

Article

Influence of Cutting Temperature on the Tensile Strength of a Carbon Fiber-Reinforced Polymer

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Abstract: Carbon fiber-reinforced plastics (CFRP) have seen a significant increase in use over the years thanks to their specific properties. Despite continuous improvements in the production methods of laminated parts, a trimming operation is still necessary to achieve the functional dimensions required by engineering specifications. Laminates made of carbon fibers are very abrasive and cause rapid tool wear, and require high cutting temperatures. This creates damage to the epoxy matrix, whose glass-transition temperature is often recognized to be about 180 °C. This study aims to highlight the influence of the cutting temperature generated by tool wear on the surface finish and mechanical properties obtained from tensile tests. Trimming operations were performed on a quasi-isotropic 24-ply carbon/epoxy laminate, of 3.6 mm thickness, with a 6 flutes diamond-coated (CVD) cutter. The test specimens of 6 mm and 12 mm wide were obtained by trimming. The reduced width of the coupons allowed amplification of the effect of defects on the measured properties by increasing the proportion of coupon cross-section occupied by the defects. A new tool and a tool in an advanced state of wear were used to generate different cutting temperatures. Results showed a cutting temperature of 300 °C for the new tool and 475 °C for the worn tool. The analysis revealed that the specimens machined with the new tool have no thermal damage and the cut is clean. The plies oriented at -45° presented the worst surface finish according to the failure mode of the fiber. For the worn tool, the surface was degraded and the matrix was carbonized. After cutting, observations showed a degraded resin spread on the machined surface, which reduced the surface roughness and hid the cutting defects. In support of these observations, the tensile tests showed no variation of the mechanical properties for the 12 mm-wide specimens, but did show a 10% loss in mechanical properties for the 6 mm-wide specimens. These results suggest that the thermal defects caused by tool wear affect tensile properties, but only from a certain coupon width below which the machining defects increase their influence on the properties.

Keywords: carbon fiber-reinforced plastics (CFRP); trimming; machining; cutting temperature; tensile strength; surface roughness; tool wear

1. Introduction

Carbon fiber-reinforced plastic (CFRP) materials have remarkable specific mechanical properties, especially regarding the modulus-to-weight and strength-to-weight ratios. This explains their popularity and their increasing use in the transportation sector (aeronautics, rail and automotive), where reducing the weight of a structure enables significant energy savings.

Despite the continuous improvement of molding methods to produce laminated parts, a trimming operation is still necessary to remove excess material on part edges to achieve the functional dimensions required by specifications. Machining methods commonly used for metal are tested on composite

materials. Laser machining was investigated by many researchers and it was found that this method induces significant thermal damage to the material [1–3]. The cutting water jet was also investigated and it was found to introduce a very poor surface finish of the trimmed components [4,5]. Conventional trimming using cutting tools remains the simplest and least detrimental method for the material and will be studied in this work.

Unlike metals, the machining of composites is difficult and inevitably generates defects such as delamination, fiber pull-out, matrix cracking, and plastic deformation on the machined edges [6,7]. These defects depend substantially on cutting parameters and machining configuration [8]. High cutting speed and low feed rate is the best combination in terms of surface integrity and surface roughness for CFRP machining [6,9]. Other authors confirm the same conclusion and also report that cutting forces are, as well, lowest for this combination [10–16]. The fiber orientation also has an influence on the surface finish. Pecat et al. [17] found that a smooth surface was seen when milling with 0° and $+45^\circ$ orientations, while under -45° and 90° their micrographs showed severe damage in the form of cracks. Chatelain et al. [18] also studied the effect of the ply orientation on roughness for the trimming process of quasi-isotropic aerospace CFRP laminates. They found that each ply orientation had its own “typical” roughness profile. The surface roughness across the laminate was measured for different fiber orientations (0° , 45° , 90° and -45°) of the CFRP laminate using the longitudinal method. The -45° ply orientation showed the worst surface roughness. Other research also confirmed that the worst surface roughness is observed on the plies oriented at -45° [15,18,19].

As with mechanical damage, cutting parameters influence thermal damage and tool wear. The cutting temperature decreases with an increase of the cutting speed and a decrease of the feed rate. The same trend is observed for tool wear [20–23]. The cutting temperature decreases with increasing cutting speed because the contact time between the work piece and the tool is reduced and the chip size increases. Under these conditions, the material flow rate increases and the temperature is more easily reduced by the chips [21,23]. Finally, the cutting temperature increases with increasing tool wear [6,20,24]. These results show how important it is to control the cutting parameters in order to limit the cutting forces, tool wear and cutting temperature, reducing the size and quantity of defects.

The addition of very abrasive materials such as carbon fibers (sometimes more abrasive than the tool itself) makes the machining of such materials difficult. These fibers cause rapid tool wear which increases the cutting temperature [6,12,20,25]. The tool wear in particular affects the quality of trimmed surfaces. As opposed to metals, Hamedanianpour [20] showed that tool wear increase means better surface finish due to the softening and spreading of the epoxy matrix on the surface of trimmed CFRP parts. Composites also have a low thermal conductivity (due to the resin properties). So, the heat generated by the machining operation and tool wear is concentrated on the cutting zone and does not propagate to the rest of the work piece. The cutting temperature is problematic when it exceeds the glass transition temperature T_g of the resin. This degrades the matrix and possibly leads to losses of mechanical performance [26]. However, for the machining of composites, the influence of temperature on their mechanical performance has not been explicitly demonstrated. The objective of this work is to show how thermal degradation during machining reduces the tensile strength and modulus of the laminate. It also aims to determine a relationship between the tool wear, the cutting temperature and their impact on surface finish and tensile properties.

2. Experimental Procedure

2.1. Machining

Trimming operations were conducted to produce rectangular tensile test coupons of two different widths, 12 mm and 6 mm, each being 250 mm in length. Two tools were used (new and worn) to produce different thermal damage. The ASTM standard recommends a specimen width of 25 mm. This dimension is required to eliminate the influence of edge defects induced by the cutting operation, thus ensuring representative material tensile properties. However, in the present case, and to highlight

the influence of edge defects on machining quality, 6 mm and 12 mm wide test specimens were cut in order to amplify the influence of edge defects on the measured properties. The intention was to use the tensile coupon not to evaluate the material itself but instead to evaluate how the machined defects influence the tensile properties, which become reference properties in the absence of defects (or when the coupon is large enough to make the influence of defects negligible). This can be done here considering the laminate is composed of thin unidirectional layers. It would be different in the case of plies made of woven fabrics, for which the coupon width must be adjusted to encompass enough unit fabric cells to be representative of the material.

To trim the tensile test coupons, a 3-axis computer numerical control (CNC) HURON K2X10 high-speed machining center and special setup was used (Figure 1). This setup included lateral clamps to maintain the plate during machining, and end clamps to maintain the specimen to be cut. After each pass of the tool, the plate was turned to have a symmetrical temperature profile for each side of the specimen (Figure 2). Moreover, with this arrangement, the same extra material was obtained for each test specimen. This material corresponded to a specimen with edges machined using the down-milling machining mode rather than the up-milling mode. This meant there were $(n-2)$ specimens machined in the down-milling mode and n specimens machined in up-milling mode (Figure 2). All these specimens were kept and compared to one another. Finally, the extremities of the specimens were cut to the desired length of 250 mm (10') with an abrasive saw. A total of 60 tensile-test specimens were produced as indicated in Table 1. The specimens were made in four iterations (T1 to T6; T7 to T12; T13 to T22 and T23 to T34). The thermocouples provided the cutting temperature profiles at the cutting edge of the teeth for each sample, except for the following specimens, T3, T11 and T12, where the thermocouples broke through the effect of centrifugal force, and were peeled off due to the flow of chips. Cutting forces were measured using a 3-axis dynamometer table (Kistler 9255B) (Figure 1).

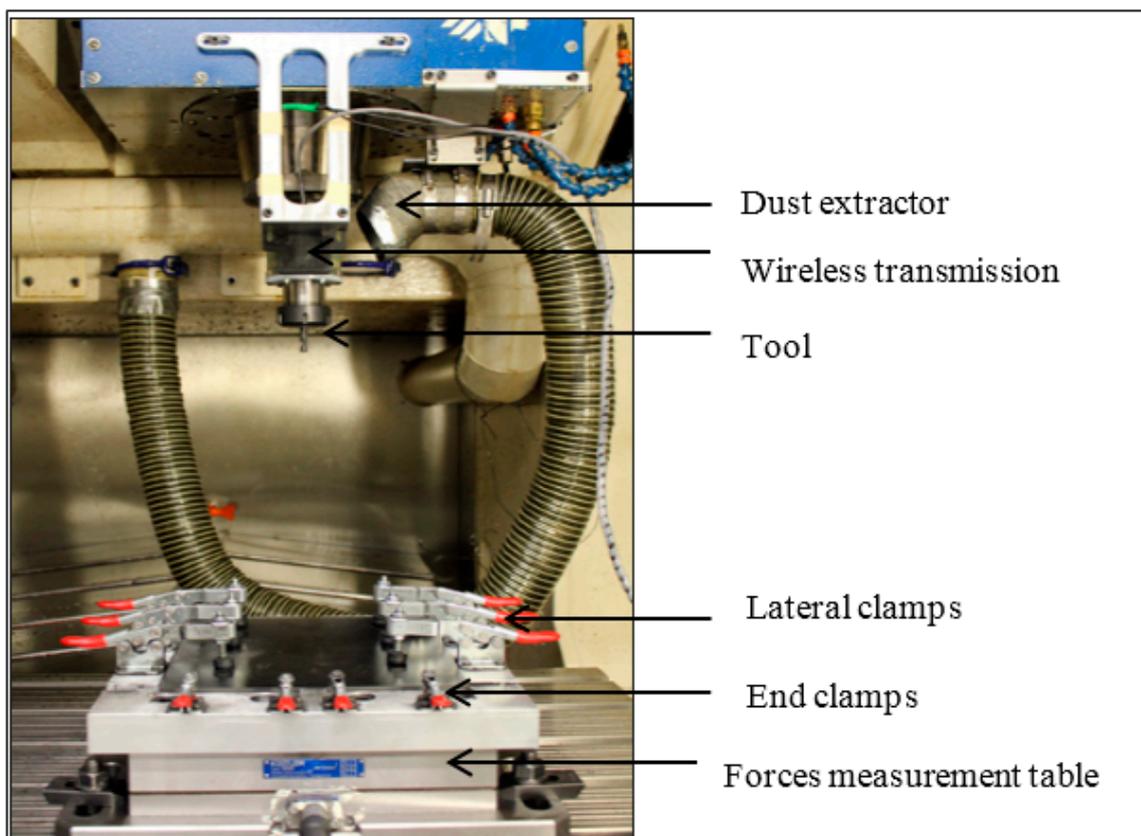


Figure 1. Machining assembly.

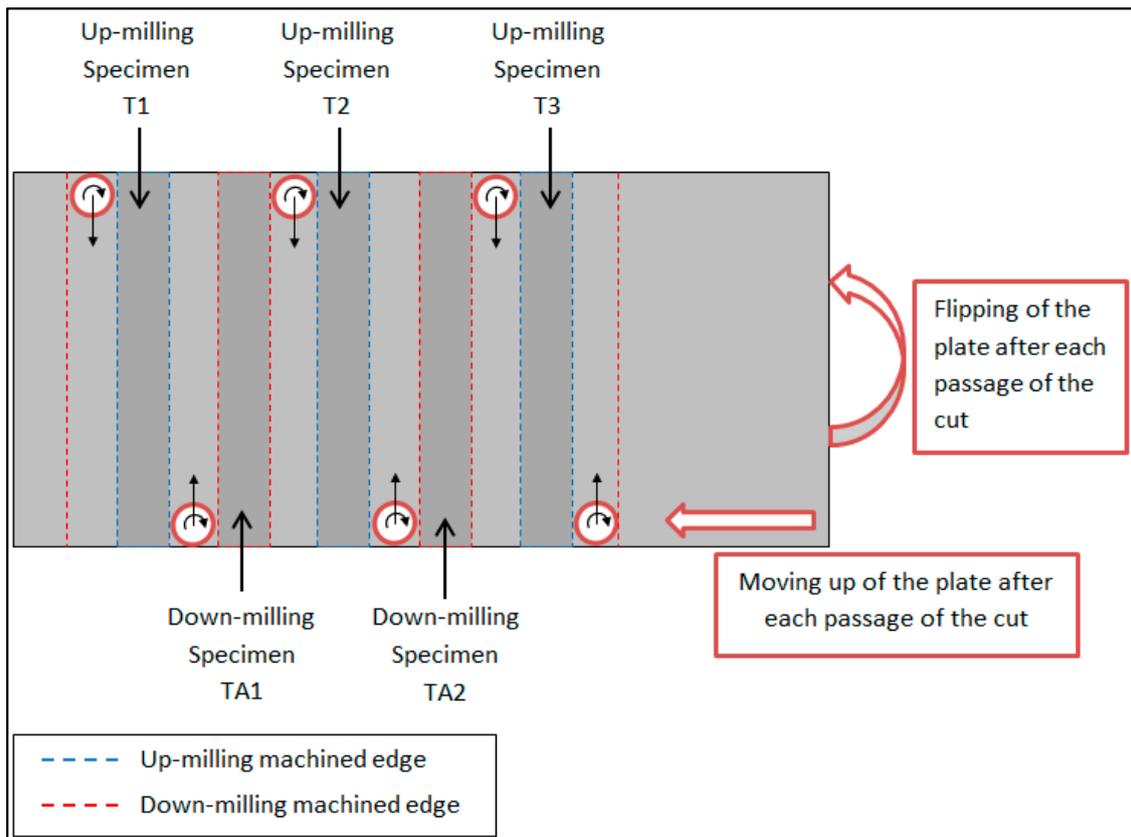


Figure 2. Sample production procedure.

Table 1. Experimental plan.

12 mm-Wide Specimens				
Two Cutting Conditions Machining Configuration	New Tool		Worn Tool	
	Up-Milling	Down-Milling	Up-Milling	Down-Milling
Number of Repetitions	6	4	6	4
Coupon ID	T1, T2, T3, T7, T8, T9	TA1, TA2, TA8, TA9	T4, T5, T6, T10, T11, T12	TA4, TA5, TA10, TA11
6 mm-Wide Specimens				
Two Cutting Conditions Machining Configuration	New Tool		Worn Tool	
	Up-Milling	Down-Milling	Up-Milling	Down-Milling
Number of Repetitions	11	9	11	9
Coupon ID	T13, T14, T15, T16, T17, T29, T30, T31, T32, T33, T34	TA13, TA14, TA15, TA16, TA29, TA30, TA31, TA32, TA33	T18, T19, T20, T21, T22, T23, T24, T25, T26, T27, T28	TA18, TA19, TA20, TA21, TA23, TA24, TA25, TA26, TA27

The specimens were machined in full axial (full-plate thickness) and radial depth of cut to generate the maximum heat during cutting. It was also decided to machine in up-milling configuration because this configuration provides the least mechanical damage. The cutting parameters (Table 2) were kept constant for all tests and were selected to generate low cutting forces and low tool wear [20,24]. A constant surface temperature was maintained during machining. The cutting temperature reached a constant level after a transient period, of a logarithmic form, occurring when the tool started cutting. This transient period had to be avoided to study the thermal damage at a given temperature along the cutting edge. We wanted the coupon edges for mechanical tests cut with constant temperature as much as possible to reduce variability in the results. For this reason, the tool was pre-heated using

a blowtorch to the expected cutting temperature before starting the cutting tests. In fact, preliminary tests confirmed that 300 °C was the appropriate pre-heating temperature for the new tool while 475 °C was appropriate for the worn tool. Once the pre-heat temperature was reached, the machining program was quickly started.

Table 2. Cutting parameters.

Feed/Tooth (mm/Dent/Rev)	Feed Rate (mm/min)	Cutting Speed (m/min)	Spindle Speed (RPM)
0.019	1140	300	10052

A typical temperature profile was divided into four stages as shown in Figure 3:

- Stage 1: The tool was pre-heated using a blowtorch, the temperature increased up to the required pre-heated temperature.
- Stage 2: The CNC doors were closed, the machining program was started, the tool moved from its origin to the part piece. The temperature decreased during this movement.
- Stage 3: The tool cut the material. An increase in the temperature up to stabilization was observed.
- Stage 4: The machine program ended and the tool came back to its origin. The temperature slowly decreased to ambient temperature.

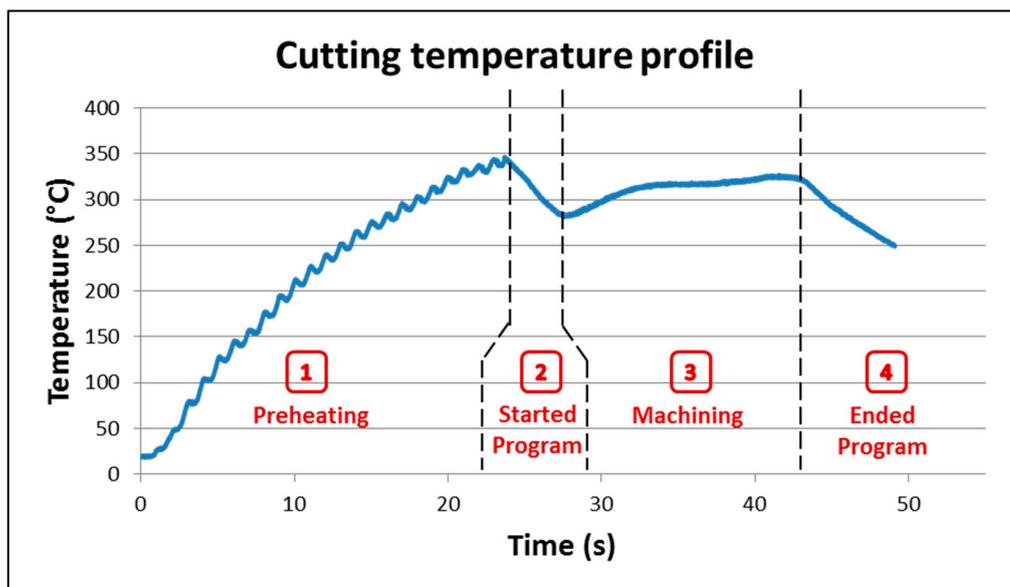


Figure 3. Cutting-temperature profile.

2.2. Material

The material was a multidirectional quasi-isotropic 24-ply CFRP laminate, shaped into plates of 3.6 mm average thickness. The plates were produced using the manual prepreg lay-up technique, followed by autoclave curing. The stacking sequence of the laminate was $[(90^\circ, -45^\circ, 45^\circ, 0^\circ, 45^\circ, -45^\circ, 45^\circ, -45^\circ, 0^\circ, -45^\circ, 45^\circ, 90^\circ)]$ with a fiber volume fraction of 64%. The high-performance epoxy resin had a curing temperature of 177 °C and a glass-transition temperature of 212 °C.

2.3. Cutting Tool

A six-flute CVD diamond-coated carbide end mill with a diameter of 9.50 mm was used for the trimming experiments. The tool characteristics are shown in Table 3.

Table 3. Tool parameters.

Diameter	9.50 mm
Number of flutes	6
Helix angle	10°
Rank angle	10°
Relief angle	8°
Effective length	35 mm
Total length	80 mm

To measure the cutting temperature, the tool was equipped with two embedded K-type thermocouples placed at 180°. They were placed against the cutting edge closest to the cutting area and bonded with OMEGABOND® 400 # OB-400 cement, which is an excellent thermal conductor and covered with epoxy resin enabling the thermocouple to remain in place during the cutting process. Preliminary tests by Mullier [24] showed that a distance of 1.7 mm from the cutting edge enables the holding of thermocouple on the tool despite the combined effect of the chip flow and temperature variation (Figure 4). The tool was then installed in a special mandrel (type M-320, manufactured by Michigan Scientific Corporation), using special connections for thermocouples, and the data was transmitted wirelessly (Wi-Fi) to the data-acquisition system (Figure 4).

**Figure 4.** Mandrel and new tool equipped with thermocouple.

2.4. Tool Wear Measurement

For the trimming operations, a new tool and a worn tool ($V_b = 50 \mu\text{m}$ before machining) were used (Figure 5). Tool wear has a significant influence on the cutting temperature, thus this approach will show the influence of the cutting temperature on the mechanical properties of the coupons. The tool wear was measured using a Keyence VHX-500FE optical microscope equipped with image-processing software. Regarding the worn tool, the measurement of the initial flank wear (V_b) resulted to $50 \mu\text{m}$ (wear of the coating and substrate), and we observed a removal of about $550 \mu\text{m}$ of the diamond coating.

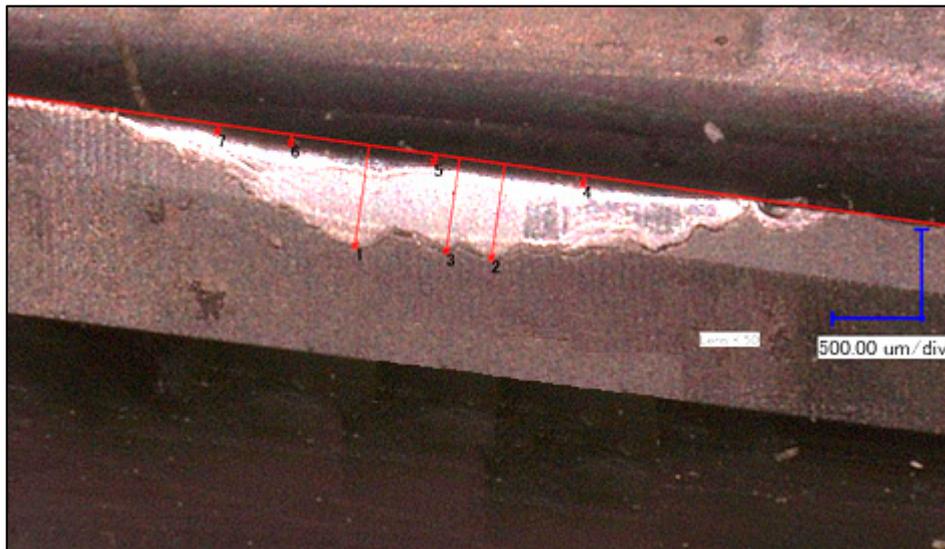


Figure 5. Tool wear before machining ($V_b = 50 \mu\text{m}$, $V_{ba} = 550 \mu\text{m}$, Lens X50).

2.5. Surface Roughness Measurement System

The roughness measurement aims to show if the tool wear and the cutting temperature have an influence on the surface roughness. The measurements were made using a SurfTest SJ-400 profilometer, from Mituyo, equipped with a $2 \mu\text{m}$ -radius diamond tip with a 90° angle in combination with SURFPAK-SJ acquisition software. To improve measurement accuracy, a Keyence VHX-500FE optical microscope was used to control the exact position of the profilometer diamond tip.

Following similar studies, the roughness measurements were performed on the plies oriented at -45° . The measurement parameters used are shown in Table 4 according to the ASME B46.1-2009 standard:

Table 4. Roughness measurement parameters.

Pre-Travel	0.2 mm
Post-Travel	0.2 mm
Evaluation length (L_m)	5.6 mm
Sampling Length (L_e)	0.8 mm
Cut-off Length (L_c)	0.8 mm
Number of Samples	7
Number of Sampling Points	12,000
Parameter	Ra (μm)

To determine the number of measurements to take on each sample, it is necessary to define the precision of the measuring machine and the operation's repeatability. For this purpose, three measurements were made on the same specimen and at the same location. Then, 12 measurements were performed on the same sample but at different locations on the edge to determine the repeatability. A deviation of $0.019 \mu\text{m}$ was found for the precision of the measurement system, and $2.119 \mu\text{m}$ for the repeatability of the measure. This shows that the measurement process was accurate, but the repeatability of the measure remained limited. This, however, enabled the observation of a trend in the results. To minimize the uncertainty of roughness measurements, it was thus decided to make a large number of measurements. For each test coupon, three random roughness measurements (on the -45° ply) were performed on each machined edge of the coupons. There were two machined edges per coupon which meant six roughness measurements per specimen. A total of 360 measurements were performed (6×60 specimens).

2.6. Tensile Testing

The tensile tests were performed on an Alliance RF/200 testing machine. They were performed according to the ASTM D3039/D3039M-00 standard. The test specimens were clamped in the grips of a length of 50 mm at each end, as recommended by the standard. The use of aluminum tabs bonded at the end of the coupon was adopted to limit the number of coupons breaking in the grips. Aluminum tabs of 12 mm \times 50 mm or 6 mm \times 50 mm (depending of sample width) were used. To prevent slippage between the specimen and the aluminum tabs, double-face sandpaper with medium grain (100) was placed between the specimen and the tab (Figure 6).



Figure 6. Sample with sandpaper and aluminium tabs.

This test was destructive and only the tensile strength was measured. Therefore, no instrumentation was required on the sample (gauges or extensometer). The confidence intervals related to the test are given in Table 5. The tensile strength was calculated by dividing the maximum tensile force recorded by the coupon cross-section measured before testing. The cross-section was measured at three locations along the coupon and the mean value was used for calculations.

Table 5. Confidence intervals.

95% Level of Confidence Intervals	
Specimen length	± 1 mm
Specimen wide	± 0.05 mm
Specimen thickness	± 0.2 mm
P (Force)	± 10 N
δ (Displacement)	± 0.01 mm

3. Results

3.1. Machining of Test Coupons

For better visibility, the average temperature profile was plotted with error intervals expanded to a confidence level of 95% for each profile, as shown in Figure 7. These curves relate to zone 3, which is the machining zone, as defined in Figure 3. Concerning the cutting temperature, the new tool was pre-heated to 350 °C (662 °F) and a constant cutting temperature of 300 °C (572 °F) was obtained (Figure 3, stage 3). The temperature was nearly constant throughout the specimen, which was excellent (Figure 7). The second tool (worn tool) was pre-heated to 400 °C (752 °F), for a cutting temperature of about 475 °C (887 °F) after the first 150 mm of cutting. It was impossible to pre-heat the tool to more

than 400 °C (752 °F), because thermal degradation of the resin maintaining the thermocouple was observed. Thus, it became difficult to obtain constant temperature levels. The time interval between the end of pre-heating and the start of machining caused a temperature drop to about 250–300 °C (482–572 °F) for both tools. Otherwise, for each machining condition, the temperature profiles for all the samples were globally the same.

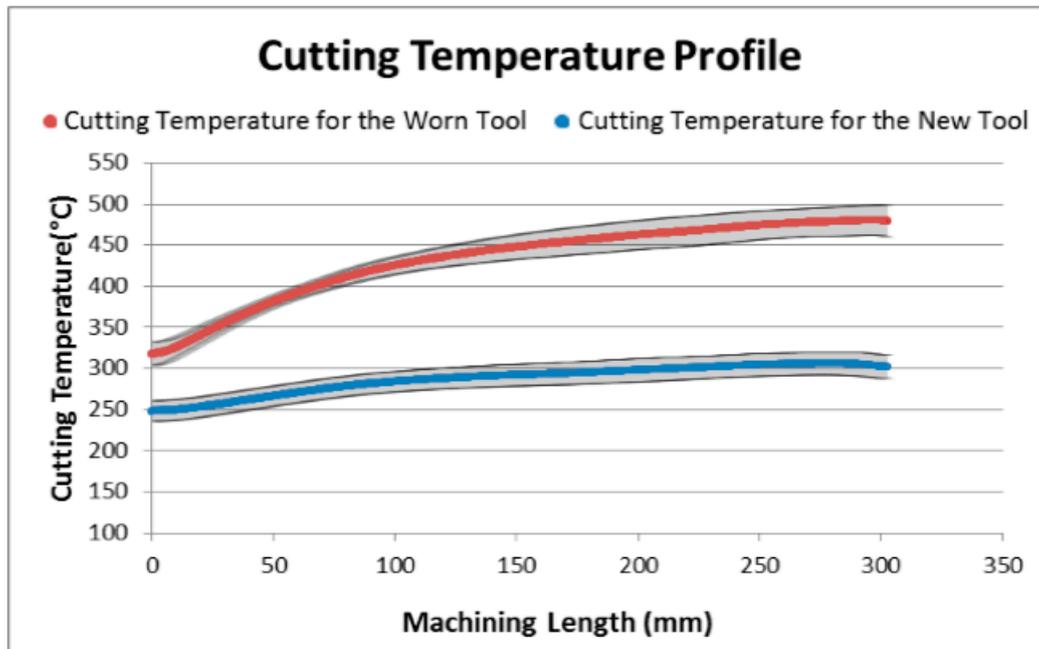


Figure 7. Cutting-temperature profile.

The results showed a significant influence of tool wear not only on the cutting temperature, but also on the resulting chip. Indeed, with the worn tool, the glass transition temperature (T_g) of the resin was greatly exceeded, resulting in resin degradation. Consequently, the chip which consists normally of a fine black powder with the new tool was transformed to a sticky paste concentrated around the cutting area. This paste can be a source of poor heat dissipation increasing the thermal damage of the composite (particularly on the upper surface) (Figure 8).

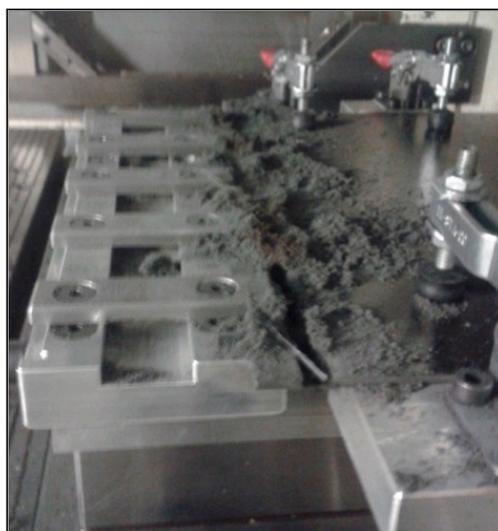


Figure 8. Chip after cut (worn tool).

Additionally, regarding the cutting zone of the worn tool after machining, the thick paste forming the chip stuck to the tool, obstructing the flute and preventing any evacuation (Figure 9). This explains the high temperature reached with the worn tool, as the heat could not be dissipated through the chip because it remained on the tool, agglomerated around the cutting area, effectively forming a thermal insulator. Combined with the friction of the tool, this phenomenon produced a cutting temperature that was considerably higher than T_g of the resin, thus creating a heat-affected zone along the machined edge. On the other hand, the chip for the new tool was found to be completely evacuated. It looked like a cold, fine black powder that did not stick to the tool (Figure 10).

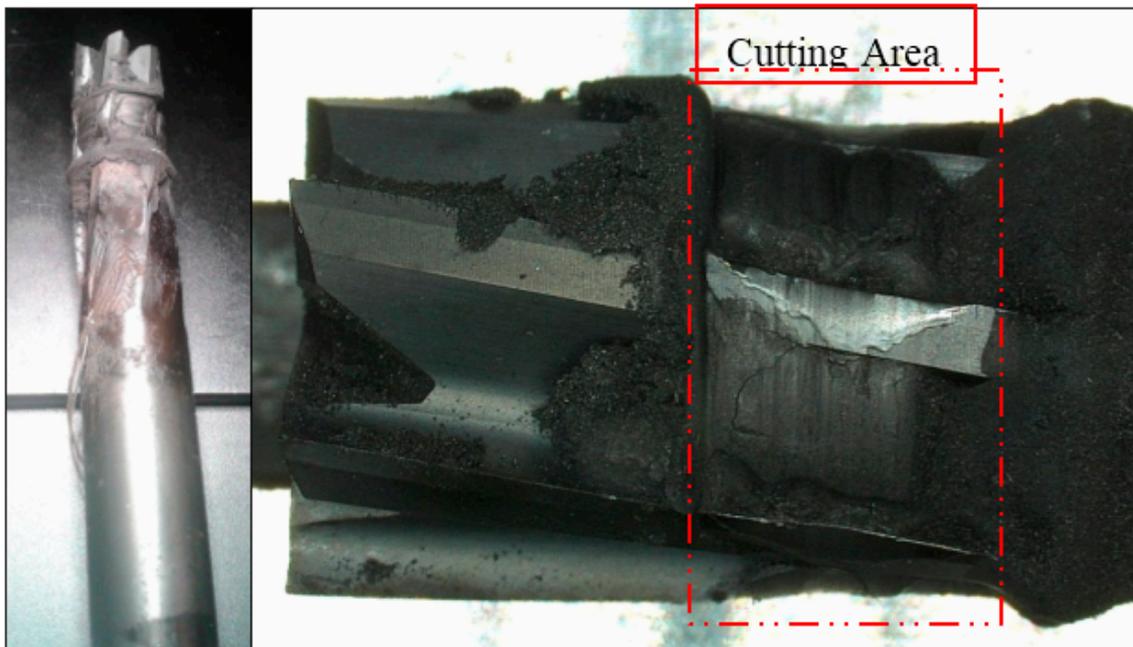


Figure 9. Cutting zone after machining (worn tool).

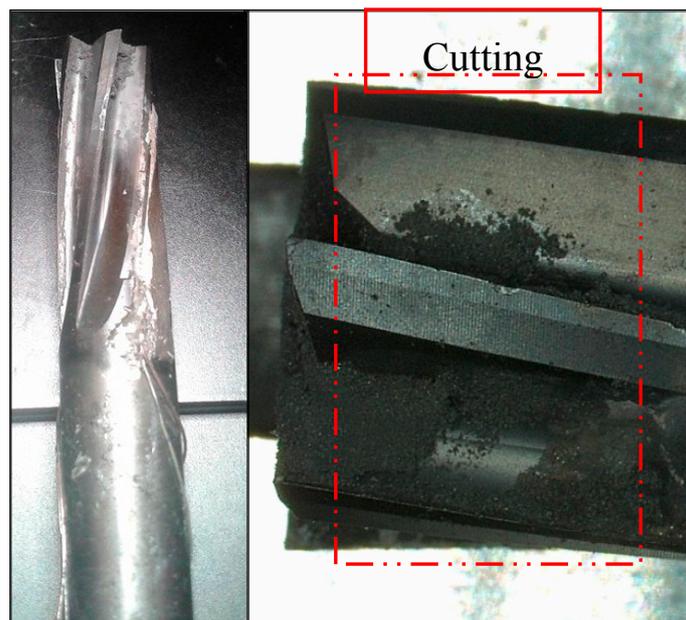


Figure 10. Cutting zone after machining (new tool).

3.2. Damage on the Surface of Test Coupons

Figure 11 presents the microscopy of the machined edges with both the new and worn tools. The surface of samples machined with a new tool showed the most damage (looking like small holes, as shown in Figure 11a) for plies oriented at -45° , which was due to the fiber-cutting mode. In this case, no thermal damage caused by the cutting temperature could be seen (Figure 11a). For samples machined with the worn tool, it was clearly shown how the presence of thermal damage affects the machined surface. The plies could not be distinguished, resulting from the spreading of the hot and sticky matrix and surface homogenization (Figure 11b). The emergence of other defects such as uncut fibers or fiber pull-out can be seen in Figure 12.

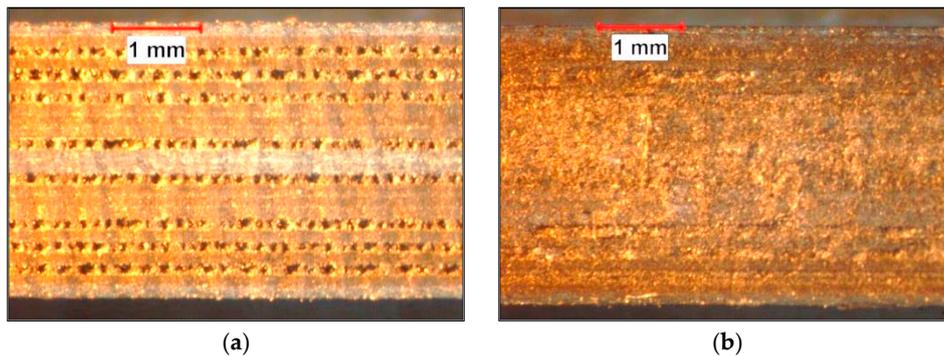


Figure 11. Machining edge: (a) using the new tool; (b) using the worn tool.

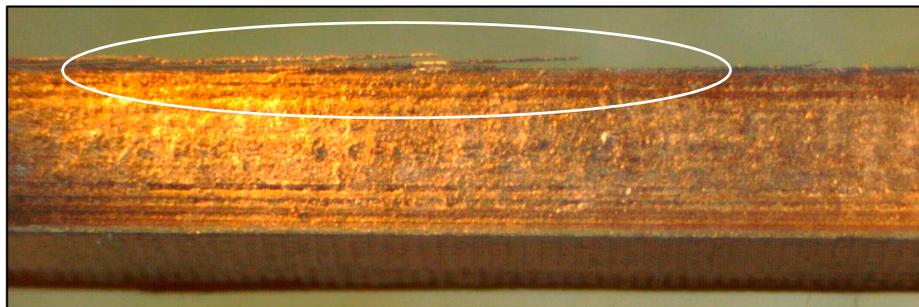


Figure 12. Delamination of test coupon machined using the worn tool.

Although the temperature at the cutting edge reached 300°C for the new tool (which is also above the glass-transition temperature), the surface did not appear to have suffered from thermal damage. The most credible hypothesis in this case is that heat was evacuated by the tool and the chip, thereby reducing its transmission to the material. Also, the diamond coating, which is an excellent heat conductor, probably helped heat dissipation. The machined surface using the worn tool was visibly thermally damaged.

3.3. Surface Roughness of Trimmed Coupons

The roughness measurements confirm what was observed in the literature. The up-milling machining configuration provided, on average, a lower roughness than the down-milling configuration (Figures 13 and 14). Machining with a worn tool also provided a lower roughness than with a new tool. This may seem surprising, but it is explained by the presence of the degraded matrix spread over the composite surface machined with a worn tool, as shown in Figure 11b.

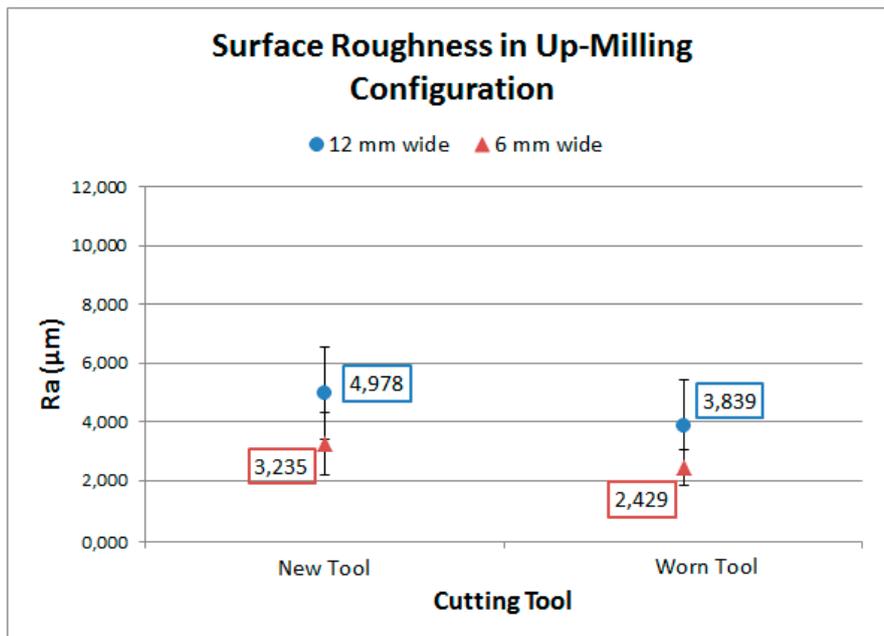


Figure 13. Surface roughness for both specimens widths in the up-milling.

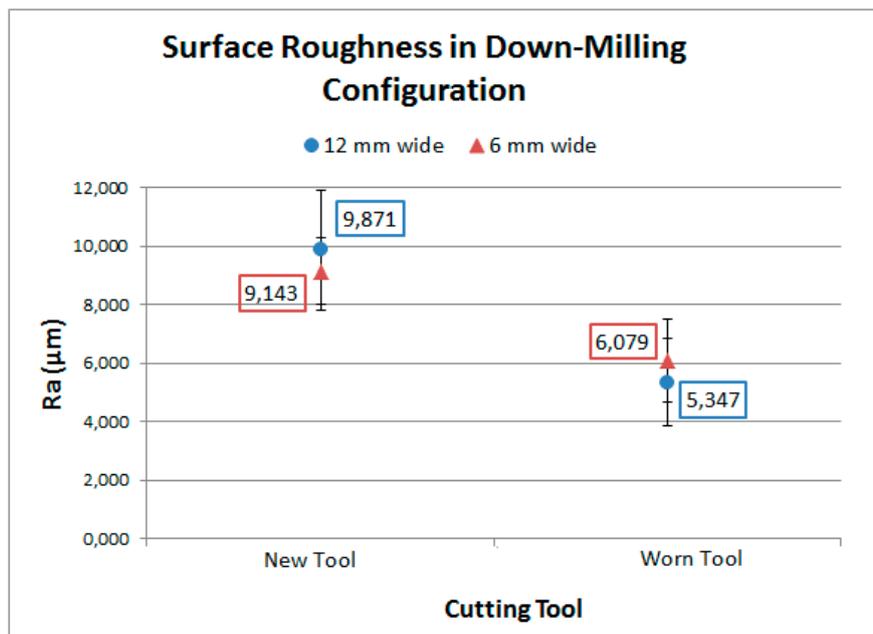


Figure 14. Surface roughness for both specimens width in the down-milling configuration.

The standard deviation of the roughness measurements is quite important, making this measure quite unreliable to qualify composite materials. This measurement makes the development of any model quite difficult because the internal defects, hidden by the presence of the degraded matrix spread over the cut surface, are underestimated by surface roughness measurements as also suggested when comparing Figure 11a,b. There was, on average, a decrease in the roughness (a better surface finish) when using a worn tool and this trend was confirmed whatever the specimen's width and machining configuration.

3.4. Mechanical Test Results

Out of the 60 samples tested, a total of 53 showed acceptable ruptures (considering ASTM D3039 requirements). A total of seven outliers were identified and removed from the analysis (Table 6). The results showed a very small variation of the ultimate tensile strength for the 12 mm-wide specimens. This low variation was equal to the interclass variation (standard deviation of a single group of samples). It can be concluded that the cutting temperature caused by advanced tool wear did not affect the tensile strength of the material for this specimen width. This phenomenon was observed for both machining configurations (up-milling and down-milling). This meant the damage (thermal and mechanical) was not significant enough to influence the tensile strength for this specimen width. For the second series of experiments however, cut to 6 mm (half the width of the first specimens), a significant difference was observed. A 10% decrease in mechanical properties was observed for test specimens machined with a worn tool compared to those machined with a new tool. The same trend was observed whatever the machining configuration (Figures 15 and 16). We can conclude that the cutting temperature generated by the tool wear influences the mechanical properties from a critical width.

Table 6. Number of good ruptures.

12 mm-Wide Specimens				
Two Cutting Conditions	New Tool		Worn Tool	
Machining Configuration	Up-Milling	Down-Milling	Up-Milling	Down-Milling
Number of Repetitions	6	4	6	4
Number of Good Ruptures	6	4	6	4
6 mm-Wide Specimens				
Two Cutting Conditions	New Tool		Worn Tool	
Machining Configuration	Up-Milling	Down-Milling	Up-Milling	Down-Milling
Number of Repetitions	11	9	11	9
Number of Good Ruptures	10	7	10	6

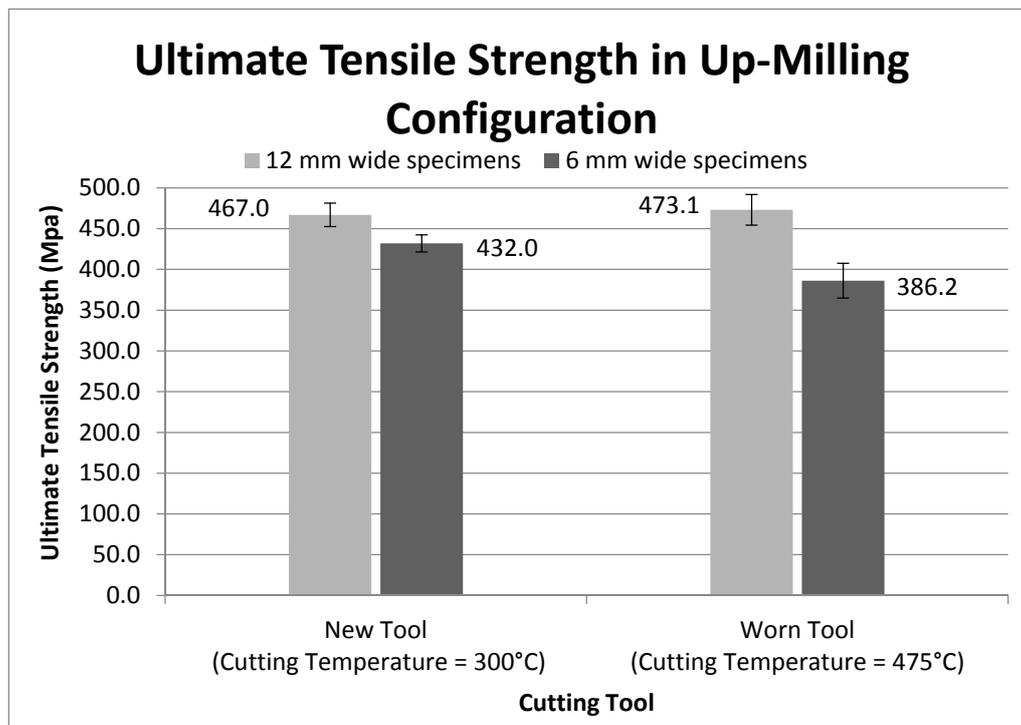


Figure 15. Ultimate tensile strength in the up-milling machining configuration.

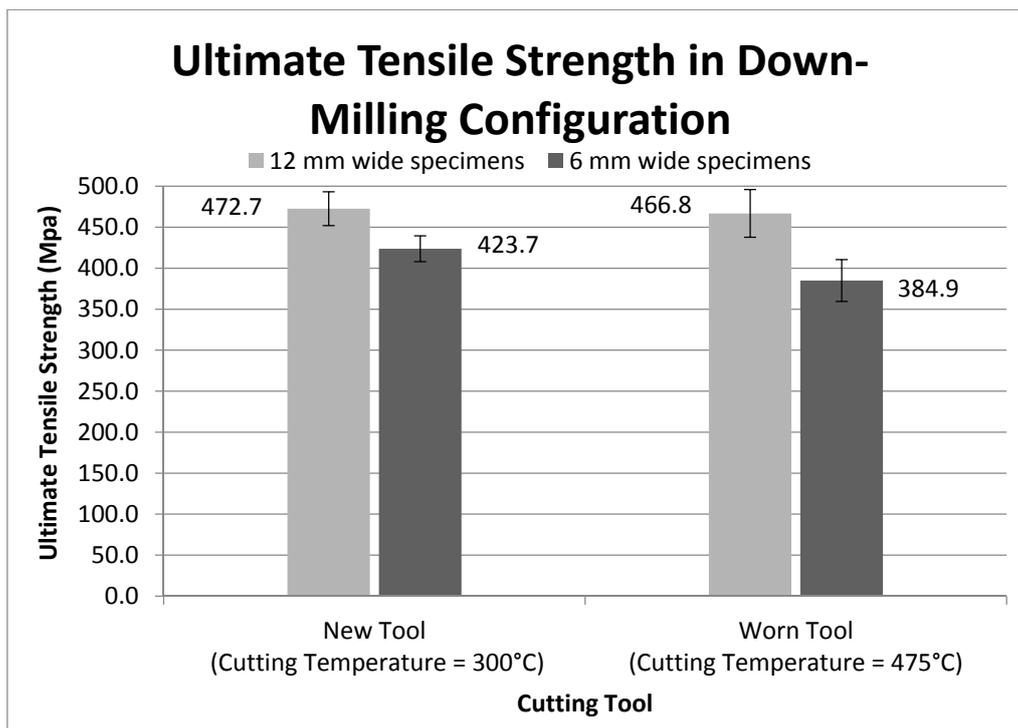


Figure 16. Ultimate tensile strength in the down-milling machining configuration.

4. Conclusions

The objective of this study was to study the influence of the cutting temperature caused by a new tool and a worn tool on the ultimate tensile strength. For this, samples of $3.6 \times 12 \times 250$ mm and $3.6 \times 6 \times 250$ mm in carbon/epoxy quasi-isotropic 24-ply laminate composite were machined using a trimming operation. The low specimen width was intended to amplify the influence of thermal damage to the specimen's edge that was created when cutting. Two cutting configurations were considered: up-milling and down-milling; and two tools were used: a new and a worn to produce different cutting temperatures. The main conclusions are:

- Concerning the cutting-temperature profile, the new tool was pre-heated to 350 °C and an almost constant cutting temperature of 300 °C was reached. The temperature was almost constant throughout the test (step), which was very encouraging. The second tool (worn tool) was pre-heated to 400 °C for a cutting temperature of 475 °C. For each condition, the temperature profiles among the samples were globally the same.
- The analysis of the cutting surface with a binocular microscope showed a clear surface and a clear distinction between the plies on the surface machined with a new tool. The most mechanical damage was observed on the plies oriented at -45° . Moreover, the surface did not appear to have been thermally damaged. The most probable explanation was that the majority of the heat generated by cutting was dissipated by the tool and the chip, and was not transmitted to the work piece. For samples machined using the worn tool, a relatively smooth surface was observed, there was no ply distinction. The glass-transition temperature of the resin matrix was definitely reached on the machined surface, resulting in a smooth surface. The matrix was carbonized and the molten resin culminated in a "blur" and smoothing. Uncut fibers or fiber pull-out were also observed for the plies oriented at 0° and -45° for the samples machined with the worn tool in the down-milling configuration.

- The roughness measurement showed that the down-milling cutting configuration was not recommended because it produced the worst results and more mechanical damage was noticed. There was also a better roughness for samples machined using the worn tool in both cutting modes.
- There was little variation in tensile strength for 12 mm-wide specimens whatever the machining configuration or tool used. A significant decrease of 10% of the tensile strength for the 6 mm-wide test specimens machined by a worn tool was identified compared to those machined with a new tool. It appeared that the edge defects caused by the cutting temperature influenced the mechanical properties at a critical size at which the defect became significant. However, it was difficult to determine whether this decline was due to mechanical or thermal defects. Future development aims to succeed in cooling the tool to room temperature in order to differentiate the mechanical and thermal damage and hence determine which is predominant.

The most relative result of this research regards the performance decrease, which was observed only on small-dimension specimens. This demonstrates that the thermal defects caused during cutting become significant on the mechanical performance of thin parts or thin walls found when holes are located near part edges. This result should be qualified, as the influence of edge defects becomes insignificant as the width of parts or walls exceeds a critical value.

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Author Contributions: Jean-Francois Chatelain designed and directed the study. Jeremy Delahaigue performed all the experiments and measurements. All authors contributed to the analysis of the results and to the writing of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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