

Influence of Thermal Damage on the Mechanical Strength of Trimmed CFRP

Guillaume Mullier, Jean François Chatelain

Abstract—Carbon Fiber Reinforced Plastics (CFRPs) are widely used for advanced applications, in particular in aerospace, automotive and wind energy industries. Once cured to near net shape, CFRP parts need several finishing operations such as trimming, milling or drilling in order to accommodate fastening hardware and meeting the final dimensions. The present research aims to study the effect of the cutting temperature in trimming on the mechanical strength of high performance CFRP laminates used for aeronautics applications. The cutting temperature is of great importance when dealing with trimming of CFRP. Temperatures higher than the glass-transition temperature (T_g) of the resin matrix are highly undesirable: they cause degradation of the matrix in the trimmed edges area, which can severely affect the mechanical performance of the entire component. In this study, a 9.50mm diameter CVD diamond coated carbide tool with six flutes was used to trim 24-ply CFRP laminates. A 300m/min cutting speed and 1140mm/min feed rate were used in the experiments. The tool was heated prior to trimming using a blowtorch, for temperatures ranging from 20°C to 300°C. The temperature at the cutting edge was measured using embedded K-Type thermocouples. Samples trimmed for different cutting temperatures, below and above T_g , were mechanically tested using three-points bending short-beam loading configurations. New cutting tools as well as worn cutting tools were utilized for the experiments. The experiments with the new tools could not prove any correlation between the length of cut, the cutting temperature and the mechanical performance. Thus mechanical strength was constant, regardless of the cutting temperature. However, for worn tools, producing a cutting temperature rising up to 450°C, thermal damage of the resin was observed. The mechanical tests showed a reduced mean resistance in short beam configuration, while the resistance in three point bending decreases with increase of the cutting temperature.

Keywords—Composites, Trimming, Thermal Damage, Surface Quality.

I. INTRODUCTION

COMPOSITE materials have been increasingly and broadly used in high technology industries. The use of CFRPs is particularly privileged by the aeronautical industry. Above all, their tremendous strength to weight ratio make them highly suitable for the building of aircrafts structures and frames, enabling substantial energy savings. In addition, these materials exhibit great fatigue strength and corrosion resistance, which are essential parameters when dealing with aircraft manufacturing. CFRP parts are made of prepreg, which consist of carbon fibers impregnated with thermoset

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resin. Prepreg sheets are laid up into a component, followed by heat curing in an autoclave. Most of the parts built using this technique need several finishing operations. Trimming and milling are to obtain the correct final dimensional tolerances by removing the excess of material, while drilling is to accommodate diverse fastening hardware. Trimming operations can be processed through different technologies, including abrasive water jet which performs well in terms of final surface finish and the laser technology, despite great amount of thermal amount occurs. The last trimming technique is the milling process referring to cutting tools, which is concerned in this paper.

When machining CFRP, damage is most probable to occur. Many studies have been carried out on the influence of machining on the surface integrity and the mechanical strength of CFRPs so far, exploring numerous parameters. The appearance of macroscopic defects such as delamination, fibers pull-out, matrix cracking or plastic deformation at the surface is intimately linked with the cutting parameters and configuration [1]-[4]. Also, high cutting speeds and low feed rates associated to up-milling machining configuration gives the best results in terms of surface integrity and roughness [5]-[9]. Surface roughness is not a sufficient criterion to understand a reduction of the mechanical strength in static loading, but is more relevant in fatigue loading [3], [10]. Further studies felt the need to investigate the inner damage, under the surface, by measuring the average cracks depth, which gave better correlation with the reduction of the mechanical strength [5], [6]. One of the main differences when comparing the machining of metal and composite materials in terms of cutting temperatures lies in the thermal conductivity of the workpiece. Unlike metals, CFRPs have low thermal conduction. Thus, the heat tends to remain concentrated in the cutting zone, causing a rise of the cutting temperature. This temperature is of great importance when dealing with CFRP machining: unsuitable cutting parameters or tool wear level can lead to matrix degradation by exceeding its glass transition temperature T_g . This particular rise in temperature is responsible for a decrease in the mechanical strength of the composite in a thin layer of the machined edges. To date, it remains unknown as to what extent this local reduction in mechanical strength affects the global mechanical behaviour of a given trimmed part.

Multiple means of reducing heat concentration exist; from liquid coolants to refrigerated air, but their use remain limited [11]. Cutting temperature rises with both increase of feed rate and cutting speed [12], [13]. Also, tool wear is of main influence in the rise of the cutting temperature [7], [11]. The

PCD tools generally give the lowest cutting temperatures [14]-[16]. However, cutting temperatures exceeding T_g , even by far, do not necessarily induce thermal damage on the workpiece [17]. This enlightens the complex heat transfer phenomenon in the cutting zone, which are highly dependent on the tool material, coating and wear level. Fewer studies tried to correlate thermal damage with its impact on the mechanical behaviour of the material. Prolonged exposure over a certain temperature threshold, even below T_g , is of severe impact on the maximum service temperature and mechanical strength [18]-[21]. Also, material resistance decreases linearly with the enlargement of the heat affected zone in laser cutting [22], [23]. Finally, impact resistance of CFRP showed to decrease with increasing cutting temperature.

The present research aims to complement the state of the art in studying the effect of the cutting temperature in trimming on the mechanical strength of high performance CFRP laminates used for aeronautical applications.

II. METHODOLOGY

A. Experimental Set-Up for Dry Trimming

The material investigated was a multidirectional 24-ply CFRP laminate, shaped into plates of 3.6mm average thickness. The plates were produced using manual prepreg lay-up technique, followed by autoclave curing. The stacking sequence of the laminate was $[(90^\circ, -45^\circ, 45^\circ, 0^\circ, 45^\circ, -45^\circ, 45^\circ, -45^\circ, 0^\circ, -45^\circ, 45^\circ, 90^\circ)]_s$ with a fiber volume of 64%. The epoxy resin was cured at 350°F (177°C), associated to high resistance carbon fibers. The glass transition temperature of the selected resin is 415°F (210°C). Six flutes CVD diamond coated end mills with diameters of 9.50mm were used in the experiments. Geometrical information of the tool is shown in Table I. Cutting temperature was monitored using two embedded K-Type thermocouples. The wires were attached to the teeth surface using epoxy, while a thermally conductive cement was used to ensure contact between the welded tip and the tool. Redundancy is to overcome the fragility of such thermocouples (thin wires, chipping of the cement).

TABLE I
TOOL PARAMETERS

Material	Cemented carbide	
Coating	Diamond	
Coating	CVD	
Diameter	9,50mm (3/8)	
Helix angle	10°	
Number of flutes	6	
Rake Angle	10°	
Relief Angle	8°	

It was experimentally determined that a distance of 1.7mm between the cutting area and the welded tip position was suitable for the thermocouple to remain stuck on the tool, resisting the chip flow and the variation in temperature throughout the cutting. As shown in Fig. 1, the temperature data was collected and wirelessly transmitted using a module

embedded in the spindle (Michigan Scientific Corporation M-320). In addition, cutting forces were recorded using a 3-axis dynamometer table (type Kistler 9255B). The trimming operations were performed using a 3-axis CNC high speed center Huron K2X10 with a maximum spindle speed of 28000rpm at 30kW. The up-milling cutting mode at full radial and axial depths of cut was utilized, so as to minimize macroscopic mechanical defects.

The machined samples were rectangular strips of constant width, cut into smaller test samples of desired length using an abrasive diamond saw (Fig. 2). The final samples will exhibit symmetrical damage (thermal and mechanical) on both bending edges (Fig. 3). Damage which may have been introduced by abrasive cutting have no particular impact as it is out from the supports.

This paper aims to find a correlation between the cutting temperature, tool wear and their impact on mechanical behaviour of the material. Previous research proved that the cutting parameters had a significant influence on the mechanical strength of a trimmed part. Therefore, cutting parameters (i.e. feed rate and cutting speed) are kept constant throughout all the tests. Tools showing different wear levels, from new to highly worn are used in order to produce a wide range of cutting temperatures. Cutting parameters were based on [24], using the same tool and type of laminate: They gave the best results in terms of roughness, rate of tool wear and cutting forces, minimizing the amount of defects from mechanical origin. However, the wireless transmission of temperature data limits the spindle rotation speed to 10,000rpm. Therefore, it was decided to keep the same feed per tooth (chip load) as used in their work. This led to a feedrate of 1140 mm/min and cutting speed of 300 m/min.

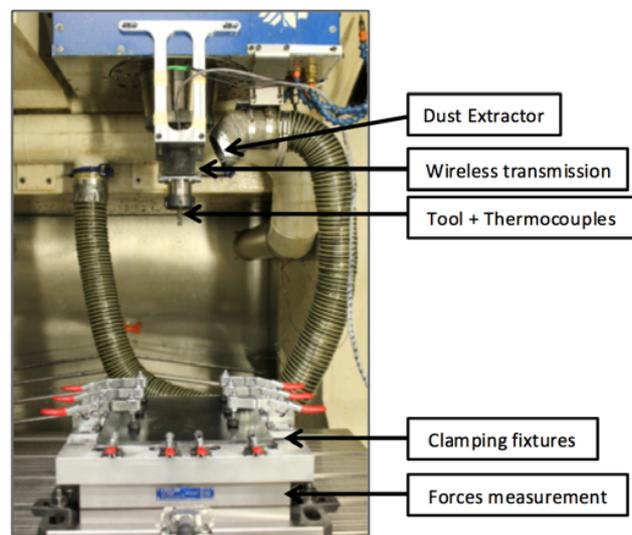


Fig. 1 Experimental set-up for dry trimming of CFRP

From our experiments, the tests have been carried out following two approaches:

- First approach consists in showing the effect of the cutting temperature on the mechanical behavior using new tools. The cutting temperature was varied by tool preheating using a blowtorch. Two series of samples were machined: the first with increasing preheat temperature and tool wear, the second with decreasing preheat temperature and increasing tool wear, in order to uncouple effects of both parameters.
- Second approach consists in showing the effect of both cutting temperature and tool wear using tools with different wear levels. The preheating temperature was kept constant in this case.

B. Mechanical Tests

Two different mechanical tests were performed: three point bending (ASTM D7264) and short beam (ASTM D2344). Dimensions of the rectangular samples and loading configurations are given in Fig. 4. From mechanical tests, the interlaminar shear stress (ILSS) is defined by (1), where P_m [N] represents the peak load applied on the sample before it breaks, b^{sb} and h^{sb} respectively the width and the thickness of the sample (measured for each sample).

$$F^{sb} = 0.75 \times \frac{P_m}{b^{sb} \times h^{sb}} \quad (1)$$

The following values can be calculated from three point bending tests. In (2), σ_{max} [MPa] represents the maximum flexural stress (maximum stress at the outer surface at midspan) where P_m^f is the peak load applied on the sample, L^f [mm] the support span, b^f [mm] and h^f [mm] the width and the thickness of the sample (measured for each sample). In (3), ε_m [%] represents the maximum strain at the outer surface, where δ_m^f [mm] is the maximum deflection at the loading point.

$$\sigma_{max} = \frac{3 \times P_m^f \times L^f}{2 \times b^f \times h^f{}^2} \quad (2)$$

$$\varepsilon_m = \frac{6 \times \delta_m^f \times h^f}{L^f{}^2} \quad (3)$$

III. RESULTS AND DISCUSSION

A. Effect of Cutting Temperature Using New Tools

A total of 96 short beam samples cut with temperatures ranging from 50 to 300°C in the middle of the samples were

produced (Table II). Strips S2 to S6 were machined with temperatures exceeding the glass transition temperature of the epoxy. The cutting temperature is converging towards the natural cutting temperature of the tool (which is function of the cutting parameters) for both series: it was found to be around 250°C (Fig. 5).

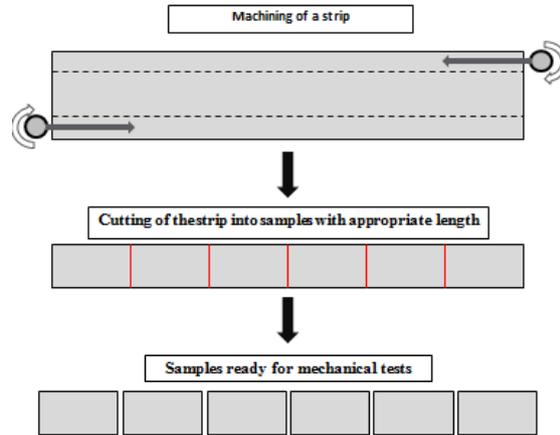


Fig. 2 Trimming of samples

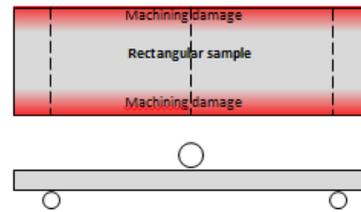


Fig. 3 Trimming of samples

	Samples Dimensions			Loading Configuration		
	h (mm)	b (mm)	L (mm)	Loading nose diam D ₁ (mm)	Supports diam D ₂ (mm)	Span S (mm)
Three points bending	3.6	13	138.2	5	5	109
Short beam	3.6	7.2	21.6	5	3	14.4

Fig. 4 Trimming of samples

TABLE II
PARAMETERS OF SHORT BEAM SAMPLES (NEW TOOLS)

	Strip n°	Cut length (mm)	Preheat temperature (°C)	Number of samples produced
1 st series	S1	0-610	150	12
	S2	610-1220	200	12
	S3	1220-1830	250	12
	S4	1830-2240	300	12
	S5	0-610	275	12
2 nd series	S6	610-1220	225	12
	S7	1220-1830	150	12
	S8	1830-2240	20	12
Cutting parameters		Vc=300m/min	Vf=1140mm/min	Total = 96

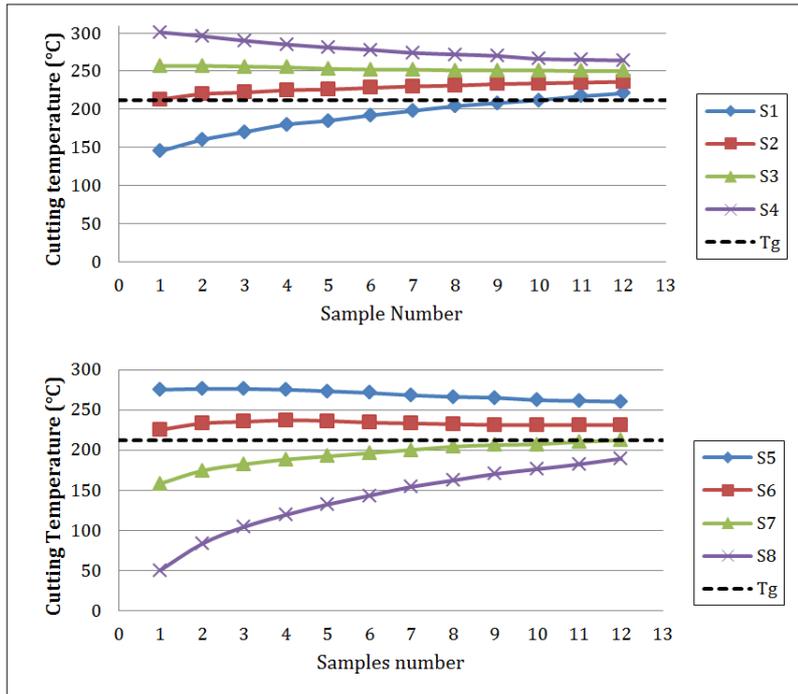


Fig. 5 Cutting temperatures of short beam samples (new tools)

TABLE III
PARAMETERS OF THREE POINT BENDING SAMPLES (NEW TOOLS)

Strip n°	Cut length (mm)	Preheat temperature (°C)	Number of samples produced	
1 st series	F2	0-610	2 (F21,F22)	
	F3	610-1220	2 (F31,F32)	
	F4	1220-1830	2 (F41,F42)	
	F5	1830-2240	2 (F51,F52)	
	F6	0-610	300	2 (F61,F62)
2 nd series	F7	610-1220	2 (F71,F72)	
	F8	1220-1830	2 (F81,F82)	
	F9	1830-2240	2 (F91,F92)	
Cutting parameters		Vc=300m/min	Vf=1140mm/min	Total = 16

A total of 16 three point bending samples were produced using the same procedure, for a range of cutting temperatures between 20 and 300°C (Table III). As for short beam samples, the cutting temperature in the middle of the samples are considered for further analysis. Temperature profiles were similar to those obtained with machining of the short beam strips.

As shown in Fig. 6, results regarding interlaminar shear stress resistance for new tools could not show any trend regarding cutting temperature and length of cut. Looking at a single strip, there is no particular trend from sample number 1 to 12. Also, the mean ILSS value of each strip is comprised between 79 and 81MPa, which is due to ordinary variation. This phenomenon indicates that the cutting temperature has no influence on the ILSS resistance of the material when using a new tool.

Results coming from the three point bending test show little variation: the trend regarding mean maximum flexural stress reverses, while the trend regarding maximum deformation is

too low to be attributed to the effect of rising cutting temperature (Fig. 7).

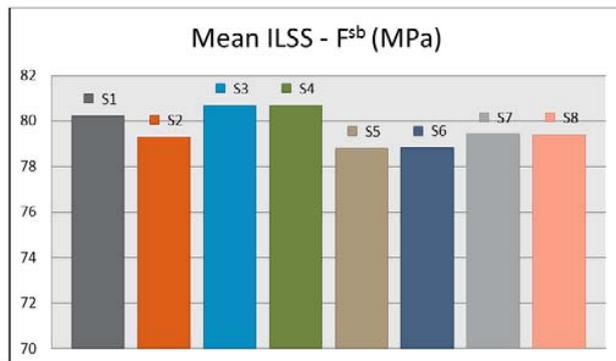


Fig. 6 Averaged ILSS values for each strip (new tools)

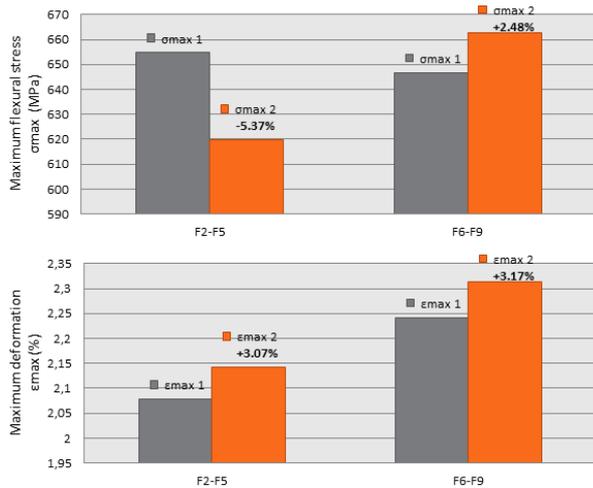


Fig. 7 Mean values from three point bending tests (new tools)

TABLE IV
PARAMETERS OF SHORT BEAM SAMPLES (WORN TOOLS)

Worn Tools	Strip n°	Preheat Temperature (°C)	Number of samples produced
F1S3 Vb= 35µm	S9	280	12 (S91..S912)
F2S2 Vb= 50µm	S10	270	12 (S101..S1012)
F3S1 Vb= 30µm	S11	270	12 (S111..S1112)
Cutting Parameters	Vc=300m/min	Vf=1140mm/min	Total = 36

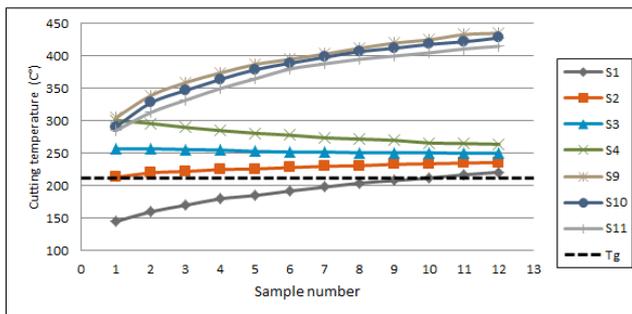


Fig. 8 Cutting temperature of short beam samples (new and worn tools)

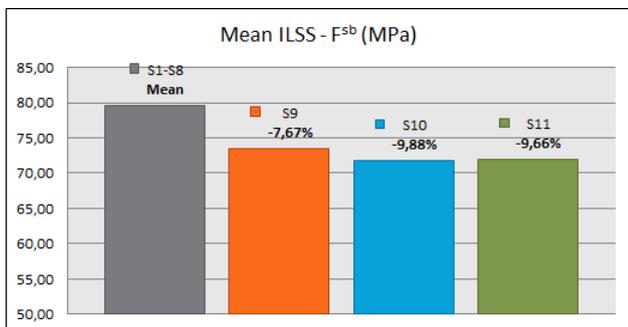


Fig. 9 Comparison between mean ILSS values of samples machined using new and worn tools

In Fig. 7, the mean values are calculated as:

$$\sigma_{max 1} = \frac{\overline{\sigma_{max}(X)}}{\epsilon_{max 1}} ; \sigma_{max 2} = \frac{\overline{\sigma_{max}(Y)}}{\epsilon_{max 2}}$$

where

$$X = (F21,F31,F41,F51), (F61,F71,F81,F91)$$

$$Y = (F22,F32,F42,F52), (F62,F72,F82,F92)$$

The stress $\sigma_{max 1}$ and deformation $\epsilon_{max 1}$ relates to first sample machined (lower cutting temperature) while $\sigma_{max 2}$ and $\epsilon_{max 2}$ relates to second machined sample (higher cutting temperature) on a given strip.

B. Effect of Cutting Temperature Using Worn Tools

The second approach proposes to proceed with the same methodology as previous, but using worn tools and an approximately constant preheating temperature. A total of 36 samples were machined using 3 worn tools exhibiting different levels of flank wear (Vb), coating integrity and cutting edge radii (Table IV). The cutting temperature now peaks up to 425°C at the end of the cutting process (Fig. 8). Globally, the temperature at which samples are machined is a lot higher than the glass transition temperature of the resin, thus thermal damage is likely to occur.

As shown in Fig. 9, ILSS did not show any conclusive variation with the cutting temperature on a given strip. However, the mean value of each strip (S9 to S11) compared to the averaged ILSS value over S1 to S8 strips shows that substantial amount of both thermal and mechanical damage occurs during machining. The loss of resistance ranges from -7.67 to -9.88%.

A total of 12 three point bending samples were produced at the same constant preheat temperature (Table V): therefore, the temperature profiles of the machined strips are similar to those obtained with the machining of the 3 short beam strips.

TABLE V
PARAMETERS OF THREE POINT BENDING SAMPLES (WORN TOOLS)

Worn Tools	Strip n°	Preheat Temperature (°C)	Number of samples produced
F1S3 Vb= 35µm	F10	270	2 (F101,F102)
F2S2 Vb= 50µm	F11	270	2 (F111,F112)
F3S1 Vb= 30µm	F12	270	2 (F121,F122)
F1S3 Vb= 35µm	F13	270	2 (F131,F132)
F2S2 Vb= 50µm	F14	280	2 (F141,F142)
F3S1 Vb= 30µm	F15	280	2 (F151,F152)
Cutting Parameters	Vc=300m/min	Vf=1140mm/min	Total = 12

In Fig. 10, the mean values calculated are nearly equal to the mean results from samples machined using new tools. However, trends regarding the cutting temperature can be seen for all the tools when considering the maximum flexural stress. The second machined sample always exhibits a lower maximum flexural stress than the first one ($\sigma_{max 2}$ VS $\sigma_{max 1}$ = -3% to -21%). This phenomenon indicates that the rising temperature during the cutting induces increasing thermal damage: this explains why the second

portion of a given strip exhibits lower resistance than the first one.

In Fig. 10, the mean values are calculated as:

$$\sigma_{\max 1} = \frac{\overline{\sigma_{\max}(X)}}{n}; \sigma_{\max 2} = \frac{\overline{\sigma_{\max}(Y)}}{n}$$

$$\varepsilon_{\max 1} = \frac{\overline{\varepsilon_{\max}(X)}}{n}; \varepsilon_{\max 2} = \frac{\overline{\varepsilon_{\max}(Y)}}{n}$$

where

$$X = (F101,F111), (F121,F131), (F141,F151)$$

$$Y = (F102,F112), (F122,F132), (F142,F152)$$

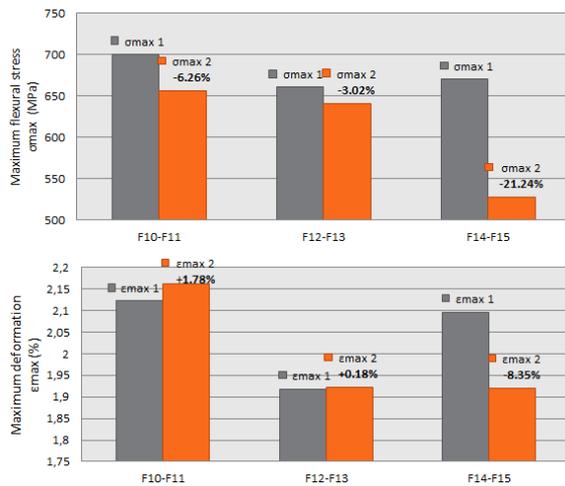


Fig. 10 Calculated mean values from three point bending tests

C. Surface Integrity

Inspection of the surface finish is an interesting way to anticipate or understand a reduction of the mechanical strength of the material. In this case, great surface integrity can be observed for the specimens trimmed with a new tool, regardless of the cutting temperature (Fig. 11). The -45° plies show some fibres pull-out, which is a typical defect when dealing with CFRP machining. As tool wear increases, degradation of the matrix occurs and the different plies become harder to differentiate from each other (Fig. 12). This strongly indicates that the resin went through deterioration, resulting in a softened and more homogeneous surface. Also, the surface appears to be darker, which suggests charring of

the matrix. In addition, little delamination on the surface plies and some fiber reorientation can be noticed. Also, looking at the surface of the laminate machined using worn tools, increasing degradation in the near zone of the cutting can be seen with the increase of the cutting speed: resin moves back towards the middle of the sample, leaving fibers out of the resin, resulting in some kind of delamination from thermal origin (Fig. 13). Damage on the surface plies for samples machined using new tools was constant and of brittle nature: simultaneous snatching of both fibers and resin and absence of delamination

IV. CONCLUSION

Machining using new tools induced constant damage on the laminate, regardless of the cutting temperature. Mechanical performances were not affected by the rise in temperature for short beam samples nor three point bending ones, even in the cases where it exceeded the glass transition temperature of the resin. Therefore, we can assume that a sharp cutting edge does not transfer the cut-generated heat to the material, but is rather evacuated by the tool itself and the chips.

In the second approach using worn tools, it was seen that depending on the loading configuration, either general resistance of the material was reduced, or the rise in temperature throughout the cutting had a negative impact. The explanation lies in the rupture mode of the sample depending on the loading configuration. Breakage occurs by interlaminar separation of the upper surface ply in the loading area for the three point bending samples, while it occurs by propagation of a crack towards the middle of the sample along a -45° ply for short beam samples.

In the first case, increasing resin damage on the surface plies near the cutting region might be responsible for the decrease in mechanical strength. As the upper surface ply breaks first, it seems logical that the first three point bending sample machined exhibits higher resistance than the second one for a given strip. In the second case, excessive charring on -45° plies and general damage induced are likely to initiate cracks more easily, which may explain why maximum ILSS is reduced compared to samples machined using new tools.

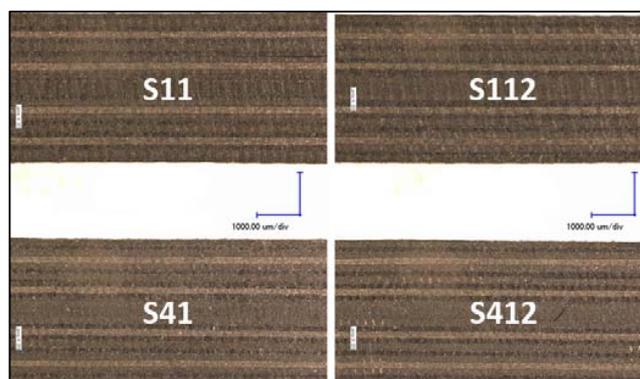


Fig. 11 Constant damage induced on the machined surface of short beam samples regardless of the cutting temperature (new tools)

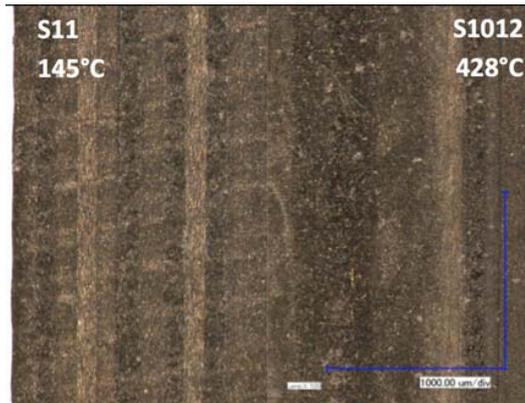


Fig. 12 Comparison between the machined surface using a new tool at low cutting temperature and a worn tool at high cutting temperature

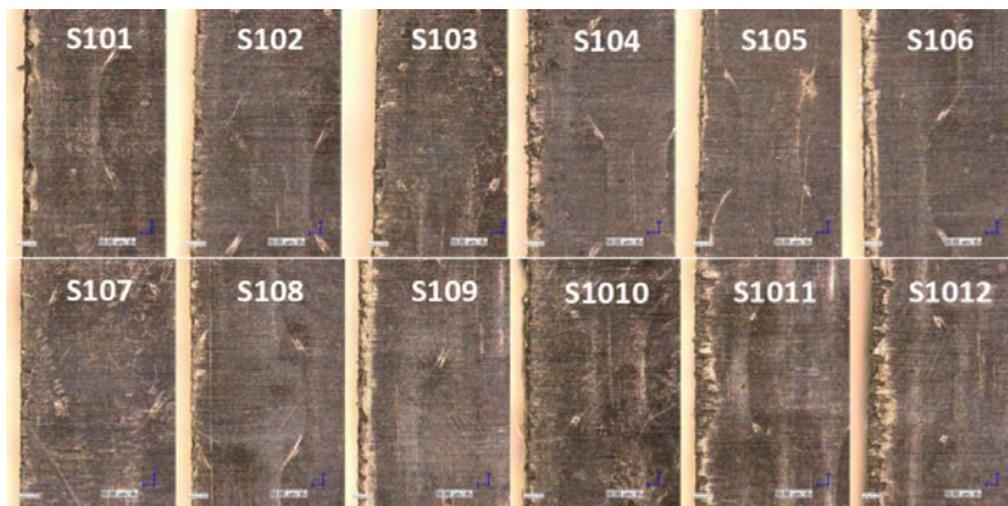


Fig. 13 Increasing damage on the surface ply of short beam samples (strip S10)

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