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Hole quality analysis of AISI 304-GFRP stacks using robotic drilling

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Abstract

Although drilling of FRP - metal stacks is the most widely used machining operation for these materials, it remains challenging in many aspects (tool wear, vibrations, delamination, poor surface finish, etc). In this context, this paper presents an analysis of drilled AISI 304-GFRP stacks using a 6 axis Stäubli TX200 robot, which is a technology increasingly used in applications such as aeronautics due to the advantages it offers (spatial accessibility, productivity, flexibility). This study focuses on hole quality based on appropriate criteria (burrs, surface roughness, roundness and delamination measurements) depending on a large range of cutting parameters.

Keywords: Robotic, Drilling, Stacks ;

1. Introduction

Due to the current needs of lowering energy consumption by mass saving and because of their excellent weight to mechanical properties ratio, composite materials and especially fiber reinforced plastics (FRP) globally tends to replace metals in many structural applications and embedded systems (automotive, shipbuilding, railways and aeronautical industries). However, metals such as stainless steel, aluminium or titanium alloys are still often required and added by bonding in critical areas for structural or assembly reasons. These materials regions are called stacks.
On the other hand FRP are near net shaped materials but still require numerous finishing, trimming-drilling operations to allow their assembly by bolting or riveting. Machining it by CNC machine is in many cases impossible, because of the size and complexity of the parts. Due to their large spatial stretching abilities, accessibility and easiness of automation, industrial robotic arms are beginning to be combined with machining spindle to replace CNC machines or human operators for drilling and trimming operations of large composite parts [1]. This technology suffers from several limitations such as: low material removal rate (MMR), low dimensional accuracy and load capability due to the relatively low stiffness of the robot. These limitations can also lead to vibrations and part or tool damage [1, 2].
Although stacks drilling is the most common machining operation for these materials [3], this remains a complex phase in the manufacturing process due to the hybrid nature of the drilled material. Studies previously showed that both metals and FRP hole quality factors are sensible to the cutting conditions : hole edge and burrs formation [4], temperatures [5, 3], surface roughness [3], dimensional tolerances [6], FRP delamination [7] , tool [8] and composite [9, 10] service life.
Furthermore vinylester resins are mainly used with carbon and glass fiber due to their better structural properties (higher structural strength and vibration loads tolerances), chemical resistance to aggressive environments and water penetration in comparison to the epoxy and polyester resins [11]. This article provides a global study on hole quality depending on the cutting parameters of drilled vinylester VE 370 GFRP-AISI 304 stacks using a Stäubli TX200 aiming to study the influence of the cutting conditions on the hole quality and to recommend the best cutting conditions.

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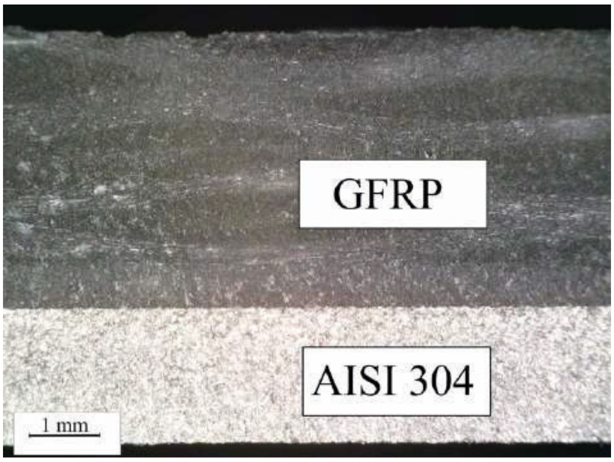

Fig. 1. AISI 304-GFRP stack cross-section.

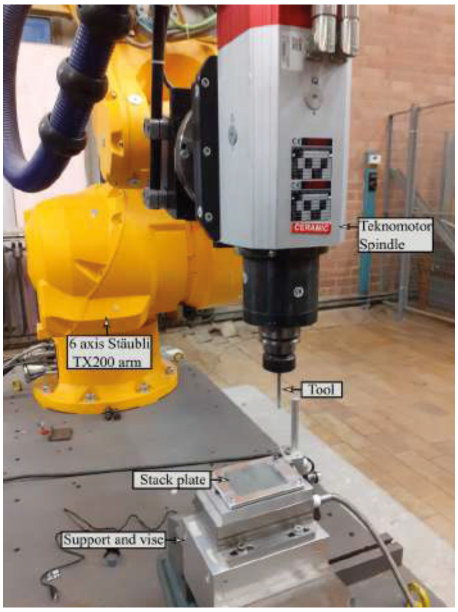

Fig. 2. Experimental set up.

2. Experimental procedure

2.1. Experimental set up

Drilled workpieces consist of a bonding between a 5 mm thick GFRP plate and a 2 mm thick AISI 304 plate. The GFRP planes were obtained by vacuum infusion with peel-plies at both sides of the sheet surfaces at room temperature. Reinforcement is made of 5 glass fibers roving 800 g/cm² into a matrix composed of : vinylester VE 370 resin (97.8%), LTP-IN Hardener (2%) and an NL51P 6% cobalt in a solvent mixture accelerator (0.2%). A curing cycle of 2.5 hours at 40°C, 2.5 hours at 60°C and 2 hours at 75°C was then be applied. This lead to 45% of fiber according to the manufacturer. The layers were then assembled after demoulding with the adapted chemical primer conditioner Plexus PC-120. Finally, 80x100 mm rectangular sheets were cut with pressurised waterjet cutter. Fig. 1 shows a cross section of the drilled plates. The choice of this cutting process and a safety distance of 15 mm between the centre of the holes and the edge of the plates allows any undesirable effects during the drilling operations (due to thermal affectations on properties).

Fig. 2 depicts the experimental installation used to perform the tests. The use of industrial robots in machining currently lacks data allowing to determine optimal operating conditions. This is why a Stäubli TX200 robotic arm confined in a secure cell will be used for the drilling operations. The robot drives a Teknomotor spindle (7.8 kW, 24000 rpm max.), with supported loads of 130 kg, dimensional repeatability of 0.06 mm and maximal feed of 10000 mm/min. The stacks are clamped into a screwed support for allowing the fixation of plates by gripping them vertically on their external edges, plate's underside is resting on a flat plane during tests which allows to avoid undesirable effects caused by bending. Based on the plate dimensions, a drilled hole pattern was created with a centre-to-centre distance of 16 mm. All the tests were carried out without lubrification and with pulsed air as coolant. This explains why the GFRP to AISI 304 cutting sequence has been prefered to avoid possible effects of the drilled metals plate on GFRP. It is expected that reached stresses, plastics deformation and temperatures are significantly higher in stainless steel. An appropriate coolant pause was applied after the drilling of each hole to avoid any thermal effects.

Tables 1 and 2 summarize the tool parameters and cutting conditions used during the drilling tests leading to the various hole quality measurements. Although the coated carbide tools provide a high hardness and are well suited for drilling abrasive materials like GFRP [12], High Speed Steel tools are much cheaper (by a ratio of 5 to 15). This make them sometimes preferred in industry. As a consequence, the study focuses initially on HSCo (High Speed Cobalt) tools as they are particularly well adapted for the drilling of austenitic stainless steels as AISI 304 materials due to their high toughness and ductility [13]. In addition, the diameter of the tools was carefully chosen to avoid undesirable effects such as deformation of the robot due to its low stiffness. It is important to note that preliminary cutting condition tests were performed for these HSCo drills and led to the following conclusions in terms of cutting conditions : under a cutting speed of 20 m/min the vertical cutting forces are too high for the robotic arm which implies that its axes are unable to follow the feed rate. On the other hand, cutting speed above 50 m/min leads to severe thermal conditions and to a tool flank wear higher than 0.3 mm. As a consequence, cutting speed from 22.5 mm/min to 45 m/min and feed rate from 0.015 to 0.035 mm/rev were chosen for HSCo drills to cover the larger possible range of cutting conditions. All tests were repeated 3 times on the same order with new tools at the beginning of each repetition.

2.2. Hole quality measurements

The following criteria was selected to evaluate the hole quality after the drilling tests :

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Table 1. Drill bits parameters.

Diameter [mm]	6.5
Material	HSCo
Point angle [°]	130
Helix angle [°]	40
Chisel half thickness [mm]	1

Table 2. Experimental cutting conditions (repeated 3 times).

Hole n°	Cutting speed [m/min]	Feed [mm/rev]
1	22.5	0.015
2	22.5	0.025
3	22.5	0.035
4	30	0.015
5	30	0.025
6	30	0.035
7	37.5	0.015
8	37.5	0.025
9	37.5	0.035
10	45	0.015
11	45	0.025
12	45	0.035

- Tool and hole visual inspection : Dino Lite digital microscope AM7013MZT (5 MPix, magnification from 20x to 250x) was used to ensure that the maximum flank wear measured at the end of the cutting lips does not exceed the commonly fixed limit of 0.3 mm through the tests.
- GFRP peel up delamination : the same digital microscope was used with a polarising filter to obesrve the delaminated area A_d and the associated maximum diameter D_{max} to obtain the delamination factor F_d and the adjusted delamination factor F_{da} for each drilled hole [14]:

$$F_d = \frac{D_{max}}{D_0} \tag{1}$$

$$F_{da} = F_d + \frac{A_d}{(A_{max} - A_0)}(F_d^2 - F_d) \tag{2}$$

D_0 and A_0 respectively stands for the nominal diameter and its nominal area. Fig.3 shows an example of the associated LOM routine (light optical microscopy) which allows to obtain a measure of the delaminated area A_d thanks to the filtering and binarisation of the hole image.

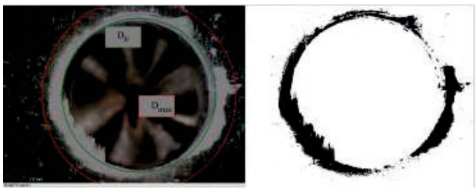

Fig. 3. LOM routine for delamination factor measurement.

- Dimensionnal and geometrical evaluation : measurements were carried out at room temperature with a Wenzel LH54 Coordinate Measuring Machine (CMM). Roundness and hole diameter measurements were taken at mid-thickness of the drilled GFRP and AISI 304 plates. Additionally, the cylindricity measurements were carried out in both composite and metallic regions.
- AISI 304 exit burrs : visual inspection were performed with the digital microscope. The average height measurements between AISI 304 exit plane and the average best plane formed at the edge of the 3 highest points of the burrs were realised with the same CMM Wenzel LH54.
- Surface roughness : surface topography measurements were performed on both AISI 304 and GFRP thickness with Diavite DH-6 specialised roughness measurement instrument. The evaluation length was set at 1.5 mm for the AISI 304 and 4.8 mm for the GFRP. This length was indeed limited by the material thickness. This means that in some cases, and especially for GFRP plates, the ISO 4288 was not fulfilled. These measurements are therefore given as an indication to allow relative comprarisons between cutting conditions.

3. Results

3.1. Tool life and visual inspection

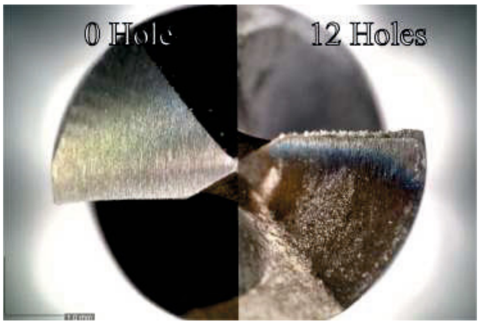

Fig. 4. Drill tip comparison before and after the drilling tests.

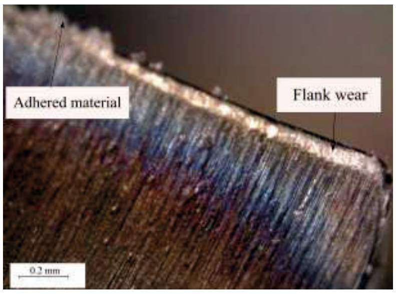

Fig. 5. Cutting lips view after 9 holes.

Inspection views were realised during the drilling tests to ensure that excess tool wear was not overly affecting hole quality measurements. Fig. 4 and Fig. 5, respectively, show comparative views of the drill tip before and after the 12 drilled holes

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and cutting lips view after 9 holes. Cutting speed linearly increases as a function of the tool diameter and directly influences the tool wear [15], which explains why flank wear increases radially along the cutting edges. Average maximal flank wear of 116 µm and 209 µm were measured after 6 and 12 holes. Unmeasurable thermals effects of dry machining significantly increase with the cutting speed and can also be seen on the tip coating, AISI 304 chips and exit caps shown in Fig. 6 .

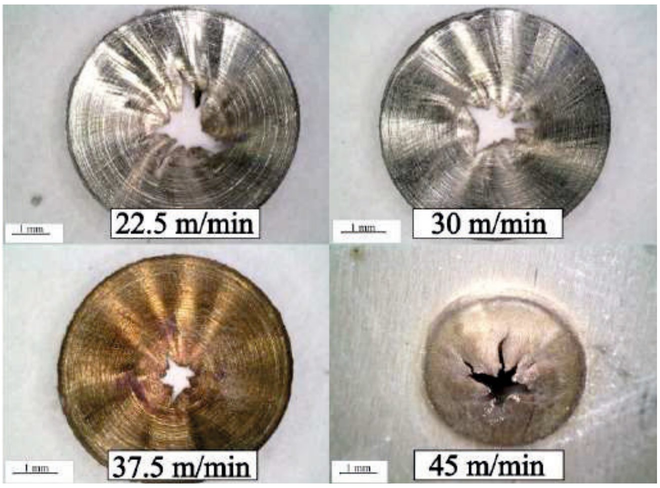

Fig. 6. Holes exit caps at 0.025 mm/rev.

3.2. Entrance delamination

The bar chart in Fig. 7 provides measurements results of the adjusted delamination factor F_{da} for the 12 cutting conditions. The global first observation, related to Table 3, is that results are more repeatable at lower feed : indeed, the average standard deviations doubles from 0.07 to 0.15 for feed of 0.015 and 0.025 mm/rev. It is then noted that delamination factor tends to increase from 1.45 (global minimal value) to 1.67 at this lower feed, which is a trend noted for classical drilling of FRP plate on CNC machine [16] since drilling delamination directly is linked to the thrust force. As the feed is increased (at 0.025 and 0.035 mm/rev), delamination factor tends to oscillate between similar tests, especially for a cutting speed of 30 m/min. The global expected trends of delamination is an increase with the feed due to the associated rise of thrust force. This trends are not noticed [16]: average delamination results goes from 1.5 to 1.7 at 0.025 and 0.035 mm/rev.

Table 3. Average standard deviations of delamination factor at constant feed [mm/rev].

Feed [mm/rev]	F_{da} average standard deviation
0.015	0.07
0.025	0.15
0.035	0.17

Based on the fact that literature and experiences show that delamination of FRP composites is directly related to the thrust force of the drill, it may seem counterintuitive that delamination factor does not decrease with cutting speed. because it is shown that the thrust force decreases with cutting speed for metals. However, it is shown by Caprino et al. [17] that unlike metals, FRP and especially GFRP specific the cutting forces do not significantly depend on cutting speed but only on the chip thickness (and consequently on the feed for drilling). As a result, his means that increasing the cutting speed in GFRP layers does not affect thrust force and will not tend to decrease delamination factor.

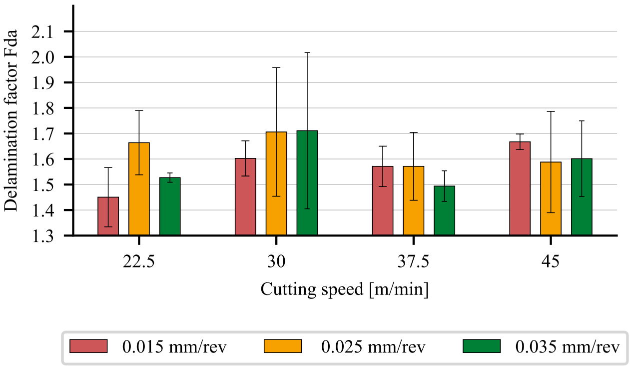

Fig. 7. Delamination factor F_{da} measurements.

3.3. Exit burrs

Exit burr height measurements values are given in Fig. 8. Lower height values of 0.29 mm were observed for 0.035 mm/rev and 22.5 m/min cutting parameters. It is important to note that due to the spatial clearance of the set up configuration imposed by industrial requirements, the diametrical extremities of the drill's cutting lips did not go vertically below 0.7 mm down to the drilled exit plan of AISI 304. As it can be seen in Fig. 6, at cutting speeds of 45 m/min, the height of the burrs is greater than this 0.7 mm distance and the separation of the cap has not occured. This phenomenon made impossible the height measurements of exit burrs at this cutting speed were. As expected, for a constant feed, values of burrs height tend to increase with the cutting speed due to the heating up involved. Average values of 0.31, 0.51, 0.64 mm and superior to 0.7 mm were observed for cutting speed of respective 22.5, 30, 37.5 and 45 m/min. It was also noticed that the influence of the feed on burrs height is not constant and depends on the given cutting speed. An increase of feed from 0.015 to 0.025 mm/rev leads to a decrease of height from 0.31 to 0.26 mm for cutting speeds of 22.5 to 37.5 m/min. It is not the case for the 30 m/min cutting speed (increase from 0.5 to 0.6 mm).

3.4. Geometrical tolerances

A comparison between the nominal and measured diameter of hole is depicted in Fig. 9 for composites and metallic parts. As it is clearly visible, average values of measured hole diameters are larger to the 6.5 mm diameter nominal value. Further-

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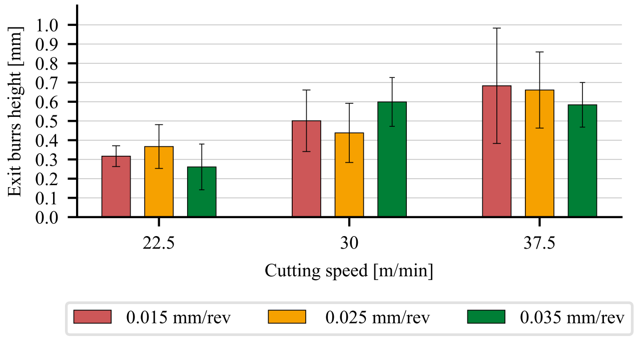

Fig. 8. Exit burr height measurements.

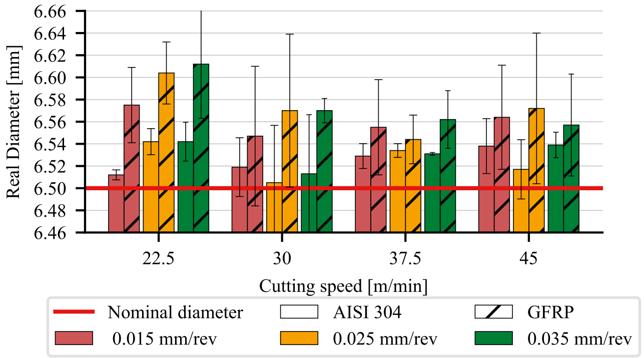

Fig. 9. Real diameter [mm].

more, real vs nominal differences are significantly higher for GFRP layers than AISI 304 : average differences of 0.069 mm and 0.027 mm were computed. Smaller differences of 0.005 and 0.047 mm were found at 30 m/min and 0.015 mm/rev for GFRP and 30m/min and 0.025 mm/rev for AISI 304. It is important to note that even if these lower average results were obtained for 30 m/min cutting speed, repetability of the tests is more critical than at lower cutting speeds. Indeed, standard deviations up to 0.062 mm were observed for the cutting speed higher than 30 m/min while it only reaches 0.024 mm for cutting speed of 22.5 m/min.

The overall trends for GFRP show a decrease in the diameter gap when cutting speed is increased until 37.5 m/min: average differences of 0.097, 0.062 and 0.054 mm are measured for respectively 22.5, 30 and 37.5 m/min and tend to re-increase to 0.064 m/min for the maximum cutting speed. In addition, the feed influence seems to increase differences for low cutting speed (22.5 m/min) but the rise is less steeper when the latter increases from 30 m/min to 45 m/min.

Influence of cutting parameters on AISI 304 results is much less marked and the lack of stability of the results when the cutting parameters are increased prevents the identification of trends. However, it appears that the smallest of the cutting conditions (22.5 m/min and 0.015 mm/rev), which gives average differences close to the minimum of 0.012 mm, will lead the best stability of measurements.

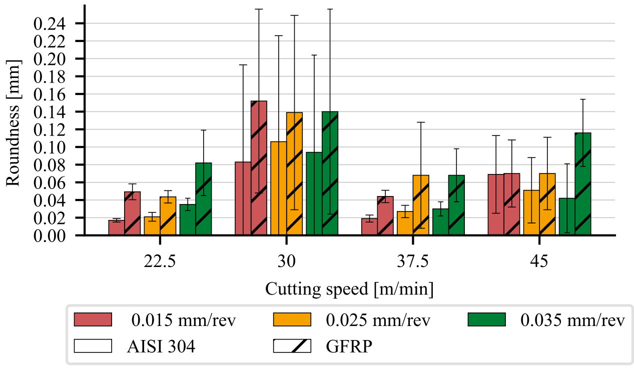

Fig. 10. Roundness [mm].

Fig. 10 shows the roundness deviation measurements for both GFRP and AISI 304 layers. As previously described, deviations are higher on glass fiber than on stainless steel plates, both minimal values of 0.043 mm and 0.017 mm were observed at 22.5 m/min for composites and metallic parts. Maximal roundness values of 0.152 mm (GFRP) and 0.106 mm (AISI 304) and associated dispersion are still observed at 30 m/min, similarly to diameter and delamination factor observations which is the sign of an external perturbation. The assumption of the occurence of a natural frequency of the robot has still to be confirmed. Outside these disturbances, average values of roundness globally increase with the cutting speed, especially at 45 m/min. Indeed, values from 0.055 to 0.085 mm (for GFRP) and from 0.024 to 0.050 mm (for AISI 304) are measured at cutting speed values from 22.5 to 45 m/min. At constant cutting speed, rise of feed tends to increase results for GFRP (except for the unsteady 30 m/min cutting speed). The same statement can be made for stainless steel part except for the highest cutting speed (45 m/min) which exhibits a decrease of roundness deviation.

Finally, it should be noted that measured trends for cylindricity are similar to the previous statements made for roundness. Minimal measured values at 22.5 m/min and 0.015 mm/rev are 0.42 mm into GFRP parts and 0.013 mm into AISI 304 mm. While maximal encountered values of 0.098 mm (GFRP) and 0.067 (AISI) are encountered at the unsteady 30 m/min cutting speed.

3.5. *Surface roughness*

Fig. 11 provides the results of arithmetic roughness Ra measurements of AISI 304 holes. Lower values of 0.61 µm are observed at the lowest cutting conditions (22.5 m/min and 0.015 mm/rev). It clearly appears that at constant low feed (0.015 mm/rev), measurements are widely increasing with cutting speed. Indeed, Ra values triple from 0.69 to 2.15 µm at for 22.5 m/min to 45 m/min. However, this trend appears to be less pronounced when the feed is increased to 0.025 and 0.035 mm/rev. Global average values confirm these statements : Ra doubles from 0.78 to 1.43 µm when the cutting speed is doubled from 22.5 to 45 m/min.

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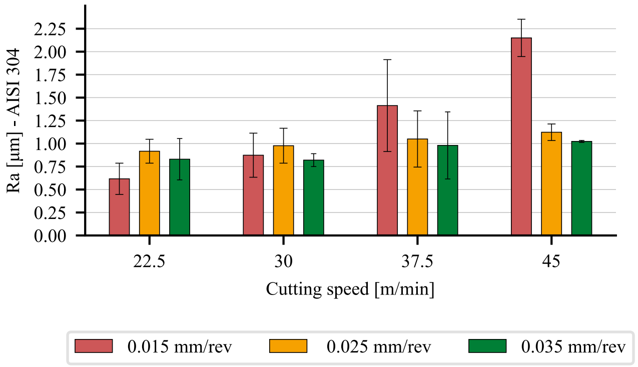

Fig. 11. Ra [μm] measurements on AISI 304 holes.

As previously explained, GFRP measurements did not followed ISO 4288 . Additonally, due to poor surface conditions and the presence of uncut fibre blocking the stylus movement, some holes could not be measured. However, when it was possible values between 4 and 10 µm were measured on holes, average values of 5.93, 6.56, 6.50, 5.95 µm were obtained for the considered 22.5, 30, 37.5 and 45 m/min cutting speeds.

4. Conclusion

Based on the spectrum of drill hole quality criteria analysis and depending on the cutting conditions, authors recommend the use of the lowest cutting condition for dry robotic drilling of stacks GFRP-AISI 304 (i.e. a cutting speed of 22.5 m/min combined with a feed of 0.015 mm/rev) for which hole quality is globally optimized for HSCo tools:

- From the AISI 304 layers perspective : it has been shown that exit burr size directly depends on the cutting speed, for which the temperature effects increase dramatically above 45 m/min with respect to the chips, exit caps and bad wear effects on tool observed. Furthermore, measured diameter difference, roundness and cylindiricity especialy tend to be lower with feed. Finally surface roughness measurements show minimal values of 0.61 µm at recommended conditions.
- From the FRP layers perspective : due to the non-influence of cutting speed on drilling thrust forces, the lower adjusted delamination factors F_{da} of 1.51 are observed at the recommended conditions. In addition, the lower roundness and cylindricity values are met at the recommended cutting parameters, and nominal vs. real diameter differences of 75 µm are close to the minimum. Indeed, the lowest values of cylindricity are met at 30 m/min but gives lower repetability.

Finally, perspectives of this study include investigations on the perturbations observed at a cutting speed of 30 m/min, a focus on tool wear and the necessity to evaluate the potential gains of using carbide tools on hole quality criteria as well as on the productivity.

Acknowledgements

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