1 Introduction

Nowadays, composite materials are more and more used in various industries such as aircraft, spacecraft, automobile, marine, chemical processing equipment or sporting goods thanks to their high performances and their high strength to weight ratio. Composite parts are manufactured near net shape in order to reduce the number of machining operations, which weaken the material. Main machining operations realised on composite materials are: trimming, surfacing and drilling. Machining composite materials involves many problems due to the lack of knowledge in this domain such as: machinability of composite materials or impact of machining quality on mechanical behaviour.

In the French industry, one of the methods used to determine the optimal cutting parameters is the tool/material pairing. It consists in minimizing the specific cutting force in order to maximize tool life. Many studies have studied dry drilling of 2D woven or unidirectional carbon/epoxy composites [1], [2].

Different damages have been identified when drilling carbon/epoxy composites. Those damages can be separated in three categories, in function of their location: at the entrance, the wall and the exit of the hole. At the entrance of the hole, peel-out delamination is the main default generated and is dependent on the geometry of the tool, the machined materials and the cutting parameters [7 m]. Damages appearing on the wall of the hole are dependent on the relative angle between fibers direction and cutting speed, the machined materials and the edge radius. Different mechanisms of chip removal have been identified depending on the angle θ and generate different machined surface [3]. Push-out delamination appears at the exit of the hole. This default appears when the thrust forces are too high, which generates a crack that propagates at the interface between two plies. It is dependent on the feed rate, the material and geometry of the drill, and the wear of the tool. This delamination is the main damage appearing in drilling carbon/epoxy composites. In order to reduce delamination, interlock composites have been chosen. Thanks to the reinforcements in the third direction, they are assumed to prevent the appearance this damage.

In the literature, many different geometry drill bits made of different tool materials have been tested for drilling composite laminate. Six categories of drill bit can be identified: twist drill bit [4–9], step drill bit [5], [10–15], brad point drill bit [10–12], [15], [16], slot drill bit [1], [10–12], [16], [17], straight flute drill bit [17–19] and electro-deposited trepanning tool (also known as core drill bit) [10–12], [16], [20], [21]. Amongst the tool materials used, the most used are uncoated cemented carbide (ISO grades K10, K20, etc.), coated cemented carbides and polycrystalline diamond (PCD).

Thrust force is one of key indexes to describe machinability of composite laminates as it directly affects the quality of drilled holes especially drilling induced delamination [7], [22–24]. The effects of different cutting parameters on thrust force have been studied. Most of investigators [1], [7], [15], [17], [25–28] found that the effect of spindle speed on thrust force is insignificant while the effect of feed rate is remarkable and generates an increase in thrust force when feed rate increases. In order to determine the impact of thrust force on delamination, many analytical and empirical models have been developed. It is believed no delamination appears below a critical thrust force when drilling composite laminates. Hocheng and Dhawan developed the first analytical model to determine
This critical thrust force [29]. They used linear elastic fracture mechanics (LEFM) method to determine the critical thrust force models related to push-out delamination for twist drill bits. They considered thrust force as a single concentrated load through chisel edge that depends on the composite laminate mechanical properties and the thickness of the uncut plies under the drill bit. Hocheng and Tsao extended this model by developing a series of comprehensive analytical models [16], [21], [30] of critical thrust force for various drill bits (brad-point drill bit, slot drill bit, step drill bit and trepanning tool) and compared them with the twist drill bit results. A comparison with experiments was realized and showed good agreement with theoretical models. Trepanning tools seem to accept the highest critical thrust force, which justifies the choice of this study. Updhyay and Lyons [23] modified the critical thrust force model of Hocheng and Tsao, assuming that thrust force is distributed along the cutting edge. Those results confirm that thrust force is the key to avoid delamination when drilling composite laminates. More recently, Lazar and Xirouchakis [19] have studied precisely the distribution of the mechanical load along the cutting edge for a tapered drill reamer and 2-facet twist drill in function of the feed rate and the drill geometry. Among the various studies encountered in literature [10–12], [16], [20], [21], trepanning tools seem to reduce delamination. However, no investigations on drilling of 3D interlock composite under lubrication have been reported.

The aim of this work is to investigate the influence of the machining parameters and tool wear on the quality of the drilled holes during machining of 3D woven carbon/epoxy using twist drill bits and trepanning tools with electro-deposited diamond grains. A comparison of the quality of the machined holes obtained thanks to these two processes of machining is proposed.

2 Experiments

2.1 Drilling tools

The drill bits chosen in this study are three lips twist drills (3LTD) of 8.57 mm diameter, in diamond-coated carbide, designed by Walter Company and trepanning tools with electro-deposited diamond grains of 8.51 mm diameter (cf. Fig. 1). For the trepanning tools, different grain size (252, 151 and 76 µm) and crimping rate (50% and 33%) are tested. Drilling tests are performed with a 5-axis CNC machine (cf. Fig. 2) with the use of a coolant (Blasocut BC25 MD). When drilling with trepanning tools, internal lubrication is always used (to remove the core sample) while tests were performed with and without internal lubrication for 3LTD.

Wear tests are carried on the same machine with the same conditions. Every ten drillings realised thrust forces are measured and tool is controlled (flank wear Vb, grains health...).

2.2 Material

The material used in this study is 3D woven Carbon Fibre Reinforced Plastic (CFRP). Carbon fibres are IM7 from Hexcel Composites and epoxide resin is PR520 from Cytec. Composite samples are realised by Light RTM and the fibre volume fraction of this CFRP is 59 %. A Snecma patent protects this material.

2.3 Experimental design

Fig. 1: Experimental set-up.
In order to determine the influence of cutting parameters on the drilling of 3D woven composites, ten different spindle speeds are tested with a fixed feed rate in order to identify its impact on thrust force and machining quality. Then ten different feed rates are tested with a fixed spindle speed. Concerning trepanning tools, diamond grain size (76, 151 and 256 µm) and crimping rate (50% and 33%) are also tested. The maximum feed rate tested for trepanning tools correspond to the maximum value allowing machining (cf. §3.1). When the feed rate is too high, trepanning tools are not able to evacuate chips and the removing mechanism is catastrophic (Fig. 3). The objective of those experiments is to determine the influence of cutting parameters on the machining quality (roughness, circularity, precision…) and thrust forces. Wear tests are also carried out with the optimal cutting parameters identified during first set of machining experiments, in order to evaluate the influence of tool wear on machining quality and thrust force.

2.4 Metrology

The thrust force and torque during machining are measured using piezo-electric dynamometer (Type Kistler 9272). The charge amplifier (Model 5019) converts the resulting charge signals, which are proportional to the force, to voltage and managed through the data acquisition system. Roughness is measured with a Mitutoyo SJ 500 roughness tester and hole diameters and circularity are measured using co-ordinate measuring machine with φ 2 mm ruby probe. Flank wear and trepanning tool wear are measured thanks to optical microscope.

3 Results

3.1 Impact of machining parameters on thrust forces

When drilling with the three lips drill, experiments showed the great influence of feed rate on thrust forces (Fig. 4b), which is in accord with the results found in literature. This phenomenon is due to the increase of the chip size when feed rate increases. Likewise, spindle speed has a minor influence on thrust forces (Fig. 4a). Thrust forces tend to decrease when spindle speed increases while drilling with 3LTD without internal lubrication (drop of 20%). It can be assumed that in this configuration machining temperatures are close to the $T_g$ of the material that creates a local softening of the machined material. This effect is strongly reduced with internal lubrication (drop of only 6%) but thrust forces are higher because of the pressure of the lubricant on the machined area.

When drilling with trepanning tools, thrust forces are found highly dependent on feed rate, for the same reason as 3LTD (cf. Fig 4c). Contrary to 3LTD, trepanning tools are not able to machine at high feed rates. When machining with a too high feed rate, the tool is not able to evacuate chips anymore and tends to push the material instead of cutting it. The machining quality is then strongly degraded and the tool gets dirty and worn. The core sample sometimes stays stuck in the tool. The average limit feed rate for each grain size is detailed in Table 1. Internal and external lubrications keep the machining temperatures low and the thrust forces are not affected by change on spindle speed.

<table>
<thead>
<tr>
<th>Grain size</th>
<th>Limit acceptable feed rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>76 µm</td>
<td>0.01 mm/rev</td>
</tr>
<tr>
<td>151 µm</td>
<td>0.03 mm/rev</td>
</tr>
<tr>
<td>252 µm</td>
<td>0.06 mm/rev</td>
</tr>
</tbody>
</table>
3.2 Impact of machining parameters on machining quality

The impact of cutting parameters on average roughness is shown on Fig. 5 for 3LTD.

When drilling with 3LTD, the average roughness is homogenous and low (≤ 3 µm) on the wall of the hole for low feed rates (≤ 0.05 mm/rev without internal lubrication and ≤ 0.075 mm/rev with internal lubrication). Nevertheless, when the feed rate is chosen higher than these values, average roughness becomes heterogeneous on the wall of the hole and defects appear where θ equals -45° (Fig. 6).

The weaving of carbon fibres is in 3D but the fibres are only oriented in 0° and 90° in the horizontal plan. Thus the angle θ take the value -45° (the worst case according to König [3]) four times around the hole (twice for the warp and twice for the weft).
average roughness at θ = 0° stays constant and low (≤ 3 µm) but at θ = -45° it increases proportionally with the feed rate (Fig. 5). Internal lubrication tends to reduce the average roughness on the wall of the hole and increases the rigidity of the tool, keeping it from vibrating at high spindle speeds.

With internal lubrication, no variations in geometrical properties are detected (diameter, circularity…) in the studied range. Without internal lubrication, at high cutting speed, vibrations appear and generate a larger diameter with some circularity issues.

When drilling with trepanning tool, the average roughness is homogenous and low (≤ 4 µm) on the wall of the hole whatever the cutting parameters are. As the grains are randomly distributed along the tool, the θ angle of each grain is different and no macroscopic roughness is generated (Fig. 7).

Finally two sets of cutting parameters were selected for 3LTD and one for trepanning tools for tool wear tests (cf. Table 2). Those different cutting parameters are chosen in function of the previous results. Two sets of conditions are chosen for the 3LTD in order to determine the evolution of the roughness detected at 45° when the tool is getting worn. As the machining parameters do not have a great impact on machining quality when drilling with trepanning tools, one set of condition is tested. The impact of tool wear on thrust forces, roughness and geometry of the hole is studied.

Table 2: Chosen conditions for wear tests

<table>
<thead>
<tr>
<th>Test</th>
<th>Tool</th>
<th>f (mm/rev)</th>
<th>Vc (rpm)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>3LTD</td>
<td>0,05</td>
<td>3700</td>
<td>No defects</td>
</tr>
<tr>
<td>(b)</td>
<td>3LTD</td>
<td>0,08</td>
<td>5550</td>
<td>Defects at 45°</td>
</tr>
<tr>
<td>(c)</td>
<td>Trepanning tool</td>
<td>0,03</td>
<td>7500</td>
<td>-</td>
</tr>
</tbody>
</table>

3.3 3LTD wear tests

As seen in literature [31], when machining carbon/epoxy composite materials with drills the main tool wear is located on the flank face. Thus flank wear (by optical microscope) and thrust forces are studied. Their evolution in function of the number of hole drilled is represented on Fig. 8 and 9. Flank wear is measured until the diamond coating tool tips start to delaminate and accelerate tool wear. Tests are carried on after until the three tool tips are totally worn. Each test is repeated twice in order to determine the repeatability of the process. As seen in Fig. 9, when machining with the lower feed rate, the three tool tips get worn after 130 holes. Nevertheless, when a higher feed rate is chosen (cf. Fig 8), the three tool tips get worn later, after 200 holes approximately. When the flank wear Vb reaches a value of 0.8-0.9 mm, the diamond coat tends to delaminate. This delamination of the coating (scaling) can be homogenous or catastrophic (cf. Fig. 10), in function of the quality of the coating. This quality has showed to be quite variable from one tool to another. This wear lead to a drop in thrust forces in a first time, and an increase in a second time. This phenomenon can be explained by the fact that when the diamond coating delaminates, the carbide part of the drill is machining instead and is really sharp. Nevertheless, carbide resists much less to the abrasion of carbon and gets worn really quickly (10 to 30 holes). Thrust forces start to increase again when the carbide is totally worn and diamond coating is in contact with the machined surface. The tool life of 3LTD is highly dependent to the quality of the coating. Catastrophic delamination will cause a rapid wear of the tool while...
homogenous wear along the cutting edge will increase tool life.

Fig. 8: Evolution of thrust forces and flank wear when drilling with 3LTD generating roughness at 45°. (f = 0.08 mm/rev, N = 5550 rpm).

![Graph showing thrust forces and flank wear over number of holes drilled.]

Fig. 9: Evolution of thrust forces and flank wear when drilling with 3LTD without defaults. (f = 0.05 mm/rev, N = 3700 rpm).

The wear rate is different between the two conditions. Fig. 11 represents the evolution of flank wear in function of the distance covered by one tool tip. This distance is calculated by:

$$d = N \cdot \frac{t}{f} \sqrt{f^2 + (2\pi r)^2}$$

where d is the distance covered by the tool tip (mm) after N drillings, t is the thickness of the machined material (mm), f is the feed rate (mm/rev) and r is the radius of the tool (mm). The impact of the distance covered by the tool tip on flank wear is similar for both conditions while no delamination of the diamond coating is detected. After the delamination, flank wear is difficult to measure because of the disappearance of the cutting edge due to abrasion. Thrust forces are also quite proportional to this distance but also to feed rate.

Fig. 10: Optical microscope pictures of tool edges at different tool wear (a) and two sorts of diamond coating scaling: uniform (b) and catastrophic (c).

With the wear of the three tool tips, the cutting edges get round and the machining quality also drops. Fig. 12 and 13 represents the evolution of average roughness in function of the number of holes drilled. The rounding of the last edge corresponds to the increase of the average roughness at 0° and 45°. The sharpness of the cutting edges tends to decrease with wear and delamination of fibers at 45° tends to increase. Diameter of holes produced stay in the tolerance interval, even when the three cutting edges are worn and important roughness is generated on the wall of the hole.

Fig. 11: Evolution of flank wear when drilling with 3LTD in function of the distance covered by tool tip.


3.3 Trepanning tool wear tests

Trepanning tool wears in a different way than 3LTD. Tool wear is indirectly measured through thrust force. SEM was used to determine the wear of grains at the surface of the tool. After a first phase of breaking-in where thrust forces increase from 150 N to 175 N for the first 60 holes, the thrust forces increase slows down and after 560 holes drilled, thrust forces are 200 N. At this point the tool is not worn and thrust forces are quite stable. Tool life of the trepanning tool has not been measured as no particular wear signs are detected at this point.

Average roughness on the wall of the hole in function of the number of holes drilled is represented in Fig. 14. The average roughness stays low (< 3 µm) during the first 300 holes before it starts to fluctuate between 2 and 5 µm. The same phenomenon is observed for the diameter, with a diameter that fluctuates after the 300th hole (but stays in the tolerance interval). After 560 holes drilled, the number of grains has decreased but the worn condition of the remaining grains is acceptable (cf. Fig. 15).

4. Conclusions

The study on the impact of cutting tool (3 lips twist drill and trepanning tool) and of the cutting parameters on thrust force, roughness and machining precision during drilling of 3D interlock composites enables following conclusions.

While drilling 3D interlock composite, damage generated are quite similar to the one encountered with composite laminates. Thrust forces are higher because of the increased resistance of the material in the third direction.

While drilling 3D interlock composites the feed rate is the factor that influence the most thrust force. The thrust force increase is related to the chip thickness. Specific cutting forces are higher when drilling with 3 lips twist drills, which could impact tool wear. This is due to the geometry of the tool, and more precisely, to the chisel edge.
The influence of spindle speed on thrust force was negligible when internal lubrication was used. Spindle speed has a slight influence on thrust force when machining with low feed rate and without internal lubrication. The cutting resistance of epoxy resin tends to drop when the machining temperatures increase.

Roughness on the wall of the hole is dependent on feed rate when machining with a three lips twist drill. When machining at low feed rate (< 0.05 mm/rev) the roughness is uniform on the wall of the hole. When the feed rate is higher than this value, defects appear when the angle $\theta$ is -45°. These defects increase with feed rate. Spindle speed does not have any impact on roughness.

When machining with an electro-deposited trepanning tool, cutting parameters do not impact roughness. This is due to the custom orientation of the diamond grains.

3LTD wear is highly dependent on the distance covered by the tool tip (which is related to feed rate). The maximum flank wear before delamination of the diamond coating is 0.8-0.9 mm. The number of holes a tool can machine is then dependent on the feed rate chosen.

Trepanning tools are highly wear resistant. Thanks to the high resistance to abradibility of diamond grains. After the breaking-in phase, the cutting mechanisms stabilize. Tool life is estimated superior to 600 holes.

Acknowledgment

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References


INFLUENCE OF CUTTING PARAMETERS AND WEAR IN DRILLING OF 3D WOVEN CARBON/EPOXY COMPOSITES


