coaxial hose from the EFCS to the rotary coupling of the machine tool. The gas and liquid CO\textsubscript{2} then mix while flowing through the coupling, spindle, tool holder and tool. A controlled pressure of 4.1 MPa is maintained within these components and keeps all of them at a cool ambient temperature. When the liquid CO\textsubscript{2} exits the coolant ports of the tooling (drill bit in this case), the liquid expands, resulting in the generation of solid CO\textsubscript{2} particles and gas at a temperature of -79°C. This cold spray can therefore absorb much of the heat generated in the machining operation thus keeping the work piece and tooling at a cool ambient temperature. The ability of the EFCS to maintain a constant operating pressure yields a constant cool temperature inside the spindle helps keep rotary coupling seals from heating up. It also helps maintain more precise tolerances from part to part since there is no liquid coolant to warm up while being pumped through the system. CO\textsubscript{2} consumption is directly related to the size and quantity of coolant ports in the tooling. In a drilling operation, the highest amount of heat is generated at the tip of the tool. The ability of the EFCS to deliver a controllable amount of cooling directly to where chips are being formed provides a significant advantage.

2. EXPERIMENTAL MATERIALS AND METHODS EQUIPMENT

The experimentation and testing performed for this paper utilized an EFCS, designed and manufactured by Cool Clean Technologies, to provide the CO\textsubscript{2} coolant, shown in Figure 2. Test results from two different series of tests are reported in this paper. The first are tests conducted to compare the effectiveness of CO\textsubscript{2}-based cooling sprays over traditional machining, both dry and flooded, of CFRP and CFRP stack-ups. The second were tests designed to evaluate the effectiveness of drilling CFRP with CO\textsubscript{2}-based cooling sprays with and without MQL as compared to MQL-only.

2.1 CFRP-Ti Stackup Test Coupon Drilling: CO\textsubscript{2} vs Dry vs Flood Cooling

The key metrics evaluated in this series of tests were drilling temperature, tool life, hole quality, productivity, and energy savings. Data presented in this paper was gathered from both test coupons and production parts. The tooling used was carbide drills 6.337 mm (0.2495 in) diameter with a WD1 coating. Machining parameters use a spindle speed of 1528 rpm, and a feed of 0.1106 mm/rev (0.004 in/rev), which equates to 30 surface meters per minute (SMPM). The drill pecked every 1.106 mm (0.040 in), and at each peck retracted to 2.54 mm (0.10 in) above the part to allow the chips to evacuate. The details of the CFRP and CFRP stack-up tests are found in Reference 1. The summary of these results is presented below.

2.2 CFRP-Ti Stackup Test Coupon Drilling – MQL Evaluation

Four different tests are reported: two tests with CO\textsubscript{2} coolant only (N1 and N2), one with MQL only, and one with CO\textsubscript{2} coolant. The MQL was manufactured by Micro Cut. An Atlas Compco ADU was used for this series of tests. The CFRP-Ti Stackup test coupon used for this tests was:

- 1\textsuperscript{st} layer – carbon fiber – thickness = 12.7 mm (0.5 inch),
- 2\textsuperscript{nd} layer – Ti – thickness = 8.9 mm (0.35 inch).
Drills used for these tests were Precorp PCD bit – nominal diameter = 15.5 mm (0.61 inch) - fixed to fixture by clamps at 4 corners. The drill was not measured before or after drilling of the holes. One new drill bit was used for each of the four tests.

3. RESULTS AND DISCUSSION

The results for both sets of data reported are presented below. The first set of data is a summary of data presented previously as found in Reference 3. The second set of data is presented for the first time.

3.1 CFRP-Ti Stackup Test Coupon Drilling: CO2 vs Dry vs Flood Cooling

3.1.1 Drilling Temperature Analysis

The carbide drill went through a stackup of composite and titanium, with the composite component being 10.16 mm (0.40 in) thick on the top and the 12.7 mm (0.50 in) thick titanium component being on the bottom. Two panels with 32 holes each were drilled, equaling a total of 1463 mm (57.6 in) of drill travel.

Work was performed on a vertical CNC mill which ran one panel of 32 holes over the course of about 8.5 minutes, with each hole taking about 16 seconds. The drill and stackup conditions were inspected at the end of each panel.

During the drilling process the temperatures of the drill, the composite, and the titanium were recorded. Temperature data was measured with a laser IR gun as the drill broke through the bottom of the part. These data are summarized in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Drill - Temp °C</th>
<th>Composite - Temp °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>EFCS CO2</td>
<td>37</td>
<td>24</td>
</tr>
<tr>
<td>Conventional</td>
<td>64</td>
<td>51</td>
</tr>
<tr>
<td>Improvement</td>
<td>27</td>
<td>27</td>
</tr>
</tbody>
</table>

This temperature measurement process was not ideal as it likely overestimated the temperature and thus underestimated the cooling benefit. Nevertheless, the data do show the general trend of lower temperatures, ranging from 20°C for the titanium layer measurements to 27°C for the drill and composite temperatures.

3.1.2 Hole Size Comparison

The CO2 cooling process produced composite hole diameters in close tolerance with the hole size in the titanium. The composite hole diameter drilled with the flood coolant was significantly larger than the titanium hole, thus causing the composite hole size to increase above the 6.35 mm +0.0762 mm (0.249 in +0.003 in) customer specification. Figure 3 below shows the difference in the hole sizes between the CO2 cooling fluid and the conventional flood coolants.
The CO\(_2\)-based cooling system provided a significantly better hole size tolerance within specification, as compared to the holes drilled with conventional coolant. The flood coolant produced a significantly larger hole in the composite during the first half of its tool life as is shown in the graph. Improvement occurred as the drill cutting edge was dulled resulting in smaller chips causing less damage to the composite hole size. The CO\(_2\)-based cooling system produced a hole with 0.025 mm (0.001 in) variability vs. 0.127 mm (0.005 in) for conventional coolants, or 5X less variability.

![Figure 3. Hole Size Comparison.](image-url)

### 3.1.3 CO\(_2\) Coolant Application to Dry Drilling of CFRP-Ti Stackup [3]

Dry drilling of CFRP-Ti Stackup’s is a methodology used when the drilling application cannot support the use of a coolant. The key problem with this method is the relatively short tool life and hole quality problems in the CFRP layer of a CFRP-Ti stackup. The time required to drill a single hole was 3 minutes dry and 1.3 minutes with CO\(_2\) coolant, resulting in a time savings of approximately 1.7 minutes. Further, 30 holes can be drilled dry while the addition of CO\(_2\) permits the drilling of an additional 6 holes (total of 36 holes). This relatively small increase in tool life turns into a significant savings when taking into account that the PCD drills typically used to drill CFRP cost around $750 each. Based on the data presented, the projected savings from the use of a CO\(_2\)-based cooling for this drilling application was nearly $20,000 per month.
### 3.1.4 Summary of CFRP-Ti Drilling Data

A simple summary of the advantages of CO\textsubscript{2} cooling when drilling CFRP-Ti stackup material is presented here. The cross section of the CFRP-Ti stackup and where critical measurements were taken are represented as:

- “Ti Mid” was taken at the midpoint of the titanium understructure;
- “CO Mid” was taken at the midpoint of the composite skin;
- “CO Exit” was taken at the exit point of the drill of the composite skin.

The comparison of the impact of dry drilling versus CO\textsubscript{2}-cooled drilling is presented in Figure 4 - 6.

![Figure 4](image1)

**Figure 4.** “CO Mid” Diameter Variation: Blue indicates conventional coolant, Red indicates CO\textsubscript{2}-based coolant.

![Figure 5](image2)

**Figure 5.** CO Exit Hole Diameter Variation: Blue indicates conventional coolant, Red indicates CO\textsubscript{2}-based coolant.
3.1.5 Drilling Hole Tolerance, Quality, Speed

In Figures 4 - 6 above, the red data points show a tighter tolerance while staying within the quality range as indicated by the two horizontal red lines in CO-Mid, CO-Exit and Ti-Mid locations. All of this was done while increasing the productivity of the two step process by a total of 30%.

Furthermore, conventional coolants were able to produce approximately 30 holes within roundness specification, while CO₂ coolant produced 65 holes within the specification. Hole quality at the midpoint and exit of the CFRP layer and at the midpoint of the Ti layer remain within specification.

- Tool life increases by 40 - 60% when compared to conventional systems.
- Number of holes doubled while still within hole tolerance specification.

Based on data presented in Reference 3, the CO₂ Coolant provides 30% increase in machining speed, resulting in increased production throughput compared to current production baseline machining parameters and a significant energy savings in the range of 10 - 15% for the overall system.

3.2 CFRP-Ti Stackup Test Coupon Drilling – CO₂ vs. MQL vs. CO₂+MQL Evaluation

This next set of data was collected from tests using an ADU equipped with a CO₂-based coolant generated by the EFCS. The objective of these tests was to evaluate the impact of adding MQL to the CO₂ coolant stream.

3.2.1 Hole Diameter Data

A metric for evaluation of this benefit was the measurement of hole diameters in the CFRP and Ti layers at 0° and 90°. For each data set collected, a series of 8 measurements were collected.

- Minimum and Maximum diameters of Ti at 0 degrees;
- Minimum and Maximum diameters of CF at 0 degrees;
- Minimum and Maximum diameters of Ti at 90 degrees;
- Minimum and Maximum diameters of CF at 90 degrees.

Table 2 presents a summary of the operating conditions used in this series of tests. For completeness, the temperature of the tool is also reported in this table. The hole diameter data collected for this series of tests is presented in Figures 7 – 11.

**Table 2 – Summary of Operating Conditions for CO\(_2\)/MQL Study**

<table>
<thead>
<tr>
<th>Test ID / #</th>
<th>RPM</th>
<th>Feed Rate, mm/rev (in/rev)</th>
<th>CO(_2) Coolant Rate, kg/hr</th>
<th>MQL Rate, ml/min</th>
<th>Holes</th>
<th>Tool Piece Temp, °C (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO(_2) N1 / #1</td>
<td>270</td>
<td>0.051 (0.002)</td>
<td>8</td>
<td>NA</td>
<td>1-30 Hole</td>
<td>10 (50)</td>
</tr>
<tr>
<td>CO(_2) N2 / #2</td>
<td>270</td>
<td>0.051 (0.002)</td>
<td>8</td>
<td>NA</td>
<td>1-30 Hole</td>
<td>10 (50)</td>
</tr>
<tr>
<td>Micro Cut / #3</td>
<td>270</td>
<td>0.051 (0.002)</td>
<td>NA</td>
<td>3</td>
<td>1-30 Hole</td>
<td>55 – 66 (130 – 150)</td>
</tr>
<tr>
<td>CO(_2) + MQL / #4</td>
<td>270</td>
<td>0.051 (0.002)</td>
<td>8</td>
<td>0.9</td>
<td>1-16 Hole</td>
<td>10 (50)</td>
</tr>
<tr>
<td>CO(_2) + MQL / #4</td>
<td>270</td>
<td>0.076 (0.003)</td>
<td>8</td>
<td>0.9</td>
<td>17-20 Hole</td>
<td>18 (63)</td>
</tr>
<tr>
<td>CO(_2) + MQL / #4</td>
<td>400</td>
<td>0.076 (0.003)</td>
<td>8</td>
<td>0.9</td>
<td>21-30 Hole</td>
<td>25 (77)</td>
</tr>
</tbody>
</table>

Figure 7 – Hole diameter variation for 30 holes drilled with 15.5 mm (0.6100 in.) drill with CO\(_2\) Only as coolant – Test #1.
Figure 8 – Hole diameter variation for 30 holes drilled with 15.5 mm (0.6100 in.) drill with CO2
Only as coolant – Test #2. Note – Graph shows experimental excursion at hole #8 which
occurred when problem with vacuum influenced solid CO2 (dry ice) build up, resulting in large
chip.

Figure 9 – Hole diameter variation for 30 holes drilled with 15.5 mm (0.6100 in.) with Micro Cut
MQL, Test #3.
Figure 10 – Hole diameter variation for 30 holes drilled with 15.5 mm (0.6100 in.) drill with CO₂ and MQL (Micro Cut) – Test #4. Note that there was an operational artifact that occurred for hole #24. During the drilling of this hole, the drill was accidentally stopped, and then restarted, resulting in the data deviation shown.

As noted above, the data collected with the CO₂+MQL case was collected under three different conditions, the data presented in Figure 10 is further subdivided into the following conditions:

- Figure 10a - CO₂ + MQL – Holes 1 – 16: 270 RPM, feed rate = 0.051 mm/rev
- Figure 10b - CO₂ + MQL – Holes 17 - 20: 270 RPM, feed rate = 0.076 mm/rev
- Figure 10c - CO₂ + MQL – Holes 21 - 30: 400 RPM, feed rate = 0.076 mm/rev

Figure 10a – Hole diameter variation for holes 1-16 drilled with 15.5 mm (0.6100 in.) drill with CO₂ and MQL (Micro Cut) – Test #4.
Figure 10b – Hole diameter variation for holes 17-20 drilled with 15.5 mm (0.6100 in.) drill with CO$_2$ and MQL (Micro Cut) – Test #4.

Figure 10c – Hole diameter variation for holes 21-30 drilled with 15.5 mm (0.6100 in.) drill with CO$_2$ and MQL (Micro Cut) – Test #4. Note that there was an operational artifact that occurred for hole #24. During the drilling of this hole, the drill was accidently stopped, and then restarted, resulting in the data deviation shown.
3.2.2 Statistical Analysis of Hole Diameter Data

To help evaluate the relative importance of these data, statistics on these data for each test parameter is presented below. Table 3 shows the basic statistics of the data collected.

Table 3 – Statistics on Hole Diameter Data Collected on CO₂/MQL Data Set

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Stat</th>
<th>Ti-0 max</th>
<th>Ti-0 min</th>
<th>Ti-90 max</th>
<th>Ti-90 min</th>
<th>Ti - All</th>
<th>CF-0 max</th>
<th>CF-0 min</th>
<th>CF-90 max</th>
<th>CF-90 min</th>
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<tr>
<td>CO₂ N1</td>
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<td>15.54</td>
<td>15.52</td>
<td>15.54</td>
<td>15.52</td>
<td>15.53</td>
<td>15.48</td>
<td>15.47</td>
<td>15.48</td>
<td>15.47</td>
<td>15.47</td>
</tr>
<tr>
<td></td>
<td>StDev</td>
<td>0.006</td>
<td>0.004</td>
<td>0.007</td>
<td>0.005</td>
<td>0.012</td>
<td>0.003</td>
<td>0.003</td>
<td>0.004</td>
<td>0.004</td>
<td>0.005</td>
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<tr>
<td>CO₂ N2</td>
<td>Mean</td>
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<td>15.53</td>
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<tr>
<td></td>
<td>StDev</td>
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<td>0.014</td>
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<td>0.019</td>
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<td>Mean</td>
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<td>StDev</td>
<td>0.003</td>
<td>0.004</td>
<td>0.002</td>
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<td>0.007</td>
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<td></td>
<td>StDev</td>
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<td>0.021</td>
<td>0.011</td>
<td>0.002</td>
<td>0.002</td>
<td>0.012</td>
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</tbody>
</table>

An examination of Figures 8, 10, and 10c show the effects of experimental artifacts in the hole diameter data. These experimental artifacts which were generated by errors in the experimental methodology, bias the statistics presented in Table 3. To better see the process implications of this study, the following hole diameter data were removed from the modified statistical data set presented in Table 4:

- Hole #8 CO₂ N2
- Hole #24 from CO₂ + MQL

Table 4 presents the statistical data excluding these data points.
Table 4 – Statistics on Hole Diameter Data Collected on CO₂/MQL Data Set – Experimental Artifacts Removed from Data Analysis

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Stat</th>
<th>Test Parameter</th>
<th>Ti-0 max</th>
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<th>Ti-90 min</th>
<th>Ti - All</th>
<th>CF-0 max</th>
<th>CF-0 min</th>
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<td>Mean</td>
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<td>StDev</td>
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<td>StDev</td>
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<td>0.007*</td>
<td>0.006*</td>
<td>0.004*</td>
<td>0.012*</td>
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<tr>
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<td>StDev</td>
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<td>0.002</td>
<td>0.007</td>
<td>0.005</td>
<td>0.003</td>
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<td>CO₂+MQL</td>
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<td>15.51</td>
<td>15.50</td>
<td>15.51</td>
<td>15.48*</td>
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<td>StDev</td>
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</table>

* Statistics exclude data excursion due to experimental artifact

3.2.3 Experimental Observations

During the testing described herein, the following observations were made.

1. The surface finish of Ti was evaluated qualitatively and showed that CO₂ and CO₂+MQL produce a better surface finish on the Ti compared to MQL alone.
2. Examination of the CFRP-Ti interface showed no sign of interlayer abruption or smearing.
3. CO₂ creates a fluffier chip and is better at breaking the chips than MQL, which results in less eroding damage to the CFRP layer and therefore creates a tighter hole.
4. These tests were done as a preliminary assessment of the technology. Therefore standard tooling was utilized. It is expected that tooling optimized for CO₂ cooling (tooling geometry, coating, inserts (PCD tip) can have a great impact on drilling performance.

3.2.4 Analysis of Results

Based on the data presented in Figures 7 – 11 and in Tables 2, 3 & 4, the following observations are presented:

1. The use of CO₂ or CO₂ + MQL as a coolant for CFRP-Ti stackup drilling significantly reduces the temperature in the cut zone when compared to MQL alone, as shown in Table 2.
   a. The average tool piece temperature for the two CO₂ only tests was 10°C,
   b. The weighted average of CO₂ + MQL was 16°C,
   c. The temperature of MQL cooled tooling was 60°C.
2. Hole diameter data for both CO₂ only runs, Figures 7 and 10, exceeded the hole tolerance specification. However the CO₂ + MQL met the tolerance requirements for this application.
3. The diameter of the CFRP hole is marginally smaller when using CO₂ alone 15.47mm – 15.48 mm (0.6092, 0.6095”) and CO₂+MQL 15.48 mm (0.6095”) than MQL 15.50 mm (0.6103”) alone, which is likely due to the cooler drill temperatures measured with the CO₂ only and CO₂+MQL test case.

4. The diameter if the Ti holes for all tests are roughly the same; ranging from 15.51 to 15.53 mm for all tests.

5. Increases if drilling feed and speed in Test #4, as shown in Figure 10, 10a, 10b and 10c did not significantly impact the quality of the hole drilled. Thus it is possible to decrease the time required to drill 1 hole by 2x while maintaining hole quality tolerance and tool life.

6. Burr height data collected in Test #4 CO₂+MQL showed tolerance exceedances at the higher feeds and speeds, beyond Hole #17.

4. SUMMARY

Based on data published originally in Reference 1, CO₂ coolant is able to provide productivity increases of 30% or more when compared to conventional coolants in drilling CFRP-Ti stackup and composite milling. This processing time reduction, coupled with increased tool life of 10% or higher, improved surface finish by up to 2x and a dry work environment.

Based on the results of a comparison of MQL drilling vs. MQL+CO₂ and CO₂ alone, the addition of CO₂ coolant does not alter the average hole diameter in the Ti layer. However the addition of CO₂ cooling generally results in a slightly small hole diameter in the CFRP material. Furthermore, CO₂+MQL is expected to increase productivity by 2X without creating observed delamination issues within the CFRP layer.

5. REFERENCES


