

Dry Drilling of Stackup Composite: Benefits of CO₂ Cooling

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ABSTRACT

The use of composite materials and composite stackups (CO-Ti or CO-Al) 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 CFRP and titanium 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 CO₂ through tool cooling, it is possible to protect both layers. Through work supported by the National Science Foundation (NSF) and Department of Energy (DOE) it is shown that CO₂ through tool cooling productivity can be significantly increased while maintaining required hole tolerances in both the composite and Ti layers. Improvements in tool life have been demonstrated when compared to either emulsion or dry drilling. By providing dry CO₂ cooling through the tip of the drill, resin binders in the CFRP don't soften, and cool Ti chips don't degrade the composite at either exit or mid-levels. The summary of this paper is that when drilling stackups of composite material, oil-free, CO₂ through tool cooling provides significant benefits over other types of cooling or lubrication.

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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. Carbon dioxide (CO₂) cooling has the ability to significantly reduce the heat in the cut zone, while maintaining a dry machining environment. This paper will explain the numerous benefits of using CO₂ cooling systems both externally and through the tooling for milling composites and 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].

BACKGROUND

The automotive and aerospace industries use Carbon Fiber Reinforced Plastic (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 Titanium (Ti), are called a stackup.

The use of composite materials for applications demanding strength, flexibility, elimination of corrosion, at minimal weight is well documented. Using composites rather than aluminum in aircraft structures saves weight on the order of 20%. This weight reduction is combined with the ability to achieve aerodynamically more advantageous shapes through precision molding, resulting in better payload fractions and reduced fuel requirements. For the Boeing aircraft line, 777 consists of 11% composite by weight, while the 787 Dreamliner contains more than 50% composite by weight and about 80% by volume. The Bell/Boeing V-22 Osprey uses composites for the rotor blades, the rotor hubs, the wings, the interconnect drive shafting, the nacelle structure, the fuselage and empennage, except for the fuselage frames. Carbon fiber manufacturing is also used in Formula 1 racers, high-end bicycles, and the Bugatti Veyron sports car. To keep its edge as a producer of high performance vehicles, BMW uses carbon fiber technology for the passenger frame of the i3 electric car, which went on sale last fall [4].

All of these factors combined explain the ever increasing popularity of composite materials in many high performance applications. This is in spite of their significantly higher raw

material costs and relatively involved processing - frequently requiring expensive autoclaves or other pressure and heat producing devices to compact and cure the materials.

A key machining/drilling challenge for CFRP applications is that traditional liquid coolants, particularly petroleum-based coolants, should not be used for cooling during machining operations. For this reason, nearly all composite manufacturing operations are performed completely dry. Since CO₂ cooling is a dry process, it is a perfect solution for heat buildup in this difficult, expensive and time consuming operation of composite stackup machining.

Drilling of CFRP

One of the major challenges of using CFRP or CFRP layered with Titanium (CFRP-Ti) is drilling holes in this stackup material for bolts or rivets to secure the CFRP-Ti panels in place. The carbon fibers in the CFRP-Ti are very abrasive to drill, plus significant heat is created in the drilling process which damages the resin binders of the composite material. The addition of a Ti layer introduces an even more damaging chip which can erode the corners and inner diameter (ID) of the drilled hole and therefore create a sloppy fit between the panel and fastener. One of the most commonly used and most difficult to drill stackups is CFRP-Ti where a layer of CFRP is either glued or fastened to a Ti panel. This stackup is most commonly used for the fuselage of aircraft. Thousands of holes which are typically 0.64 cm diameter need to be drilled through the stackup in order to fasten the panels to the frame of the aircraft.

End Milling of CFRP

The manufacturing process of an aircraft wing involves starting with oversized sheets of CFRP that have been formed into the approximate size and shape required. An overhead gantry mounted CNC milling spindle is then often used to trim the sheet to the finished dimensions. The dust-like chips created in this machining operation are very abrasive and there is a large amount of heat generated. The heat generated in the milling process, just like in drilling, can soften the binders in the resin which holds the layers of carbon fiber fabric together. This softening can lead to the layers delaminating and eventually failing.

CO₂ Cooling Technology

The CO₂ based Environmentally Friendly Coolant System (EFCS) used for these tests delivers a cooling fluid consisting of CO₂ ice crystals, CO₂ gas, and in some cases air, directly to the cut zone where cooling is required (See [Figure 1](#)). The

solid CO₂ crystals, which are formed from the expansion of Liquid CO₂, sublime and flash to CO₂ gas. This conversion is capable of absorbing significant amounts of heat, approximately 127-207 kJ/kg. This spray system provides variable spray pressures, fluid lubricities and compositions using a unique liquid-solid-gas spray. The EFCS will deliver solid crystals 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. The end result is:

- Solid dry ice (CO₂) crystals blasted into the heat zone to deliver significant cooling.
- Solid crystals have mass that can be forced through vapor barriers and heat zones.
- Cutting tool stays cool from the solid CO₂, keeping the cutting edge sharper to extend tool life significantly greater than conventional processes.
- CO₂ EFCS process is dry and can be used on materials that cannot use conventional liquid flood coolant, such as composites.

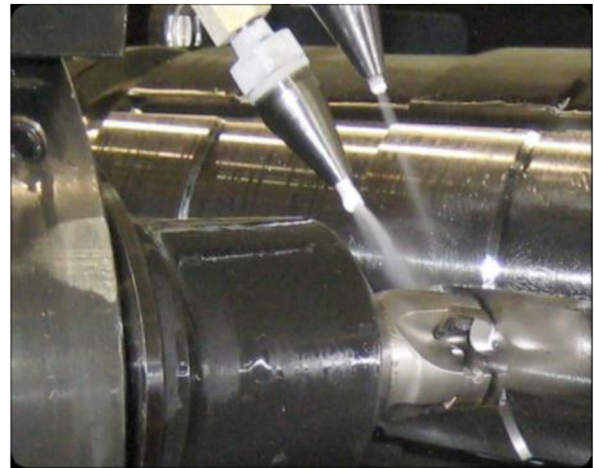


Figure 1. CO₂ Cooling Spray - External.

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 CO₂ coolant, shown in [Figure 2](#).



Figure 2. EFCS used for these tests.

The EFCS system is capable of delivering CO₂ coolant to the tool-work piece interface in two methods. The first method, shown in Figure 3, is used for drilling and delivers CO₂ coolant through coolant ports in the tool. The second method, which delivers CO₂ through an external nozzle, is used for milling.



Figure 3. Through-Tool CO₂ Cooling.

Through-Tool CO₂ Coolant

EFCS through tool cooling uses both gas and liquid CO₂. Both phases are delivered through a single coaxial hose from the EFCS to the rotary coupling of the machine tool. The gas and liquid CO₂ then mix while flowing through the coupling, spindle,

tool holder and tool. A controlled pressure of 41 Bar is maintained within these components and keeps all of them at a cool ambient temperature. When the liquid CO₂ exits the coolant ports of the tooling (drill bit in this case), the liquid expands, resulting in the generation of solid CO₂ crystals and gas at -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. CO₂ 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.

External CO₂ Coolant Spray Applicator

EFCS external spray applicator nozzles, as shown in Figure 1, use liquid CO₂ and compressed clean dry air (CDA). A coaxial hose comprised of a capillary tube inside a relatively larger diameter air hose delivers both liquid CO₂ and CDA to a Coanda nozzle. Sub-cooled liquid CO₂ at a pressure of approximately ranging from 41 to 62 Bar enters the capillary tube at the EFCS and drops in pressure down to ambient along the length of the tube. This pressure drop causes a phase change from liquid, to liquid and gas, to solid and gas, which forms CO₂ cooling spray. As the solids exit the nozzle tip, they are accelerated by the nozzle air, which delivers the cooling spray to the cut zone. These solid crystals of CO₂ have controllable mass and therefore momentum, which gives CO₂ coolant the ability to provide cooling directly to the tooling-work piece interface with a capability beyond that of liquid coolants. The amount of cooling is controlled by the amount of CO₂ delivered to the nozzle. Because the spray applicator nozzle delivers the cooling spray on a 'line-of-sight', it is necessary to optimize the position of the nozzle relative to the tooling. Once this has been accomplished, the superior heat capacity of the CO₂ coolant is capable of removing significantly more heat from the tooling and work piece than liquid coolants when milling CFRP.

Composite Stackup Drilling

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).