CRYOGENIC ASSISTANCE DURING CFRP DRILLING

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Abstract

The CFRP cutting mechanisms are highly linked to fibers orientations. Firstly, this paper deals with a mechanical characterization of CFRP under cryogenic temperatures. An instrumented compressive test with fibers oriented at 45° regarding the crushing direction has been conducted ranging from -196°C to 20°C to follow the evolution of the failure stress of the epoxide resin. Secondly, a semi-orthogonal radial turning experiment on unidirectional CFRP (T800M21 UD) disc with and without cryogenic assistance has been performed. As the fibers are oriented perpendicular to the spinning axis, on one turn, the tool cuts all the fibers with angles varying from 0° to 360°. During these specific tests the cutting forces have been monitored to characterize the cutting forces evolution versus fiber orientation. The experiment showed that cryogenic machining increases cutting forces but decreases surface roughness compare to dry machining.

Keywords: CFRP, Cryogenic, Fiber Orientation.

1 Introduction

Nowadays the aircraft industry uses more and more titanium alloy/CFRP stacks instead of aluminium alloy. Titanium and CFRP are well known as difficult-to-cut materials because of the high temperature reached during titanium drilling, leading to carbonization of CFRP matrix. Consequently, cryogenic assistance has been investigated for titanium drilling, but its impact on CFRP cutting performances are not yet established.

The mechanical properties of CFRP under cryogenic temperatures have not been investigated yet. Barker [1] analyzed the temperature dependence of the elastic parameters E and ν of the CFRP. He used multidirectional CFRP for torsion and tensile tests from -80°C to 180°C and it seemed that the temperatures under 120°C do not affect elastic properties.

The fiber orientation was defined by McKenzie [2] for wood cutting process but it can be applied to CFRP as well. He described two angle χ_1 and χ_2 between the fiber direction the tool cutting edge and the cutting direction respectively as shown in figure 1. In orthogonal configuration χ_1 is always equal to 90°.

According to Wang [3], the cutting mechanisms of CFRP involve different failure modes and varying finished surfaces depending on the fiber orientation. Recently Henerichs [4] showed the link between the fiber orientation and the cutting forces values. Indeed, he has proved that there is specific fiber orientation such as χ_2 = 0° for which the cutting forces are the lowest and the surface quality is the best. On the contrary when χ_2 = 90°, the cutting forces are much higher and the finishing surfaces are rougher.

The main default in CFRP drilling is the peel-up and the push-down delamination which are highly linked to the cutting and the feed forces. For Bonnet [5] the increase in the feed rate generates an increase of the cutting and feed forces and as a consequence more delamination.

Few studies have been conducted about cryogenic drilling on CFRP. Barnes [6] compared the surface quality in the drilling operation between dry machining, conventional cutting fluid and cryogenic LN2 cooling. He showed that cryogenic cooling increases the cutting forces and the tool wear. According to Xia [7], the cryogenic drilling on CFRP reduces the tool wear compare to the dry one, even if he showed an increase in the cutting forces with a cryogenic cooling mode.

The influence of fiber orientation with cryogenic assistance has never been investigated yet.

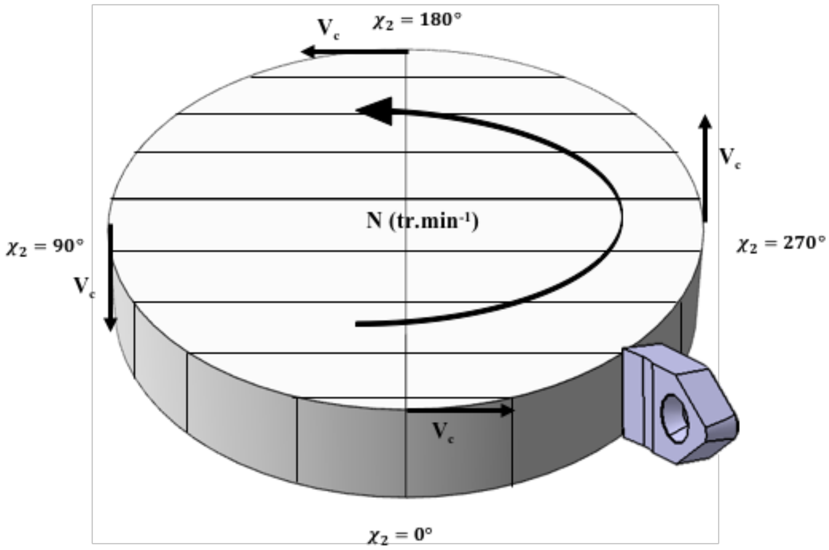

Figure 1: Orthogonal cutting configuration of CFRP UD ($\chi_1 = 90°$).

2 Experimental and methods

2.1 Materials and samples

The tested work material is a unidirectional (UD) CFRP composed of 200 plies of carbon fiber T800 embedded in an epoxy resin matrix M21. This CFRP contains 60% volume fraction of fiber. Its properties are described in Table 1**Erreur ! Nous n'avons pas trouvé la source du renvoi.**.

	CFRP T800 M21	**Fiber T800**	**Epoxy resin M21**
Density (kg.m^{-3})	1550	1820	1100 - 1500
Young modulus in compression (GPa)	145 longitudinal direction 7.8 transversal direction	294	3 - 5
Shear resistance	0.1		
Elongation at rupture (A%)	1.6 % longitudinal direction 1,0 % transversal direction	1.9 %	2 – 5 %

Table 1: Properties of the tested material.

For the compressive tests, 30 cuboid samples were manufactured by water jet cutting and milling sized 14*16*20 mm^3, with fiber oriented at 45° (figure 2.a) towards the crushing direction to apply principally the stress on the epoxy resin matrix which is the most dependent to temperature variation.

For the semi-orthogonal cutting tests, two 150 mm diameter discs were manufactured by water jet cutting and turned to get the final dimension as indicated on figure 2.b.

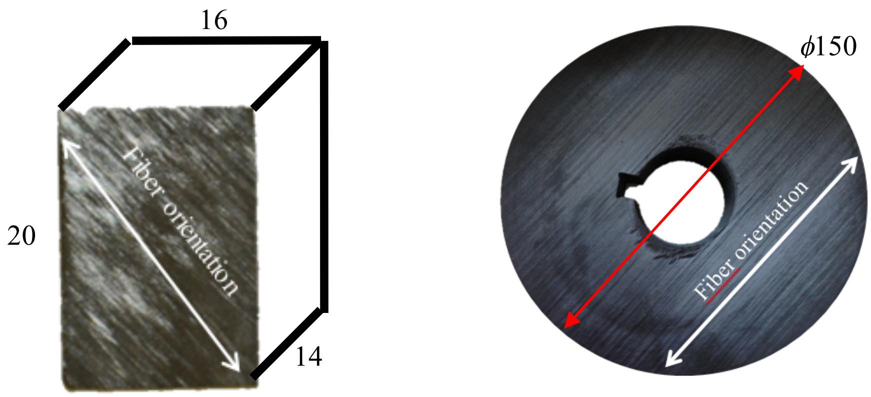

Figure 2: Design of the samples

(a) Compression test and (b) orthogonal cutting test.

2.2 Compressive test set-up

The compressive tests were performed on a tensile/compressive machine INSTRON in with a 100 kN force sensor (figure 3). The velocity was set at 5 mm/min. The sample was placed between two titanium pieces in order to limit the heat conduction. The temperature in the sample and in each piece was measured with a type K thermocouples. The sample and the pieces were located in a container filled with liquid nitrogen was poured into it and tests were performed when was reached the desired temperature. The displacement of the cross-beam was measured by a laser sensor. The load and the displacement of the cross-beam were recorded with a data board acquisition with a 20 Hz acquisition frequency.

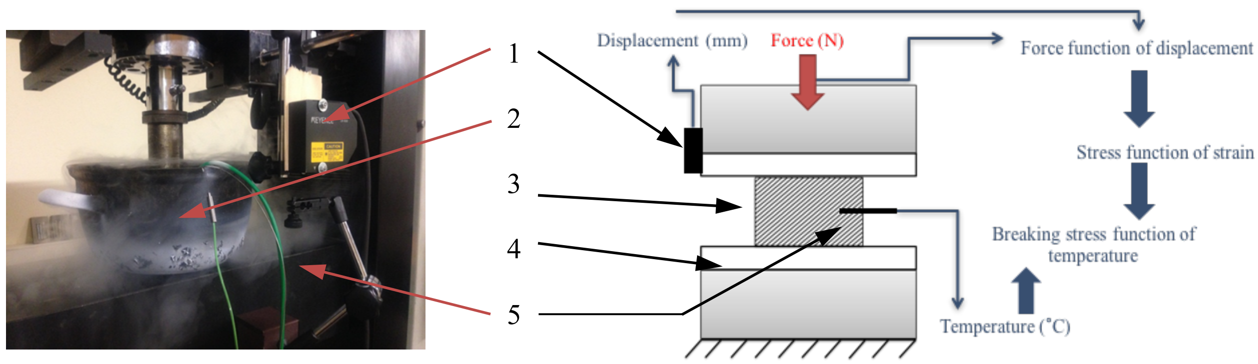

Figure 3: Compression tests set-up with:

1. Laser sensor
2. Container with liquid nitrogen
3. Sample
4. Titanium sheet
5. Thermocouple

The objective of this campaign is to monitor the force as a function of the displacement for each cryogenic temperature and then to analyze the evolution of the mechanical properties according to the temperature.

2.3 Compression test

The Stress/Strain curves have very similar shapes at every temperature, figure 4 shows a short plastic deformation zone.

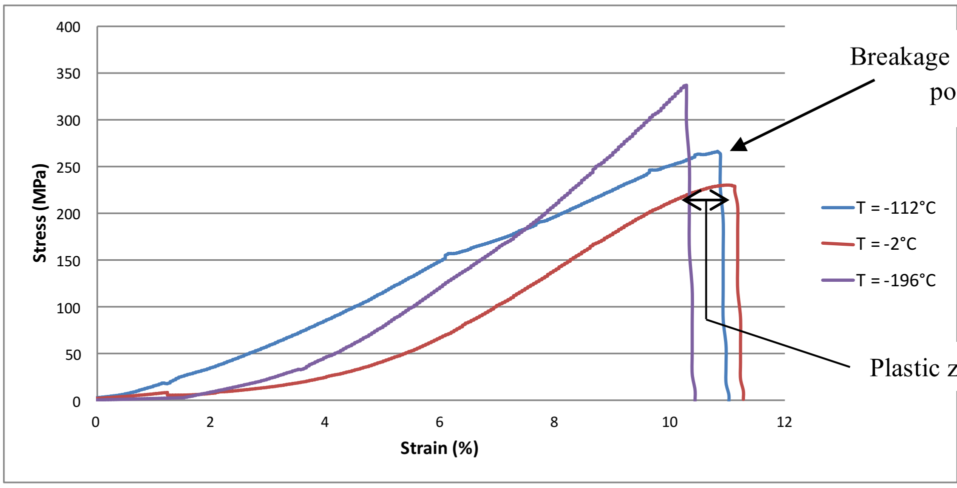

Figure 4: Typical Strain/Stress curve for T = -112°C.

The breakage stress increases as the temperature decreases as indicated on figure 5. At cryogenic temperature, the epoxy matrix is stiffer but also more brittle which may involve higher cutting forces during cryogenic machining processes. Nevertheless, the evolution of the breakage stress according to the temperature is linear which involves no fundamental changes in mechanical properties of CFRP under cryogenic cooling. Thus, this experiment confirms that is possible to use cryogenic assistance for CFRP machining.

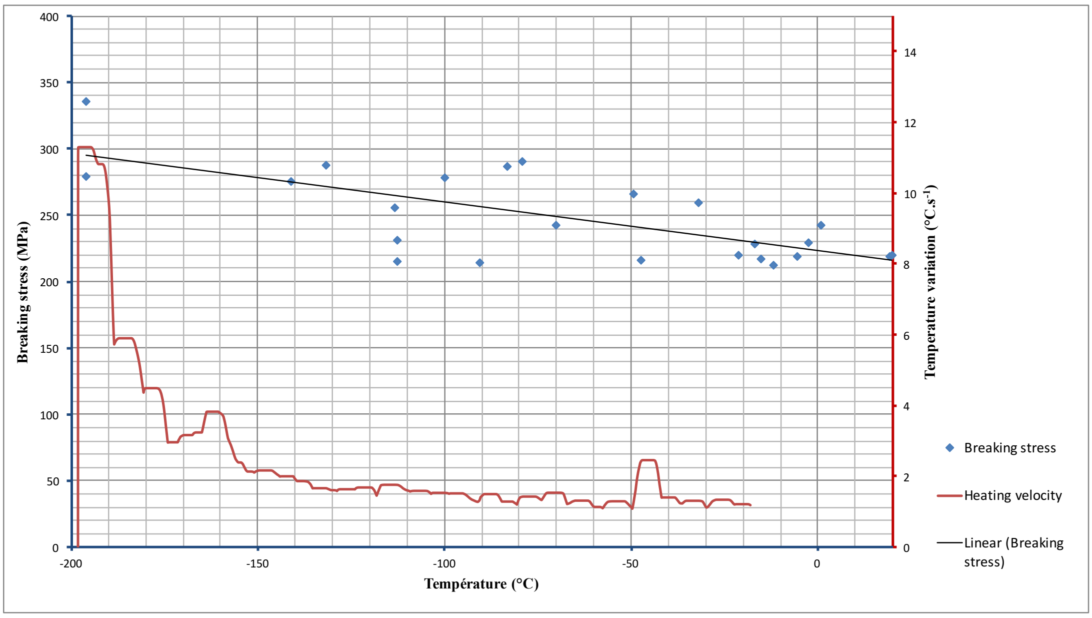

Figure 5: Evolution of the breakage stress with temperature.

2.4 Orthogonal cutting test set-up

This experiment is inspired by the research of Goli [8] and Costes [9] on orthogonal wood cutting and grain orientation analysis.

A 5-axis milling CNC machine was used for the experiments, the workpiece was located into the machine tool spindle which was kept horizontal to the machine table. Cutting forces were monitored and recorded by a Kistler 9257A triaxial piezoelectric dynamometer and a data acquisition board with an 1 kHz acquisition frequency. Three feed rates (0.08, 0.16, 0.24 mm.rev^{-1}) and three cutting speeds (15, 45, 150 m.min^{-1}) were tested. The cutting depth for each test was fixed at 3 mm. All tests were performed under dry and cryogenic machining modes.

In order to limit tool wear, a PCD tool with a 15° rake angle and a 10° clearance angle was used and changed between both modes.

In parallel, a 3D laser profilometer Keyence LJ-V7060 scanned the post-machined surface to analyze its surface roughness.

2.5 Mathematical analysis of cutting forces

For orthogonal cutting, two fundamental cutting forces are defined, the cutting force F_c, which is parallel to the direction of the cutting speed, and the feed force F_f, which is perpendicular to the direction of the cutting speed as shown in Figure **6**.

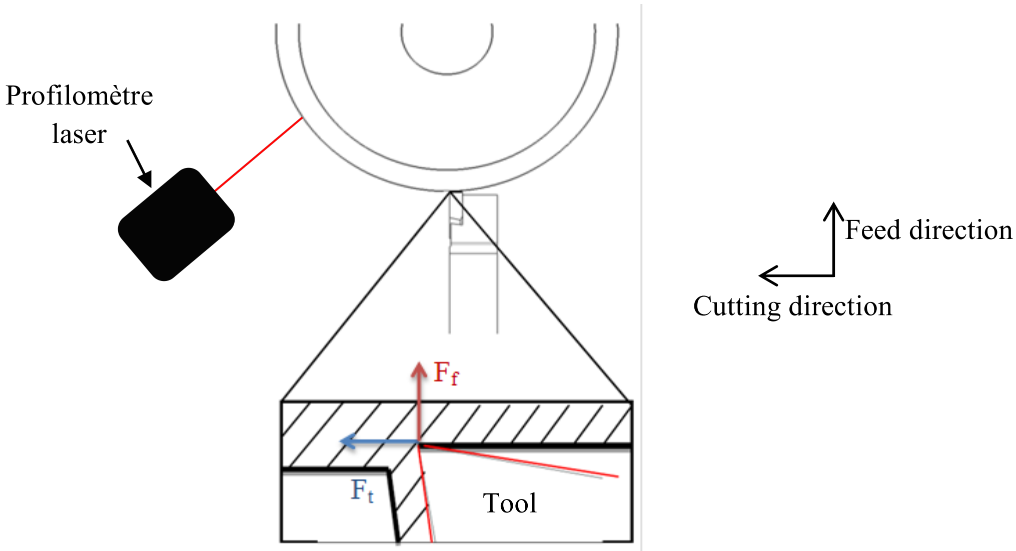

Figure 6: Forces diagram of the tool during orthogonal cutting.

The cutting forces are correlated with h the uncut chip thickness (or feed rate during orthogonal cutting), b the width of the cut and K_c, K_f which are the cutting coefficients used in the equations (1) and (2):

$$F_c = K_c bh \quad (1)$$

$$F_f = K_f bh \quad (2)$$

3 Results and discussions

3.1 Cutting forces analysis

The cutting forces were recorded for all orientations during one revolution of the disc. Thus, the specific coefficients K_c and K_f have been analyzed in order to highlight the special orientations where the maximal or minimal forces take place. As the workpiece is symmetric towards its central axis, all results are equal modulo π.

As shown in Table 2, maximal K_f locations are between 30° and 50° for each cutting parameter whereas the minimum K_f locations are between 140° and 150°. The same has been observed for K_c minimal location which is also close to 150°. For K_c maximal, cutting conditions have an influence on the orientation. For dry machining the location is approximatively 95°. With cryogenic cooled workpiece, the location is around 60° for f equals to 0,08 mm.rev^{-1} but around 75° for other feed rates (Figure **8**).

The evolutions observed on figures 7 and 8 describe also the locations where specific cutting coefficients increase and decrease. Cutting conditions (V_c and f) have also an influence on these orientations. Specific cutting coefficients K_c and K_f start increasing from 0° without dependence on cutting parameters. But they critically fall down close to 100° for a feed rate of 0,08 mm.rev^{-1} and around 85° for higher feed rates.

This difference is due to a brittle fracture of the matrix. This fracture is the consequence of high level of the cutting forces and the impact of the heating generation. The highest feed rates imply higher tangential and feed forces and the orientation determine which component of the CFRP will take the most part of these forces. Thus, for orientation where epoxy matrix takes a large part of the forces, these ones may be higher than the brittle fracture limit of the polymer, following an instant decrease of the forces. Heating generation has also an impact because higher forces imply more heat and so affect more the epoxy matrix structure.

Cutting conditions	**Cutting speed (m.min^{-1})**	**Feed rate (mm.rev^{-1})**	K_{fmax} / χ_2	K_{fmin} / χ_2	K_{cmax} / χ_2	K_{cmin} / χ_2
Dry machining	**15**	0,08	3988 / 32°	-8 / 153°	2238 / 87°	-8 / 153°
		0,16	2129 / 34°	-41 / 151°	1352 / 88°	-13 / 139°
		0,24	1920 / 31°	-32 / 155°	1527 / 91°	12 / 148°
	45	0,08	4720 / 36°	-27 / 148°	2995 / 95°	7 / 152°
		0,16	2802 / 43°	-72 / 156°	2130 / 98°	1 /150°
		0,24	2073 / 33°	-98 / 157°	1534 / 92°	0 /152°
	150	0,08	4168 / 48°	-65 / 150°	2976 / 97°	0 / 154°
		0,16	2492 / 33°	12 / 154°	2059 / 89°	2 / 149°
		0,24	1923 / 41°	-43 / 147°	1448 / 102°	-15 / 153°
Cryogenic cooled workpiece	**15**	0,08	5851 /34°	7 / 132°	3035 / 58°	3 / 152°
		0,16	3706 / 32°	-36 / 158°	2369 / 78°	0 / 151°
		0,24	2587 / 36°	14 / 146°	1869 /72°	4 / 145°
	45	0,08	6298 / 38°	3 / 149°	3569 / 63°	1 / 149°
		0,16	4272 /31°	-76 / 139°	3421 / 77°	0 / 159°
		0,24	2850 / 37°	-37 / 153°	2403 / 73°	-1 / 157°
	150	0,08	5572 / 53°	-25 / 149°	2740 / 57°	0 / 149°
		0,16	4736 / 42°	-31 / 152°	2589 / 81°	4 / 152°
		0,24	2539 / 35°	-54 / 157°	2046 / 67°	-5 / 154°

Table 2: Maximal and minimal specific coefficients (MPa) and their orientations for each cutting parameter.

Cutting speed and feed rate are critical parameters for cutting forces level indicated in Figure **7** and 8, specific cutting coefficients sharply decrease while feed rate increases. Table 2 shows the best cutting parameters are V_c equals to 150 m.min^{-1} and f equals to 0,08 mm.rev^{-1}.

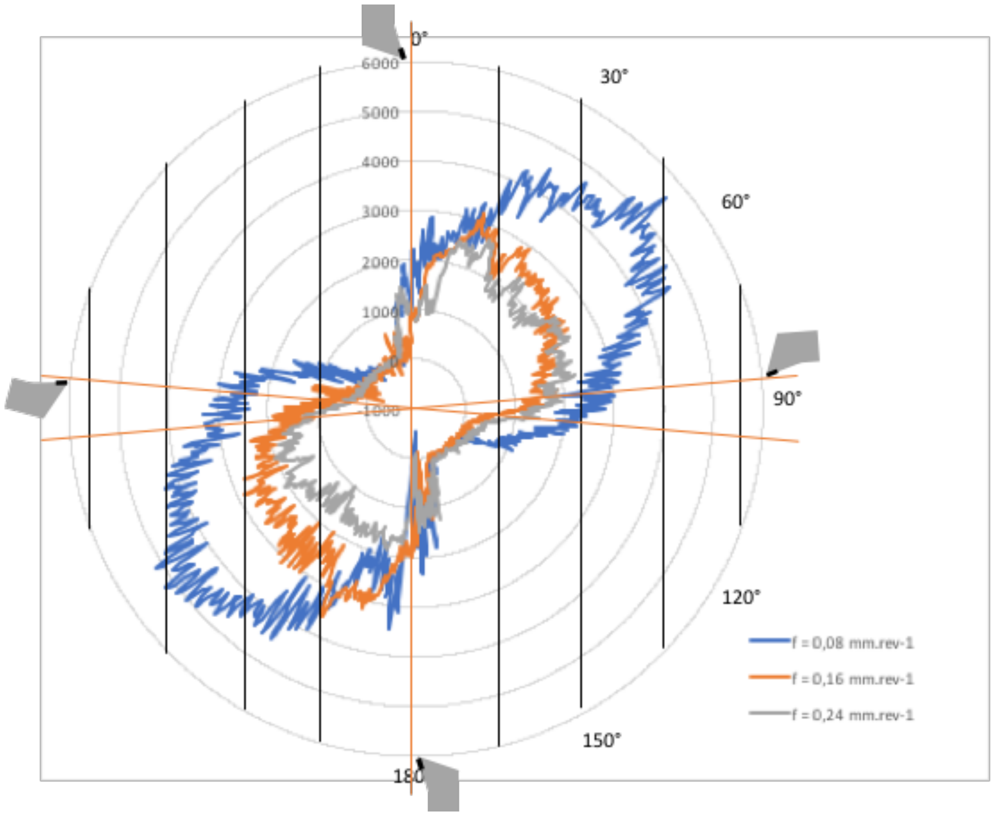

Figure 7: Specific feed coefficient K_f for cryogenic assistance (V_c = 150 m.min^{-1}).

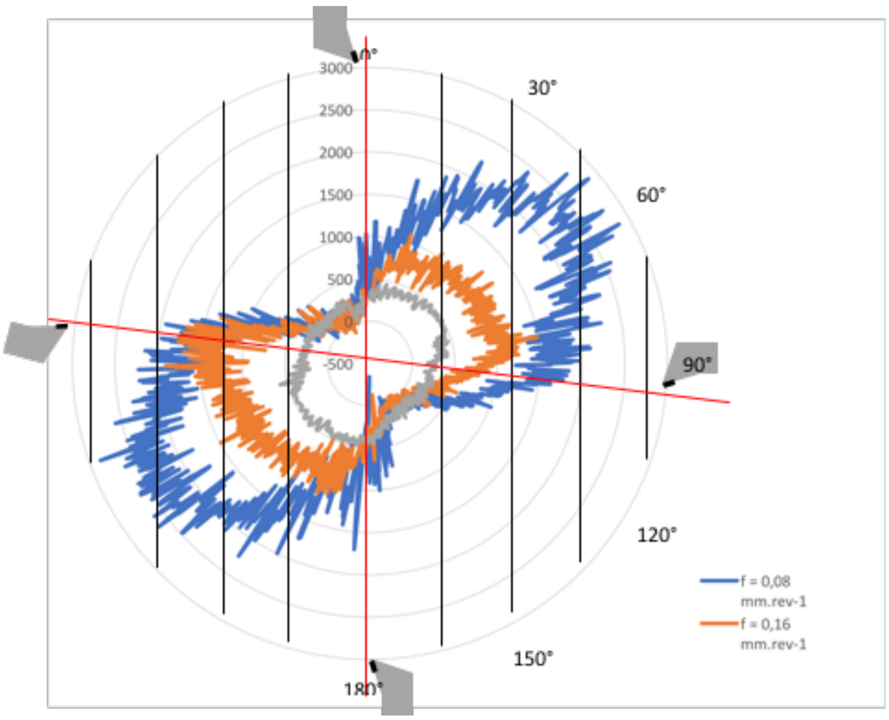

Figure 8: Specific cutting coefficient K_c for cryogenic assistance (V_c = 150 m.min^{-1}).

3.2 Impact of cryogenic assistance on cutting forces

At cryogenic temperatures, the epoxy matrix is stiffer but also more brittle. Therefore, the cutting forces are higher under cryogenic conditions compare to dry machining (figures 9 and 10). For the specific feed coefficient K_f, the brittle fracture of the matrix in cryogenic machining is highly detectable for χ_2 equals to 95° whereas the decrease of K_f is around 120° for dry machining.

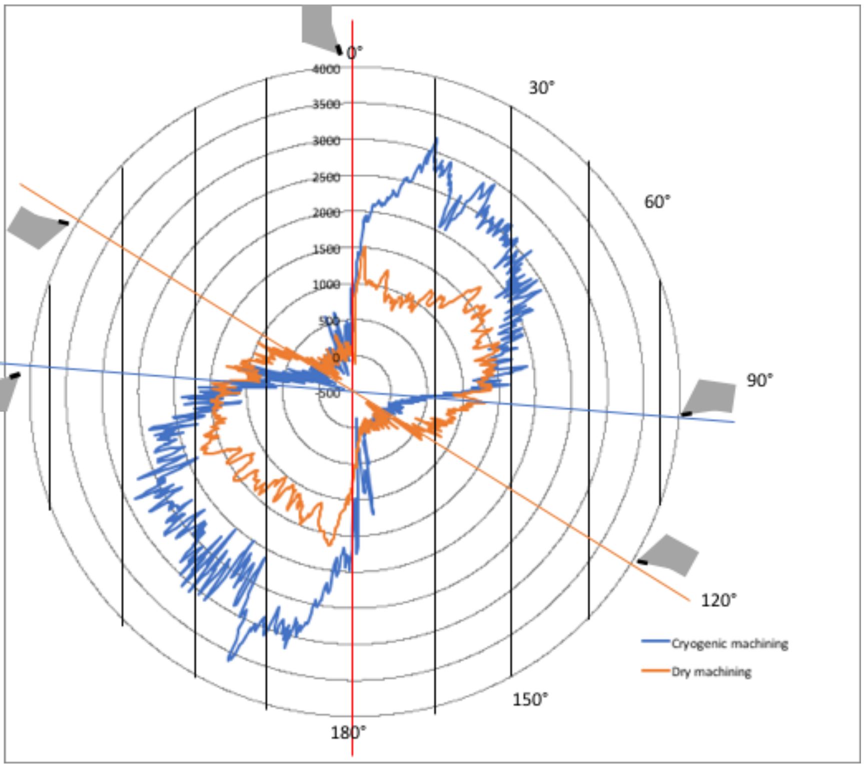

Figure 9: Specific feed coefficient K_f for cryogenic machining and dry one (V_c = 15 m.min^{-1}).

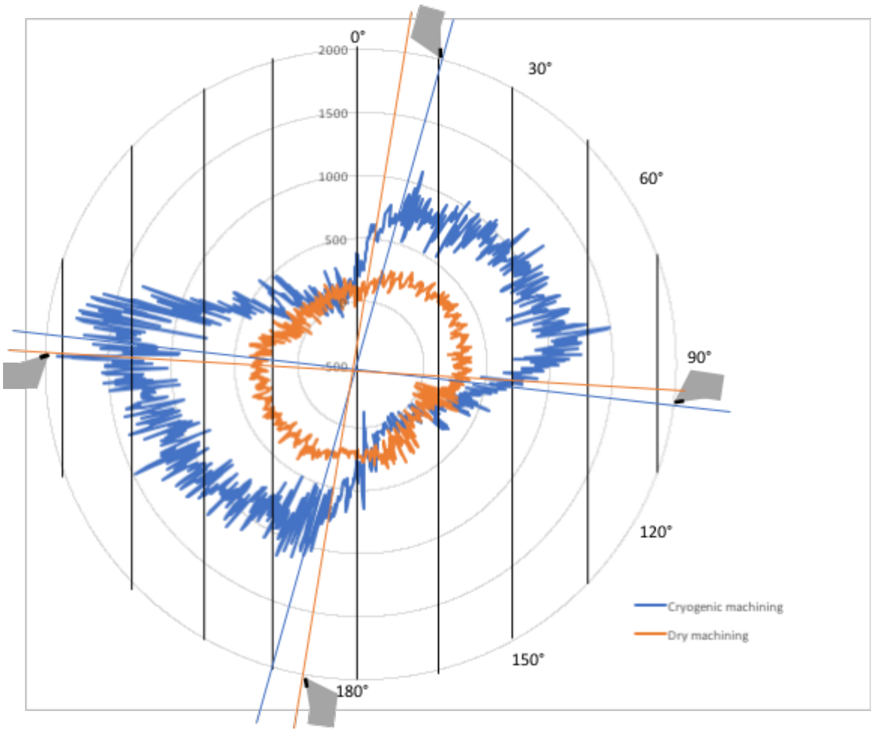

Figure 10: Specific tangential coefficient K_c for cryogenic machining and dry one (V_c = 15 m.min-1).

Not only does cryogenic machining increase cutting forces but also it impacts the matrix integrity. Indeed, the increase in cutting forces implies a brittle fracture of the matrix along the fiber, this fracture led to use the delamination as the effective cutting mechanism and thus reduce the cutting forces from 90° to 180°. On the contrary for dry machining, such level of forces is not reached, the stress is still under the breakage stress of the matrix (seen in paragraph 2.3). Therefore, the cutting mechanism is still in a compressive mode and the forces remain until 120°.

This suppose that cryogenic machining would cause more inter-fiber crack than dry machining.

3.3 Surface analysis

Surface roughness has been measured through a scan analysis. At cryogenic temperatures, the epoxy matrix is stiffer which affects the quality of the machined surface as shown in figure 11.

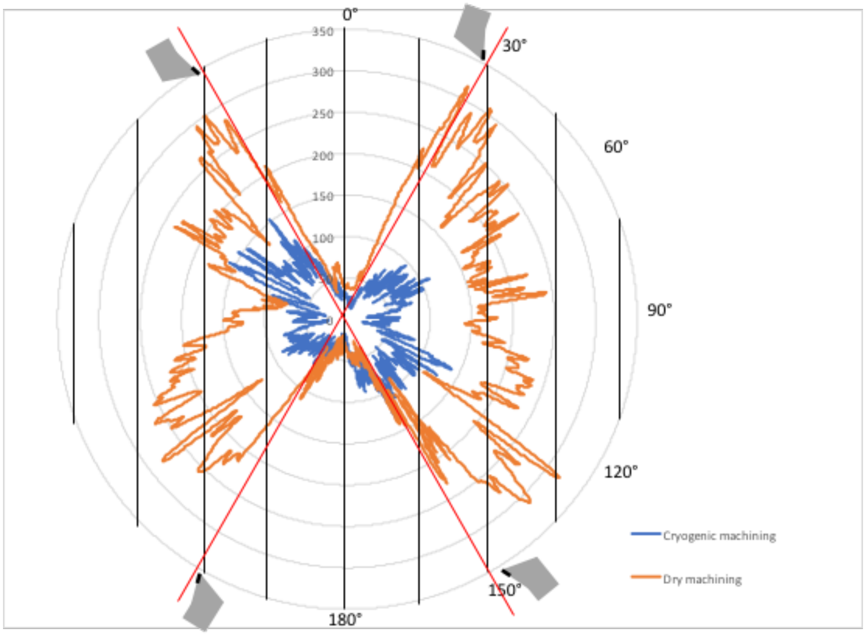

Figure 11: Roughness R_z (µm) towards fiber orientation (V_c = 150 m.min^{-1} and f = 0,08 mm.rev^{-1}).

In dry drilling, high cutting temperatures increase the decomposition of the matrix, resulting in poor support for fibers. This causes fibers to be pulled out and removed. Consequently, poor surface roughness occurs due to cavities. Lower temperatures increase the durability of the matrix and help to maintain the position of fibers and thus better surface roughness can be obtained in cryogenic machining of CFRP.

Figure 12 shows the evolution of the roughness Sa regarding the cutting condition. From this figure, the increase of the feed rate tends to increase the roughness. Cryogenic machining is still the best option, whatever the cutting parameters are, in order to reduce the surface roughness.

Cryogenic machining provides better surface quality, despite the higher level of forces it implies. Therefore, it seems to be a better solution to machine the CFRP without consideration of tool wear.

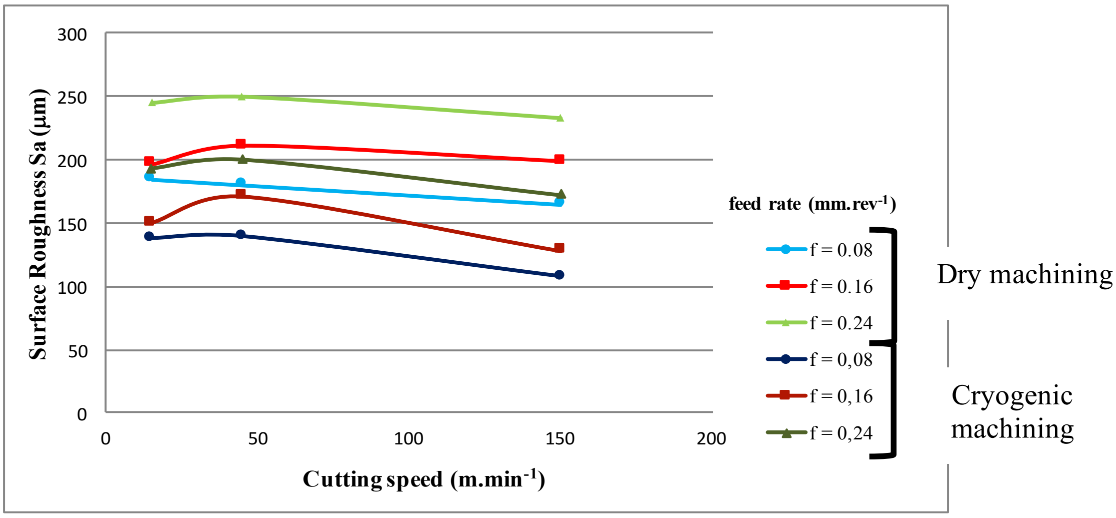

Figure 12: Surface roughness Sa for dry and cryogenic machining regarding the cutting parameters.

4 Conclusion

Cryogenic machining has a huge impact on CFRP cutting performance. On one hand, it increases the cutting forces which may lead to an increase of the delamination in drilling operations. On the other hand, a lower surface roughness could be obtained through cryogenic machining.

The fiber orientation influence is also different at cryogenic temperature. The higher cutting forces generate a brittle fracture of the matrix which occurs at different orientation depending on cutting parameters. This result implies a use of different tool geometry for cryogenic machining and for dry one. Therefore, the influence of the other angle χ_1 has to be investigated to find the best tool geometry for CFRP cryogenic drilling.

The higher forces in cryogenic machining are also more likely to lead to inter-fiber shear cutting mechanism which can create cracks in the CFRP matrix. Yet, the use of the cryogenic machining seems to be the best solution to avoid thermal damages of the matrix which cause a non-reversible deterioration of the epoxy matrix.

Therefore, a balance between cryogenic machining to reduce surface roughness and dry machining to reduce cutting forces could be investigate, such as using CO_2 instead of LN_2 as cryogenic liquid.

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