Effect of Tool Geometry Special Features on Cutting Forces of Multilayered CFRP Laminates

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Abstract: - The cutting forces generated during the machining processes are very important, especially when machining Fibre Reinforced Plastics (CFRP). Controlling these cutting forces constitutes one of the keys to reducing the quality issues or defects induced in CFRP parts. Cutting forces are governed by many phenomena, such as material properties, cutting conditions and tool geometry. Over the last five years, new geometries have been proposed to improve the performance of CFRP cutters, with most developments relating to carbide-coated cutters. Popular special CFRP features include cross-cut tools with positive negative helix angle and grooved-teeth tools. In the present study, these two geometries were compared to a carbide standard cutter. The cutters were used for detouring quasi-isotropic laminates with different thicknesses, and the comparison was based on the cutting forces. The signals recorded were collected under different cutting conditions, and then analyzed. It was found that unstable cuts may occur during the machining of CFRP laminates. Some stable speeds and feeds were identified for the different cutters, and for these stable conditions, the force amplitude and profile were compared. It was found that adding features to the standard geometry significantly affects the cutting forces. While the cross cut geometry generates a compressive thrust force, the grooved geometry induces a quasi-null thrust force accompanied by less fluctuation of the feed force and the normal cutting force.

Key-Words: - Detouring, composites, CFRP, tool geometry, groove-teeth, cross cut, cutting forces.

1 Introduction
Presently, various tool materials exist that are capable of withstanding the abrasiveness and strength of Carbon fiber reinforced plastics (CFRPs), namely Diamond, Polycrystalline diamond (PCD) and coated carbide. While these three materials offer high hardness, which is a key property for successfully machining CFRPs, only solid carbide offers the flexibility of different cutter geometries, accompanied by reasonable costs. The efficiency of a carbide cutter is determined by the coating and the cutting edge geometry. The cutter geometry can be defined by different angles in the tool-in-hand system, the tool-in-machine system or the tool-in-use system [1]. For an end mill cutter, the principal angles that significantly affect the cutter performance are the rake angle, the clearance angle, the tool nose radius and the helix angle.

The cutting tool's rake angle is the angle between the cutting edge and the cut itself, and it may be positive, negative, or neutral. The first allows lower cutting forces, while the latter provides a stronger tool wedge. For CFRP machining, both geometries have major impacts on the chip formation mode [2]. For unidirectional laminates, the chip formation mode is primarily a combination of the fiber orientation angle and the cutter rake angle [3]. The rake angle may also affect the quality of the machined surface, and increasing the rake angle improves the overall quality of the machined edge [3]. The clearance angle prevents the cutter from rubbing against the machined surface. For composite materials, this is the angle that controls the bouncing of fibers on the clearance face, and as a result, the clearance angle may therefore affect the cutting forces [2]. Furthermore, it was observed that using large clearance angles improves the edge quality of the machined laminates [4]. Another important tool geometry parameter is the nose radius. The tool nose radius is the angle formed by the point of the tool; it may be large, for high strength operations needed when roughing parts, or sharp, for fine operations needed during finishing operations. Generally, the cutter edge is prepared with particular shapes in order to strengthen it. Those shapes include a honed radius, a chamfer, a
nose radius and, or a combination of all three. For composite materials, cutters with honed radii are preferred, especially when they are sharp. A cutter is deemed to be sharp enough when its nose radius is less than the fiber diameter. Generally, the fiber diameter ranges between 5 and 20 μm. However, a very low nose radius can weaken the cutter, making plasticization of the edge cutter possible under the resistance of the strong fibers. It has been experimentally proven that for CFRP, the nose radius affects the chip formation mode [5].

Finally, it is important to address the influence of the helix angle, which is the angle formed by a line tangent to the helix and a plane through the axis of the cutter. Generally, for metallic alloys, end mills with small helix angles develop the greatest cutting force and surface roughness [6]. In fact, if the flutes were straight, the whole tooth would impact the material at once, causing the cutter to have the same axial chip load along its axis. This is the main reason why the effect of the helix angle is negligible when the laminate thickness is small. In fact, if the depth of cut is less than 5% of the helix pitch, the effect of the helix angle will be negligible due to the low variation of the axial chip load along the cutter axis [7]. This means that for a thin laminate, the use of a straight or helical angle will have a similar effect. Generally, helical cutters generate a higher axial force than do straight cutters. Acting normally on the laminate, this axial force causes delamination and fuzzing in the surface ply, which is not supported in the force direction [8,9]. To reduce the effect of the unidirectional axial force, new cutters utilizing a double helix are proposed by manufacturers. The two helixes are opposed, which may generate compression from both sides of the laminate, and thus prevent delamination. Another compromise to this geometry is a grooved tooth. Instead of creating a macro helix angle on the whole body of the cutter, it is possible to create a smaller helix angle on each tooth. If repeated along the tooth, the grooves will present a sort of micro helix angle. Such a geometry would be expected to reduce the cutting forces and enhance the cutter performance. An example of a grooved tooth end mill is presented in Figure 1.

![Fig. 1: Example of grooved tooth geometry](image)

Various studies in the CFRP machining field have been interested in the standard definition of the tool geometry (helix angle, rake angle, and clearance angle and nose radius). However, to the authors’ knowledge, the matter of special features has not been covered in depth. The goal of the present study is to evaluate the effects of two non-standard features added to cutters designed for CFRP machining. The comparison will be based on cutting force analysis, surface roughness and delamination. To that end, this paper is organized as follows: the first section deals with the methodology adopted for the experimental work, followed by a discussion of the results, focusing on the analysis of the effects of special features on both force amplitude and profile. These are followed by an analysis of the resulting surface finish and the part delamination.

2 Methodology

The laminates for machining tests were prepared in a controlled aeronautical environment using pre-impregnated technology. The stack having 64% of fiber volume fraction was autoclave-cured. The orientation of the plies was such that the quasi-isotropic properties of the laminates were obtained. The layer orientation and laminate thickness are summarized in Table 1.

| Table 1: Properties and configuration of the machined CFRP laminates |
|---|---|---|---|---|
| Thickness [mm] | Volume fraction | Total number of plies | Average ply thickness [mm] | Ply orientation |
| P1 | 3.47 | 64% | 24 | 0.144 | 4/8/8/4 |
| P2 | 4.63 | 64% | 32 | 0.144 | 6/10/10/6 |
| P3 | 5.79 | 64% | 40 | 0.144 | 8/12/12/8 |

The presence of major processing defaults can represent the first source of cutting force signal distortions, and if major defaults are present, it becomes difficult to interpret or model the cutting forces. The square-shaped laminates were therefore inspected prior to machining. A C-Scan was used to verify the absence of any major processing defaults. Once inspected, the laminates were pre-drilled for tightening on a machining fixture, as shown in Figure 2, where the experimental set-up is
presented. The pre-drilling was necessary both for screwing the laminate to the fixture and in order to facilitate the smooth entry of the cutter in the laminate when detouring each coupon using different cutting conditions. The figure 2 shows the aluminum back plating system (#2) using 49 screws and a torque wrench to secure the laminate (#1). Detail A shows a sample of a machined test coupon. Each side of the squared sample was machined under specific cutting conditions, and different combinations of cutting parameters were tested. The subassembly (laminate and back plate) was tightened to a three-axis dynamometer table type Kistler 9255B (#3). The charge amplifiers generate five output signals transmitted to a data acquisition card (type DT-9836). The sampling frequency was set at 48 kHz/canal, for a recording time of 16 seconds. A USB communication protocol was used to interpret the output signals of the data acquisition card, with a Matlab-based signal processing program. The measurement system was statically and dynamically calibrated on an MTS tension machine. Both static and dynamic calibration allowed the estimation of the drift errors and their correction if they exceeded the acceptable limit of ±10 mN/s for the three directions. To allow the detection of the slightest chatter signals, no filter was applied on the force signals. The signals were exported to Matlab for further analysis. All machining tests were realized under dry conditions using the same tool geometry. The analysis performed on the resulting force signals for different cutting parameters and different tool geometries is presented in the following sections.

3 Results and discussion

3.1 Tool geometry and stability

As earlier mentioned, different tool geometries were used to machine the CFRP laminates, and their descriptions are summarized in Table 2. The last column of the table shows the cutting tools pictures recorded with a 5X magnification factor.

<table>
<thead>
<tr>
<th>Tool#</th>
<th>Flute number</th>
<th>Diameter</th>
<th>Material</th>
<th>Helix angle</th>
<th>Rake angle</th>
<th>flank angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>#C1</td>
<td>8</td>
<td>10.00 mm</td>
<td>Carbide CVD coating</td>
<td>10°</td>
<td>10°</td>
<td>15°</td>
</tr>
<tr>
<td>#C3</td>
<td>8</td>
<td>9.525 mm</td>
<td>Carbide CVD coating</td>
<td>10°</td>
<td>10°</td>
<td>15°</td>
</tr>
<tr>
<td>#C6</td>
<td>6</td>
<td>9.525 mm</td>
<td>Carbide CVD coating</td>
<td>±30°</td>
<td>20°</td>
<td>15°</td>
</tr>
</tbody>
</table>

From the results presented in Figure 3, it can be observed that tools C1 and C3 provide similar results in terms of cutting forces. The two cutters have very similar geometries, which explain the same profile obtained for the X cutting force component in terms of amplitude and profile. A similar result is observed for the Y component. The axial component is higher for cutter C1 than for cutter C3, which may be due to added grooves on tooth C1. The recorded force signals when machining with the C6 cutter are much higher than with the other two cutters. In fact, the axial cutting force is 5 to 10 times higher than regular geometries. The high amplitudes observed in the three cutting directions for tool #C6 are most probably due to a dynamic instability. To confirm the presence of such instability, a Fourier analysis of the recorded signal in the steady-state period was conducted. The results obtained are plotted in Figure 4.
The spectra of the $F_x$, $F_y$, and $F_z$ forces show that the totality of the signal energy is carried by a single 3809 Hz frequency. The latter is neither a harmonic of the spindle speed (111.4 Hz) nor a harmonic of the tooth passing frequency (668.4 Hz). The dynamic instability was also confirmed by sound recording during the cutting test. The presence of a sharp sound was noticed during machining. In the author’s opinion, the instability was due to a combination of two causes:

1. The laminate width is thinner than the cross cut part of the cutter.
2. The selection of a spindle speed close to a resonance of the system tool-part-machine.

If one of the above factors is altered, the instability will disappear. The spindle speed was increased from 111.4 Hz to 166.6 Hz. Figure 5 summarizes the recorded cutting forces in the X, Y and Z directions and their corresponding spectra, using a fast Fourier transformation.

It can be observed that the amplitude of the cutting forces was significantly reduced. The FFT analysis demonstrated the absence of instability, and the signal energy carried was distributed on the spindle frequency and its harmonics. The absence of an amplified non-harmonic frequency attests to the nonappearance of dynamic instability. However, dynamic instability was repeatedly observed for several combinations of feed and speed, meaning that the cross cut geometry needs to select cutting parameters with care. In the author’s opinion, for the case of CFRPs, this geometry is less adequate for laminates having a thickness smaller than the cross part of the cutter. The previous analysis revealed the need for dynamic stability, which should enable a comparison of the geometry effect. One of the major challenges encountered was retrieving a feed and speed that are dynamically stable for the four tested geometries. A stable cut is characterized by a “clean” spectrum, where only the harmonics of the spindle speed can be observed. If the recorded force signal is plotted in the time domain, a stable profile of a cutting force signal will appear.
3.2 Effect of tool geometry on the amplitude

The forces exerted on the laminate during milling are characterized by a profile and amplitude, and any damage observed on the final part is a combination of these two characteristics. Figure 6 presents the amplitude of the cutting forces for each tool’s geometry. The fluctuation in amplitude observed is due essentially to the sinusoidal variation of the chip thickness.

The highest amplitude cutting forces were recorded in the feed direction X for the three geometries. This amplitude can be characterized by different mathematical descriptors, and the peak-to-peak value can properly describe the observed fluctuation. The highest peak-to-peak value is recorded for the standard geometry in the X direction, most probably due to the reduction of the high contact surface of cutter teeth in the cutting zone. This led to a higher rate of material removal at each tooth, which significantly increased the recorded amplitude of the feed cutting force. When, for the Y direction, the highest amplitudes are recorded for the grooved geometry which implies an increase of the abrasion between the cutter and the machined part surface. However, these grooves contribute to significantly decrease the axial forces. On the other hand, the standard geometry enhances the fluctuation of the cutting force between two maxima: one negative, and the second, positive. This fluctuation may cause significant damage to the laminate. The cross geometry contributed to eliminating this fluctuation by generating a directive cutting force, which is negative, meaning that force exerted on the laminate is compressive. Despite this result, the authors observed that the worst damage cases were caused by the cross cut geometry. This may be due to the fact that the damage was not mainly due to the maximum exerted force, but also to the dynamic component of the acting forces, thus making it crucial to compare the profiles of these forces, as presented in the following section.

3.3 Effect of tool geometry on the profile

Adding special features to the standard tool geometry affects both the general and the per revolution profile. A comparative graph is plotted in Figure 7, showing the cutting forces in the x direction for the three different geometries.

The first period (Zone I) corresponds to the engagement of the tool in the part. This zone is characterized by a partial engagement of the cutter in the workpiece, bringing a high amount of energy to the machined part. The force profiles of zones I and III, which are the transient periods, look very similar for the C1 and C3 geometries (Figs. 7a and 7c). For the third geometry C6 (Fig 7e), the tool entry and exit are much smoother. During the steady state, the cutter advances smoothly in the part. Once the cutter is fully engaged, the cutting forces reach the second zone (Zone II), the steady state period, which is characterized by a repetitive cutting force profile from one revolution to another. It is also characterized by nearly constant force maximum amplitude for each period. Regarding the force per revolution, the three geometries presented four different lots, with each lot corresponding to one tool revolution. It can be seen that the highest fluctuation is observed for the standard cutter. The force fluctuation can be evaluated by the peak-to-peak value corresponding to the maximum force minus the minimum force. Figure 7 (b, d and f)
presents the cutting force in the X direction during 4 revolutions of the cutter. The force profile for each passing tooth of the cutting tool can be clearly identified in the figure. Each peak of the force profile presents the passage of a tooth. The cutting force starts with a quasi-null value when the tool is engaged, and then the cutting force increases until it reaches a maximum at full tooth engagement with respect to X axis, and then decreases until the tooth separates from the workpiece, giving way to the second tooth. The next tooth follows a similar profile as the first tooth. The engagement of more than one tooth is obvious in the figure, as the instantaneous cutting force continuously increases in one revolution. The addition of grooves smoothes the force profile making the fluctuation less sudden (C1 compared to C3). It can be concluded that the smoothing of the force profile is significant when using grooved cutter.

4 Conclusion
The cutting forces provide a good indication of cutter performance. These forces give clear insights about the cutter during different phases of machining. However, to be useful, the forces must be recorded under stable conditions. In this study, different combinations of cutting conditions were conducted in order to find commonly stable conditions for three cutters with different geometries. These geometries were developed especially for the detouring of CFRP laminates. It was found that the cross cut geometry is more sensitive to instability than standard and grooved geometries. However, this cross cut geometry generates a compressive thrust force, which is the opposite of the standard geometry. It was found that the special grooves reduce the axial force to approximately a null value; in addition, they significantly reduce the fluctuation of the feed and normal cutting forces.

References: