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CFRPs drilling: comparison among holes produced by different drilling strategies

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Abstract

The drilling process of CFRPs is the most commonly employed machining operation owing to the need for joining these structures. However, these materials are prone to delaminate during the process and the presence of these defects can be a cause of rejection of these components. Therefore, this paper aims on the study of alternative drilling strategies such as: the orbital and a new drilling strategy (called circular drilling) to reduce the delaminations extension. Holes 8 mm in diameter were obtained by using different drilling strategies and cutting conditions and their influence on the cutting forces and delamination factor was studied.

Keywords: CFRPs; Drilling; Orbital drlling; Circular drilling; Delamination factor

1. Introduction

Carbon fibre reinforced plastics (CFRPs) materials, thanks to their strength to weight ratio, are widely used as structural components in several industrial application fields, especially in the aircraft industries [1]. In this latter case, these materials are largely used in civil airplanes, because their lightness reduces the fuel consumption and then increase the payload, for example in Boeing 787 more than the 50% of components are constituted by composite [2]. Although composite parts are made to near net shape, a large number of holes are often required for assembling different parts [3]. Therefore, drilling is one of the most ordinary machining operations and then the control of the hole quality is a relevant question, particularly considering that differently from traditional materials, the presence of fibers produces cracks and delamination problems into the laminate that can severely affect the mechanical properties of the structural parts [4,5]. Therefore, many research works focused the attention on the reduction of the hole damages of CFRP laminates after drilling; the most frequent forms of investigated damaged are: delaminations, peel-up and push-down mechanisms, micro-cracks and matrix burning [1,6]. Among all the above said defects caused by drilling, the delamination is one of the most critical, because it results in poor assembly tolerance and reduces the structure integrity of the material [7,8]. Indeed, this defect is responsible for the rejection of around 60% of the components produced in the aircraft industry [2,7]. Therefore, the current aim of high-tech industries working CFRP materials is to avoid and control this type of damage. Indeed, a lot of techniques are utilized to measure the delamination after drilling composites, such as optical micrograph, C-Scan and photography. Even if the C-Scan method is very accurate and allow to observe the internal damages, due to the simplicity and fastness respect to the C-Scan method, the optical micrograph is very often preferred to the C-Scan, so the most utilized parameter to evaluate the degree of damage on the composite at the entrance and the exit of a hole is the delamination factor, F_d. Therefore, the determination of the delamination factor obtained by observing only the top and

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bottom surfaces of the laminate via micrographics or photographs is a simple way to have a qualitative evaluation of the hole quality, and then to study how it is in relation with process parameters is very interesting. For this reason, several researchers studied the machining of composite materials and evaluated the damage considering the delamination factor:

Karnik et al. [9] studied the composites behavior when the delamination occurs as consequence of drilling machining, in particular they machined a CFRP composite laminate at high rotational speeds by using different twist drill tools that mainly differ in the point angle. Specifically, it was found that for minimizing the delamination, a combination of high speed rotation, low values of feed rate and point angle seemed to be the most appropriate selection. Miguelet al. [10] studied the drilling process of CFRP laminates by using different tool geometries (twist, brad, dagger and step) and differents feed rates. The results showed that for all the considered feed rates, the twist drill tool always presented the higher axial force. Also taking into account the damage area, the twist drill tool showed a lower delamination factor that increased with the increasing of the feed rate.

Aiming with the decreasing of the delamination factor after drilling, as alternative to conventional drilling, the orbital drilling strategy offers many advantages [1,11–13]. This machining technique reduces the cutting forces and the temperature on the working surface leading in a reduction of a series of defects related to the conventional drilling, such as delamination, matrix burnout and fiber pull-out.

Contrary to the conventional drilling where the hole diameter is limited by the tool one, the orbital drilling process allow the machining of borehole of different diameters with the same tool [14]. In addition, considering that in the orbital drilling process the greater movement is the circular trajectory and not the axial one, the axial cutting force results to be lower than the one reached during the conventional process involving in remarkable impact on machining accuracy, tool life, reduction of burr formation and delamination [14–16].

On the other hand, the machining time for orbital drilling is significant higher than that for the conventional drilling due to the helical tool trajectory.

In summary, from the literature review [14–16], it emerged that the orbital drilling produces a better hole quality with lower cutting forces but it is characterized by a more complex machine tool patch that involves in longer process time.

For this last reason, another drilling strategy, based on similar concept of the orbital drilling but with a simplifier and shorter tool patch could be used. To this aim, this work is focused on the study of a new drilling strategy to produce holes 8 mm in diameter under different cutting conditions. For a comparison, the same holes were also produced with the conventional and the orbital drilling strategy.

Both the cutting forces and the delamination factor were considered and correlated with the drilling technique and the process parameters.

Fig. 1. Used drilling tool.

2. Materials and Methods

2.1. Work Piece Material

CFRP composite laminates 4.4 mm thick were used as work material. The laminates were produced by the autoclave process and were made up of epoxy matrix reinforced with a 60% of volume fraction of woven carbon fibres (with an areal density of 250 g/m^2).

2.2. Experimental procedure

The experimental campaign was carried out by using a five-axis computer numerical control machine CNC (C.B. FERRARI) and cemented carbide upcut-router MFR-7 DP special drill tools (supplied by IMCO[17]). The special tools, with a point angle of 135°, have a special geometry characterized by the presence of a lateral active portion with discontinuous lateral cutting edges.

This portion is characterized by quadrilateral pyramidal teeth that are distributed in a regular pattern. In Fig. 1 a typical image of the used tool is illustrated.

The proposed drilling technique, named circular drilling, is divided in two main phases:

1) Phase I (conventional drilling): production of a hole with the same diameter of the tool by means of the conventional drilling strategy.
2) Phase II (circular milling): enlargement of the hole with a circular trajectory of the tool.

Fig. 2 schematically shows the main steps that characterize the proposed circular cutting strategy.

The experimental campaign was carried out according to the design of experiment (DOE) showed in Table 1.

In Table 1 the different tool diameters (*d*), the hole diameters (*D*), the feed rates (*f*), the drilling strategies, the radial depth of cut, *e*, and the extra axial depth, *p*, are listed.

As clear looking at Table 1, it is possible to observe that the conventional strategy was used for producing both holes 8 and 6 mm in diameters.

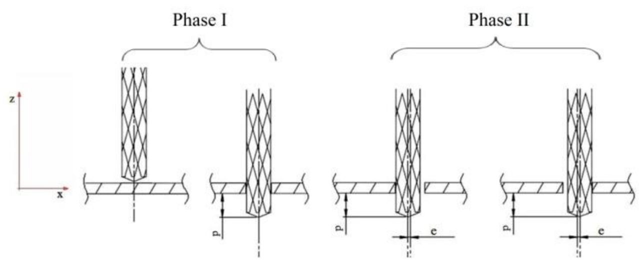


Fig. 2. Schematization of the tool position in the main steps of the process.

Table 1. Process parameters adopted for the experimental campaign.

d [mm]	D [mm]	f [mm/min]	Strategy	e [mm]	p [mm]
6	8	62 – 125- 250	Circular	1.0	5
6	8	62 – 125- 250	Orbital	1.0	3
8	8	62 – 125- 250	Conventional	-	5
6	6	62 – 125- 250	Conventional	-	5

This because the first ones were produced with the aim to compare these with the others manufactured with the other techniques, the second one were instead produced in order to estimate the magnitude of the damage generated during the phase I of the circular drilling strategy and then to consider if the damage can be regained at the end of the circular milling phase (phase II).

In order to study the trend of the forces during the drilling process, both the thrust forces, F_z, and the x-component of the tangential force, F_x, were recorded by using a KISTLER 9257 load cell. Because of in the drilling process the push-down defect effect is more severe than the peel-up one, according to other works [7,12,18] the exit hole surface of each hole were observed for the estimation of delamination factor, F_d. This is defined as the ratio between the maximum delaminated diameter and the nominal one, as indicated in equation (1).

$$F_d = \frac{D_{max}}{D_0} \quad (1)$$

3. Results and discussions

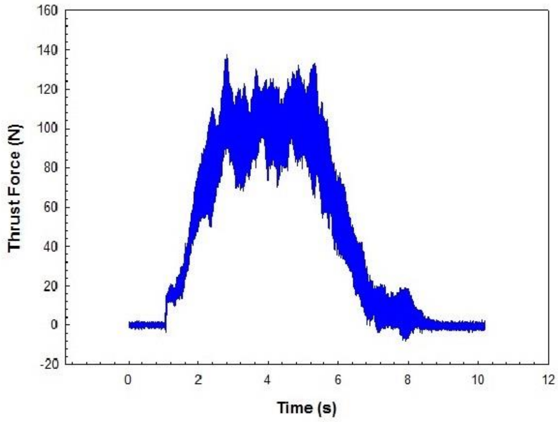
3.1. Forces analysis

Fig. 3 shows the typical trend of the forces acquired during the manufacturing of a hole at $f = 62$ mm/min for the different drilling strategies. The small oscillation in the recorded signals is explained by the cutting mechanism of the composite laminates, indeed the angle between the instantaneous velocity vector of the cutting lips and the fiber orientation, i.e. the cutting angle, changes instantaneously. Therefore, the magnitude of the force varies with these changes.

In the case of the conventional drilling, Fig. 3/a, only the thrust forces (F_z) are considered. For the orbital strategy, Fig.3/b, both the thrust forces (F_z) and the tangential forces (F_x) coexist during the drilling process. In the case of the circular strategy, Fig.3/c, only the thrust forces (F_z) are considered during the conventional drilling phase (phase I), and only the tangential forces (F_x) are considered during the circular milling phase (phase II); the transition between the two phases is identified by the vertical dashed line.

In order to evaluate the influence of the process parameters on the reached forces and correlate these ones with the degree of damage induced during the drilling process, a representative value of both the axial and tangential forces have to be taken into account. To do this, the maximum value of both the forces components were considered.

In Fig. 4 the F_x and F_z values, for each drilling strategy, as function of the feed rate are plotted.



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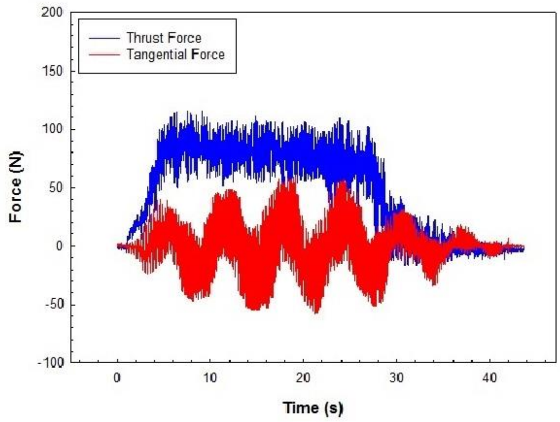

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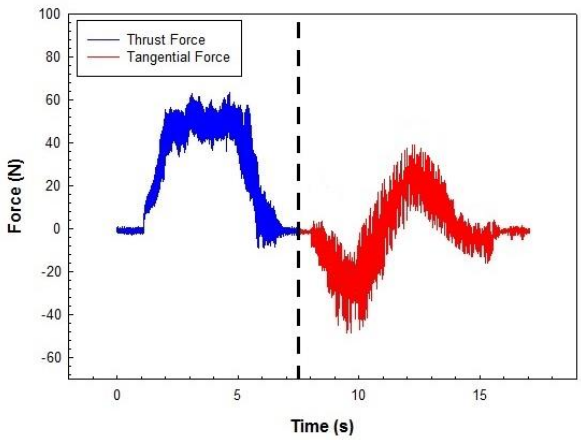


c

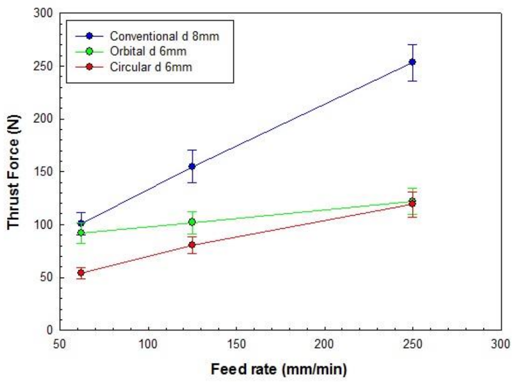
Fig. 3. Typical trend of the recorded forces during the process: conventional (a), orbital (b) and circular (c).

From this latter, it is possible to observe that the conventional drilling is always characterized by the highest values of the thrust force, since the tool diameter was larger than the other cases. For the other two cases, it appeared that the orbital drilling is characterized by higher thrust forces than the ones recorded for the circular drilling. This can be explained, considering that in the orbital drilling, the material to remove along the helical path, is more than the material to remove during the phase I (where the axial force is considered) of the circular strategy. Since the material to remove per cutting edge is greater than that in the circular strategy, the orbital drilling is characterized by higher values of axial-forces.

The thrust forces increase significantly with the feed rate, except for the holes obtained with the orbital strategy. This because the imposed feed rate in the orbital strategy is fixed along the helical path and not along the z-axes. By evaluating it along the z-direction, the feed rate is equal to around 10, 20 and 40 mm/min. Perhaps, in this process parameters window, for the used tool, the thrust force is few sensitive to the feed rate.

Also for the tangential forces the circular drilling is characterized by lower values. This is justified according to the same consideration above-said about the volume of material to remove.

In addition, considering the tool geometry, that follows a helical path, not all the length of the tool works in the same and best way to remove material in radial direction, due to the presence of the tip and of lateral cutting edges of the tool.



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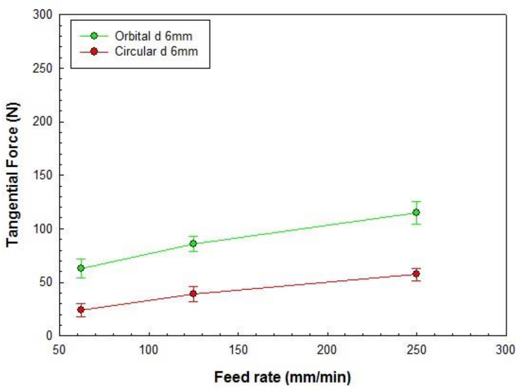


b

Fig. 4. Trend of the forces versus the feed rate for each drilling strategy: thrust (a) and tangential force (b).

3.2. Damages analysis

In Fig. 5 the values of the delamination factor reached at the end of the production of the holes 8 mm in diameter, at different feed rates, are reported.

Fig. 5 emphasizes the advantage in the use of the orbital and circular strategies respect to the conventional drilling to reduce the delamination factor.

The F_d values for the orbital drilling strategy is lower than the one observed for the conventional drilling, because unlike conventional drilling, the larger component of the tool feed motion is performed along the tangential direction and not the axial one. Therefore, the axial force component, F_z, is significant reduced while the tangential component, F_x, increases. Because the CFRPs laminates are more prone to the delamination damage under the axial force, the orbital drilling process involves a decreasing of the delamination damage and then of the F_d [16].

In the case of the circular drilling, two aspects have to be considered to justify the reduction of the delamination factor. The first one is the reduction of the axial force and the increasing of the tangential one. This redistribution of the cutting force, as above-said, represent a source of delamination reduction at the hole exit surface side. In any case, the forces are lower than the one recorded for the orbital drilling due to the fact that, in this latter case, the used tool does not work well when a helical path is imposed.

The second aspect to consider is that for the circular drilling the damage produced during the phase I (conventional drilling) can be recovered during the phase II (circular milling). Therefore, the damages inducted during the phase I could not affect the damage size at the end of the process, because the damaged material can be removed during the phase II of the process if the radial cut of depth, *e*, is longer or equal than the radial size of the damage. This is schematically represented in Fig. 6 where the conditions with a damage radial size, *x*, lower (Fig. 6/a) and higher (Fig. 6/b) than *e* are reported.

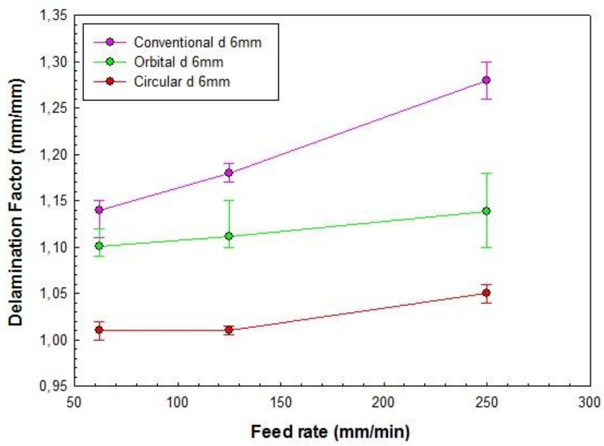
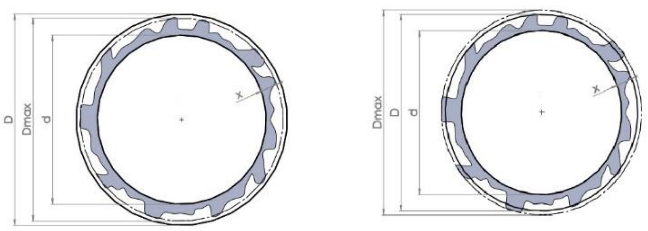


Fig. 5. Delamination factor versus the feed rate for each drilling strategy



a **b**

Fig. 6. Schematization of cases where the damage extension, *x*, is lower (a) and higher (b) than 1.0 mm

Looking at Fig.7, it is clear that the damage radial size is never longer than the radial cut of depth fixed at 1.0 mm.

This means that the measured delamination factors did not depend on the phase I (conventional drilling) of the process but on the second phase (circular drilling).

In the second phase there are no reasons for considering the exit hole surface more critical than the entrance one as in the conventional or orbital drilling, since both sides are subjected to the same cutting forces conditions. Indeed, in the case of holes 8 mm obtained with the circular drilling strategy, the damage radial size was the same on both the laminate sides.

Finally, it is also interesting to make in relation the damage with the required cycle time. In Table 2 the cycle time for each drilling strategy is listed. From this, it is possible to observe that the cycle time of the circular strategy is higher than that of the conventional drilling but lower than the one of the orbital drilling.

However, the F_d values obtained with the circular drilling at the fastest conditions (highest feed rate) was lower than the ones obtained at the slowest conditions with the conventional and orbital drilling.

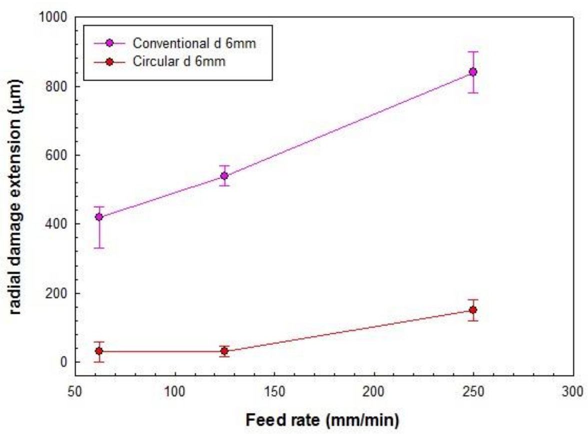


Fig. 7. Radial damage extension versus the feed rate for the Conventional and Circular Drilling strategy.

Table 2. Cycle time for producing holes with conventional, orbital and circular drilling strategy

	Conventional Drilling	Orbital Drilling	Circular Drilling
f [mm/min]	Cycle Time [s]	Cycle Time [s]	Cycle Time [s]
62	9.68	45.54	17.28
125	4.80	22.59	8.57
250	2.40	11.29	4.28

4. Conclusions

A new drilling strategy named circular drilling was studied and successfully used for the production of holes with 8 mm in diameter. The drilling strategy consists of two main phases: conventional drilling (phase I) and enlargement of the hole thanks to the circular path executed by the tool (phase II). Holes with both conventional, circular and orbital drilling strategy were produced at different cutting conditions and the following main conclusions can be drawn:

- The analysis of the forces showed that the thrust forces are higher than the tangential ones and both are sensitive to the process parameters. It was observed that the highest cutting force were detected for the conditions with the highest feed rate (250 mm/min).
- The forces reached with the proposed drilling strategy were lower than the ones reached with the conventional and orbital strategy. Since the thrust force is the highest cutting forces recorded during the process and connected with the power required for the machining operation, the proposed process is characterized by a lower cutting power.
- A similar trend of the forces versus the feed rate was observed for the delamination factor, F_d, for each drilling strategy, however the values detected with the proposed strategy are very lower than the others. In addition, differently from the holes obtained with conventional and orbital drilling strategy, the ones produced with the circular drilling strategy showed similar value of the size of the radial damage on both sides of the laminate.
- In the circular drilling, the damage induced during the first phase of the drilling process was always recovered in the circular milling phase, because the damaged material was removed.
- Under the same cutting conditions, the process cycle time of the circular drilling strategy was higher than the one of the conventional drilling but lower than that of orbital drilling. However, the F_d values obtained with the circular drilling at the fastest conditions (highest feed rate) was lower than the ones obtained at the slowest conditions with the conventional and orbital drilling.

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