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Effect of Tool Geometry and LCO_2 Cooling on Cutting Forces and Delamination when Drilling CFRP Composites Using PCD Tools

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Abstract

Lightweight materials like Carbon Fiber Reinforced Polymers (CFRPs) present certain challenges, mainly regarding the resultant surface integrity of the holes. Different techniques such as optimized tool geometries, machining techniques and cooling/lubricating techniques have been tested for improving surface integrity on CFRPs. Unfortunately using coolants presents certain challenges when machining CFRPs, as the moisture absorption can degrade the mechanical properties of the composite, on top of the environmental and health hazards created by water and oil based metalworking fluids. Therefore, this study aims to evaluate the influence of environmentally friendly liquid carbon dioxide (LCO_2) based cooling/lubricating conditions and Polycrystalline Diamond (PCD) drill bit geometries (point angle) on the delamination when drilling CFRP composites. The results showed significant influence of the tool geometry and cooling condition on the surface integrity of CFRPs, especially in the case of the former.

Keywords: LCO_2 cooling; Drilling; Composite; Sustainable machining; Surface integrity

1. Introduction

One of the driving forces for materials development in aeronautics is weight reduction. When take-off weight of the aircraft is reduced the amount of fuel burned decreases, resulting in economic benefits associated with lightweight design [1]. In addition to the cost savings, the use of high-performance lightweight materials has been in an upward trend promoted by the 75% carbon dioxide (CO_2) and 90% nitrogen oxide (NO_x) reduction relative to year 2000, specified in the research goals for 2050 by the Advisory Council of Aeronautical Research in Europe [2]. Therefore, Carbon Fibre Reinforced Polymers (CFRPs) are gaining interest for structural applications such as the fuselage and wing panels [3].

This material however, presents several machinability and surface integrity problems. For instance, the reinforcement fibres of the composite materials generate edge rounding due to their abrasive nature [4]. Polycrystalline Diamond (PCD) tools are often employed to machine composite materials, as the hardness of the tool material withstands the abrasive nature of the fibres better than carbide tools [5].

Regarding the surface integrity problems arising when machining CFRPs, fibre pull-out and delamination are the most common forms of damage. The appearance of these defects can substantially lower the strength of the components and microcracks can appear due to fatigue [3].

Fibre pull-out happens when bundles of reinforcement fibres are pulled away from the matrix. The missing fibres generate voids in the machined surface, which can be the origin of fatigue cracking and failure of CFRP structures [6]. Delamination on the other hand, is the debonding of adjacent plies. It can appear at the entry plane (peel-up delamination), at the exit plane (push-out delamination) and even in the inside the laminate [7].

Delamination could be considered the most critical surface integrity defect that can appear when drilling composites. Even

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though this type of defect represents only 6% of the total damages associated with the drilling process, compared with 27% for oval holes, repairing the delaminated area takes 5 to 6 h per hole versus 10 to 15 min for an oval hole [8].

Several studies agree on the almost linear correlation between the extent of delamination and thrust force [4], [9]–[12], therefore the techniques employed up to date to improve surface integrity when drilling composites mainly focus on the reduction of thrust force.

These techniques concentrate on optimising the tool geometry, employing advanced machining methods (e.g. vibratory assisted machining, orbital milling), or employing advanced cooling/lubricating techniques such as High Pressure Jet Assisted Machining (HPJAM), or Minimum Quantity Lubrication (MQL).

Among the use of advanced cooling techniques there are additional challenges, regarding the environmental and health hazards that conventional oil and water based Metalworking Fluids (MWFs) create [13], and the potential degradation of the mechanical properties of the laminate due to moisture absorption from the MWF [14]. For this reason, cooling alternatives with lower environmental and health impact are being under research.

The use of sub-zero liquified gases such as liquid nitrogen (LN_2) has proven to cool down the cutting zone without polluting the working area. Several studies have been carried out using LN_2 as a coolant for machining different hard-to-cut materials. Regarding the drilling of CFRPs, Xia et al. [15] proved an improvement of the surface integrity of the drilled hole, at the expense of increasing the delamination due to an increase of cutting forces.

Liquid carbon dioxide (LCO_2) is another liquified gas that can help to cool down the cutting zone without providing the excessive cooling that LN_2 creates. In addition to this, LCO_2 can be combined with lubricant media such as oils, since it can be stored in liquid phase at room temperature. Therefore lubricated LCO_2 can be supplied through a single channel [16]. Rodriguez et al. [17] reported an improvement on hole accuracy, tool wear and a reduction in burr height of the titanium phase when drilling CFRP/Ti-6Al-4V stacks with through the tool LCO_2 cooling. Nevertheless, the studies which employ LCO_2 based cooling/lubricating techniques for drilling aeronautical CFRPs are scarce.

This research work aims to improve the surface integrity of drilled CFRP holes, by employing the optimal PCD tool geometry, and using environmentally friendly cooling/lubricating techniques based in LCO_2. For that purpose, the optimal cutting tool geometry and cooling condition will be investigated, according to the lowest delamination.

For analysing the influence of the tool geometry and cooling conditions on the resultant surface integrity of CFRP holes, drills with different point angles (σ) were tested under dry, LCO_2 and LCO_2 + MQL assisted cooling/lubricating environments (Fig. 1).

2. Experimental procedure, tools, and materials

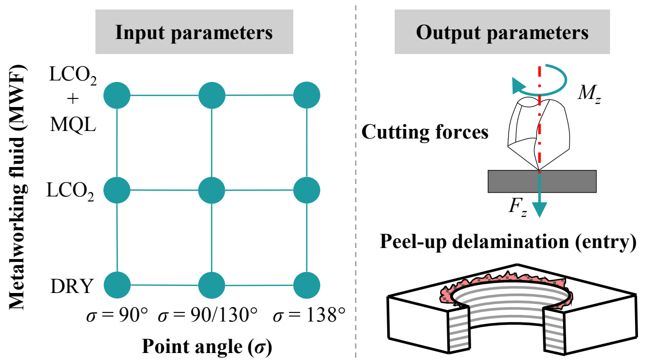

Fig. 1: Input and output parameters analysed in the experimental plan

Three PCD drill bit geometries with different point angles (σ) and a diameter of 10 mm were employed. The cutting edge radius (r_c), wedge angle (β), rake angle (γ), and relief angle (α) of the tools was measured using an Alicona Infinite Focus 3D optical microscope. The average value of three measurements in each cutting edge was obtained. In the case of the double point angle (σ = 90°/130°) drill bit, the double cutting edges were characterized, like Fig. 2 depicts.

In Table 1 the r_c and β geometrical parameters of the cutting edges of different drill bits can be compared. The effect of the cutting edge radius on the delamination can be assumed negligible, as all the tools have very similar cutting edge geometries.

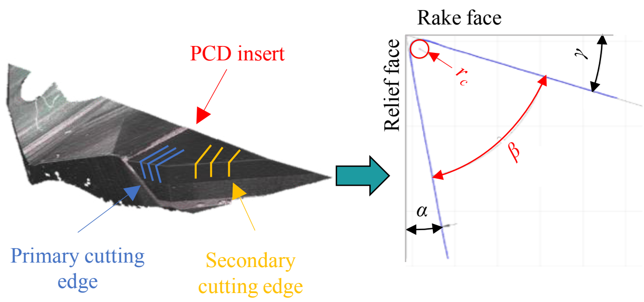

Fig. 2: PCD cutting edge characterization using Alicona Infinite Focus 3D optical microscope

Table 1: Cutting edge characterization of different PCD drills

Drill bit		σ [°]	Cutting edge radius	
			r_c [µm]	β [°]
PCD_90		90	10.7 ± 0.3	74 ± 1.3
PCD_Doub		90/130	10.7 ± 0.7	68.4 ± 2.4
PCD_138		138	11.9 ± 0.6	70.7 ± 2.2

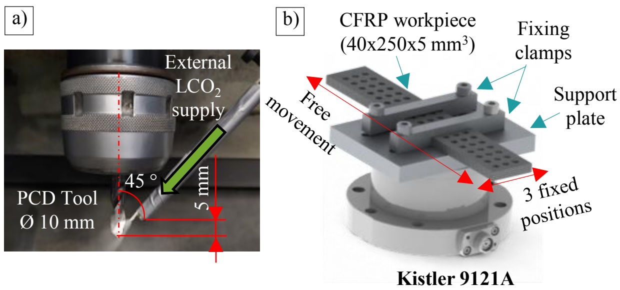

Fig. 3: Experimental set-up: a) External delivery of LCO_2 based coolants; b) Fixture designed for the Kistler 9121A dynamometer

The tests were carried out in a Mori Seiki Frontier M1 machining centre. Coolant was supplied externally using a nozzle with an internal diameter of 0.8 mm, as seen in Fig. 3a. The LCO_2 and MQL were supplied through a single channel using the Arclub One LCO_2 system [18], which ensured a flow rate of 0.2 kg/min for LCO_2 and 40 mL/h for MQL.

The external nozzle was positioned as close and as perpendicular to the workpiece plane as possible, in order to maximize heat evacuation [16]. Therefore, the vertical distance from the nozzle to the tool tip was 5 mm, while the projection angle was 45º (Fig. 3a).

The cutting forces were acquired with a Kistler 9121A dynamometer at 1 kHz sampling frequency, and the noise was eliminated using a Savitzky Golay filter. A special fixture for clamping the CFRP workpiece to the dynamometer was fabricated. It allowed to have three drilling positions in the transversal direction and free movement for adjusting in the longitudinal direction (Fig. 3b).

The cutting conditions were selected following the recommendations of the tool makers [19]. A cutting speed of $V_c = 200$ m/min and a feed rate of $f_z = 0.1$ mm/rev were selected, as moderate to high cutting speeds and low feed rates are usually recommended for machining composites with low delamination damage.

The CFRP machined is an aeronautical graded material. Each plate had a thickness of 5 mm, and were fabricated in a Resin Transfer Moulding (RTM) press using 20 layers of reinforcement per plate. The mechanical properties of the material are summed in Table 2.

Table 2: Properties of the aeronautical grade CFRP used in the experiments

Reinforcement fibres	Reference	Sigratex CW205 TW2/2
	Areal weight (g/m^2)	205
	Tensile strength (MPa)	2400
	Tensile Modulus (GPa)	300
	Strain (%)	1.7
	Density (g/cm^3)	1.8
Epoxy matrix	Reference	Hexcel Hexflow RTM 6-2
	Tensile strength (MPa)	75
	Tensile Modulus (GPa)	2.9
	Strain (%)	3.4
	Density (g/cm^3)	1.14

In order to evaluate the surface integrity of the drilled workpieces, the drilling induced delamination was measured as it is considered the most important form damage when drilling composites [8].

For quantifying the effect that delamination has on the integrity of a workpieces, different evaluation factors have been proposed in diverse research studies [4]. The adjusted delamination factor (F_{da}) proposed by Davim et al. [20] was selected for the analysis performed in the present study. Such delamination factor (Eq. 1) takes into account the contribution of areal damage and thin cracks on the delamination, as shown in Fig. 4.

$$F_{da} = F_d + \frac{A_{delam}(F_d^2 - F_d)}{A_{MAX} - A_{NOM}} \tag{1}$$

Where the delamination factor (F_d) is calculated as expressed in Eq. 2:

$$F_d = \frac{D_{MAX}}{D_{NOM}} \tag{2}$$

The delaminated areas were observed with a Keyence VHX 6000 digital microscope, using a x100 magnification. Three trials were carried out per testing condition in order to ensure the repeatability of the experiments. After the tests were completed, the cutting edge of the tools was measured again in order to detect any wear using an Alicona Infinite Focus 3D optical microscope with a x10 magnification. No edge rounding caused by the CFRP on the PCD tools was observed, therefore the effect of tool wear on the cutting forces and delamination results was assumed to be negligible.

3. Results and discussion

3.1. Cutting forces

In Fig. 5 the thrust force (F_z) and torque (M_z) results obtained with the different PCD tools and LCO_2 based cooling/lubricating conditions are shown.

As it can be observed in Fig. 5, the effect of varying the point angle of the tool on cutting forces is greater than the one observed when varying the cooling/lubricating condition.

The lowest thrust force values are generated when employing tools with a more acute point angle, as already concluded in other studies of the literature [4], [9]–[12]. On the downside, low point angles reduce the chip thickness (h), which increases the specific cutting force, and in turn the torque generated by the tool.

An explanation of the geometry of the uncut chip thickness for PCD_90 and PCD_138 twist drills is given in Fig. 6. Showing that a smaller chip thickness is generated with the PCD_138 tool compared to the PCD_90 tool. In Fig. 5b, it can be seen that the greatest torque is generated by the tools with acute point angles, namely, the PCD_90 drill bit and the PCD_Doub tool.

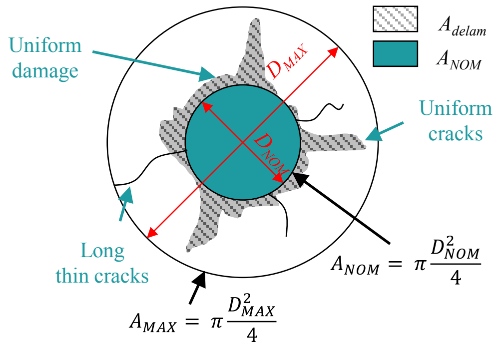

Fig. 4: Explanation of the adjusted delamination factor (F_{da}), adapted from Davim et al. [20]

A rise in the cutting forces can be observed when applying LCO_2 cooling compared to dry cutting. This might be due to an increase in the flow stress of the composite material as a result of the cold temperature of the liquified gas. Adding lubricant media such as MQL oil to the LCO_2 helped to reduce the torque to lower values than the ones obtained in dry cutting, for PCD_Doub and PCD_138 tool geometries. However, the thrust force recorded when using these tools and LCO_2 + MQL cooling/lubrication is similar to the one measured when drilling with just LCO_2, showing that the cooling effect of the liquified gas mainly affects the F_z component of force.

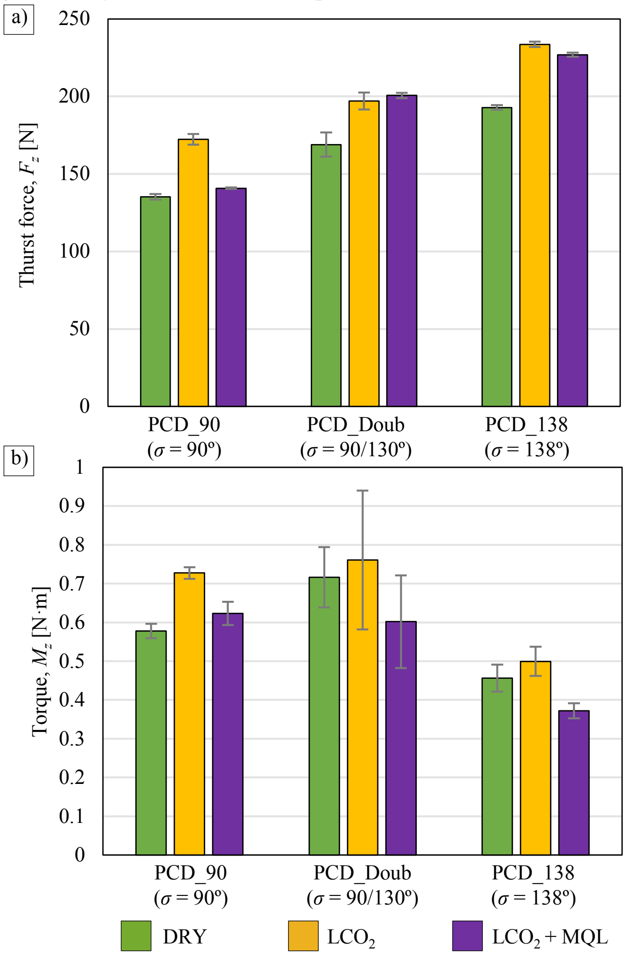

Fig. 5: Effect of tool point angle and cooling condition on cutting forces when drilling CFRP: a) Thrust force; b) Torque

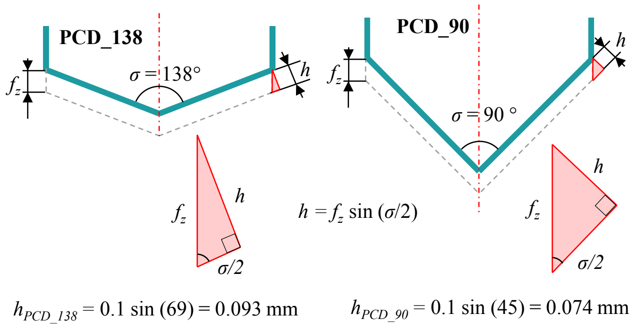

Fig. 6: Explanation of the geometry of the uncut chip thickness depending on the point angle of the tool

3.2. Delamination in CFRP

As the drilled CFRP plates were backed up by the support plate at the exit plane, the push-out delamination generated was not a critical output parameter of the tests. On the other hand, clear differences were observed in the entry or peel-up delamination obtained with the different tool geometries and cooling conditions.

In Fig. 7, the F_{da} calculated at the entry plane of the CFRP laminate with different tool geometries and cooling/lubricating techniques is shown. As it can be observed the lowest peel-up delamination is obtained with the tools that have large point angles at the initial stage of the tool (PCD_Doub and PCD_138). Similar results were obtained by Heisel et al. [21] and Durao et al. [22]. The latter research work compared tools with σ = 85° and σ = 120° and determined that even if tools with a more acute point angle generated the smallest thrust force, the drill bits with a large point angle created the least amount of damage at the entry of the laminate due to a better tool geometry. The study by Grilo et al. [23] also reported that drill bits with low point angles might leave uncut fibres when drilling CFRP, which can increase the delamination.

Regarding the effect of the MWF on peel-up delamination, it can be seen that the increase in cutting forces brought up by the cold temperatures of LCO_2 created greater delaminated areas at the entrance for all the tool geometries. When adding MQL oil to the LCO_2 the peel-up delamination decreases slightly, nevertheless dry cutting is the cooling method that obtains the lowest delamination values for every tool geometry tested.

In Fig. 8 the visual comparison of the peel-up delamination obtained in dry cutting conditions with different tool geometries is shown (delaminated areas are marked in red). Also, the comparison of the delamination produced by the PCD_90 tool in different cooling/lubricating environments is given. As it can be observed, regarding the MWF, the greatest delamination is obtained when employing LCO_2 while the delamination generated under LCO_2 + MQL cooling is slightly higher than the one in dry cutting. On the other hand, peel-up delamination decreases with increasing point angle.

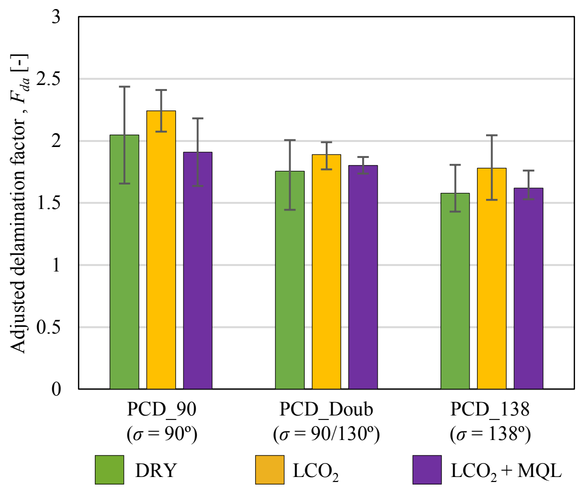

Fig. 7: Effect of tool point angle and cooling condition on peel-up (entry) delamination

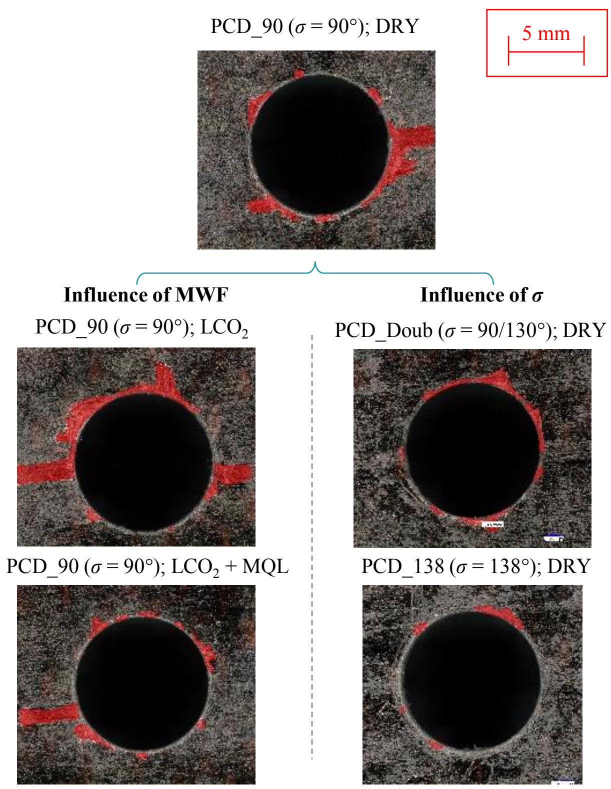

Fig. 8: Visual comparison of the delaminated areas in CFRP using different tool geometries and cooling conditions

These results indicate that, regarding the thrust force (F_z) and entry delamination, dry cutting is the optimal cooling/lubricating technology to improve the surface integrity when drilling CFRP composites. Nevertheless, the reduction in torque (M_z) observed when employing LCO_2 + MQL could indicate an improvement of the morphology of the machined CFRP surface, as proven by Ji et al. [24]. Additionally, Nagaraj et al. [25] showed that the cooling effect of sub-zero liquified gases and MQL helps to improve the dimensional accuracy of the hole compared to dry cutting. Therefore, different surface integrity outputs should be analysed in the future, in order to justify the investment on lubricated LCO_2 cooling technologies for CFRP drilling.

4. Conclusions

This research work analysed the influence of LCO_2 based cooling/lubrication and drill bit geometry, on the surface integrity when drilling CFRP with PCD tools. The main conclusions of the research are:

- Varying the geometrical parameters had a greater effect on the surface integrity of drilled CFRP than changing the cooling condition.
- Lower thrust force values were obtained with lower point angles. On the other hand, as tools with small σ generate smaller chip thickness the specific cutting force raised, which caused an increase in torque.
- From all the tool geometries tested, the PCD_138 tool appeared to be the optimal one to machine CFRPs regarding the peel-up delamination.
- Using LCO_2 cooling generated greater delamination, as the cutting forces increased. Adding MQL helped to mitigate the increase in thrust forces and delamination generated by the cold temperatures of LCO_2. However, the best surface integrity results were obtained with dry cutting.
- Regarding the influence of the coolant on thrust force and peel-up delamination, dry cutting appears to be the most optimal cooling/lubricating technique to drill CFRPs with PCD tools. Nevertheless, the reduction in M_z observed when employing LCO_2 + MQL suggests that machined surfaces with less defects could be obtained with lubricated LCO_2 in comparison to dry cutting.
- Other surface integrity parameters such as the morphology of the machined surface or the dimensional accuracy of the hole should be further analysed in order to justify the use of LCO_2 + MQL cooling/lubricating technique for drilling CFRPs.

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