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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 and drilling operations for assemblies by bolting or riveting. Machining it by traditional mean (CNC machine) is in many cases impossible, because of the size and complexity of the parts. Due to their large spatial flexibility, 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]. Drawbacks of this technology come from the fact that their low material removal rate (MMR) caused by weak global rigidity, dimensional accuracy and load capability can lead to bad tolerances, 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 precedently shown 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 epoxy and polyester resins [11]. To respond to industrial needs and lack of data, this article provides a global study on hole quality depending on cutting parameters of drilled vinylester VE 370 GFRP-AISI 304 stacks with a Stäubli TX200 aiming to study the influence of the cutting conditions on the hole quality and to recommend the best cutting conditions.

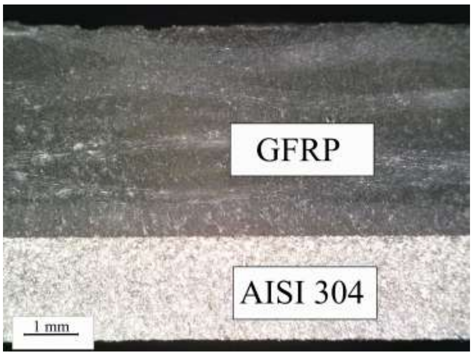


Fig. 1. AISI 304-GFRP stack cross-section.

## 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 -2.5h at 40°C - 2.5 h at 60°C - 2h at 75°C has then be applied. This lead to 45% of fiber according to the manufacturer. Layers were then assembled after demoulding with the adapted chemical primer conditioner Plexus PC-120. Finally, 80x100 mm rectangular sheets have been 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 to avoid any undesirable effects during the drilling operations (due to thermal affectations on properties).
Fig. 2 shows a picture of the experimental installation used to perform the tests. The use of industrial robots in machining is still in its infancy and the lack of concrete quantitative and quantitative data in the field is a hindrance to their wide expansion in the machining field, which explains why a Stäubli TX200 robotic arm confined in a secure cell will be used for the drilling operations, the latter 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. Stacks are clamped in 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 has been created which linearly separates each hole by a centre-to-centre distance of 16 mm. All the tests have been carried out without lubrification and with pulsed air for 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 due to the metallic nature of the material. An appropriate coolant pause was applied after each hole to avoid any thermal effects of some cutting conditions on the others.

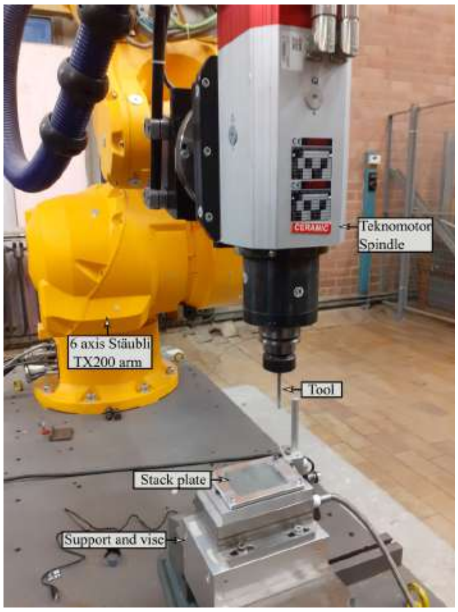


Fig. 2. Experimental set up.

Tables 1 and 2 summarize the tool parameters and cutting conditions used for the drilling tests leading to the various hole quality measurements. Although coated carbide tools provide a high hardness, which is well suited for drilling abrasive materials like GFRP [12], High Speed tools are much cheaper (by a ratio of 5 to 15). This make them sometimes preferred in industry. This why the study focuses initially on HSCo (High Speed Cobalt) tools as they are particularly well adapted for the drilling of austenitic AISI 304 materials due to their high toughness and ductility [13]. In addition, the diameter of the tools has been 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 have been carried out for these HSCo drills and have 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 axis are unable to follow the wanted feed rate. On the other hand cutting speed above 50 m/min leads to severe thermal conditions and direct tool flank wear higher than 0.3 mm. Cutting speed from 22.5 mm/min to 45 m/min and feed from 0.015 to 0.035 mm/rev have been chosen for HSCo drills to cover the larger possible range of cutting conditions. To assess repetability of the results, all tests have been repeated 3 times on the same order with new tools at the beginning of each repetition.

### 2.2. Hole quality measurements

The following criteria have been chosen to evaluate hole quality after the drilling tests were carried out :

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 20 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 assess measurements of 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]:

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

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

With $D_0$ and $A_0$ respectively the nominal diameter and its nominal area. Fig.7 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.

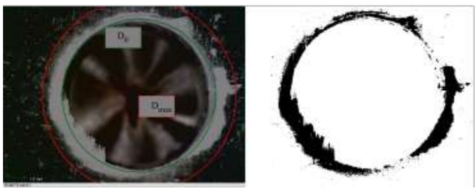

Fig. 3. LOM routine for delamination factor measurement.

- Dimensionnal and geometrical evaluation : measurements were carried out at room temperature with a Wenzel LH54 Coordinate Measuring Machine (CMM) equiped of a Renishaw PH10M head and a 1.5 mm diameter spherical probe. Metrosoft QUARTIS Measurement Software 2021 was used to compute and analyze the acquired data. Roundness and hole diameter measurements were taken at mid-thickness of the drilled GFRP and AISI 304 plates. Additionally, cylindricity measurements have been carried out for both composite and metallic regions. The latter are included in cylinders with 3mm height between planes located at 1 mm from the boundary limits of the plates for GFRP, and cylinders of 1.6 mm height between planes located at 0.2 mm from the boundary limits of the plates for AISI 304.
- AISI 304 exit burrs : visual inspection were performed with the digital microscope. 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 device previously described.
- Surface roughness : surface topography measurements were realised on both AISI 304 and GFRP thickness with Diavite DH-6 specialised roughness measurement instrument and analyzed on the diasoft software version 3.1.9, the used evaluation length was limited by materials thicknesses : i.e. 1.5 mm for AISI 304 and 4.8mm for GFRP. This means that in some case and especially for GFRP plates, measurements were impossible to be fulfilled according to ISO 4288. This standard requires an evaluation length of 15 mm to perform roughness evaluation of parts exhibiting an Ra between from 2 $\mu m$ to 10 $\mu m$, which is not possible due to the 5 mm thickness of the GFRP sheets, intermediate evaluation length values of 4.8 mm were used for the measurements. These measurements are therefore given as an indication to allow comprarisons between cutting speeds.

## 3. Results

### *3.1. Tool life and visual inspection*

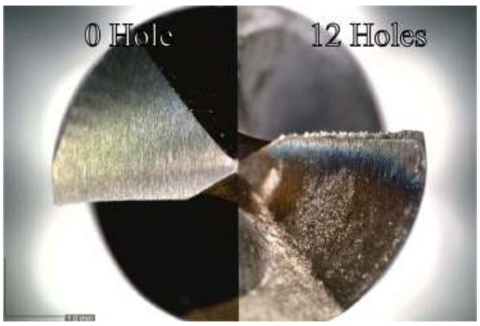


Fig. 4. Drill tip comparison before and after the drilling tests.

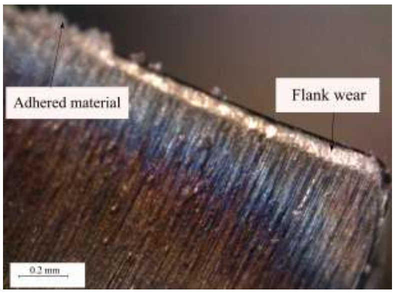


Fig. 5. Cutting lips view after 9 holes.

Tool views were taken during 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 and cutting lips view after 9 holes. Cutting speed linearly increase in function of the tool diameter and directly influence 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 .

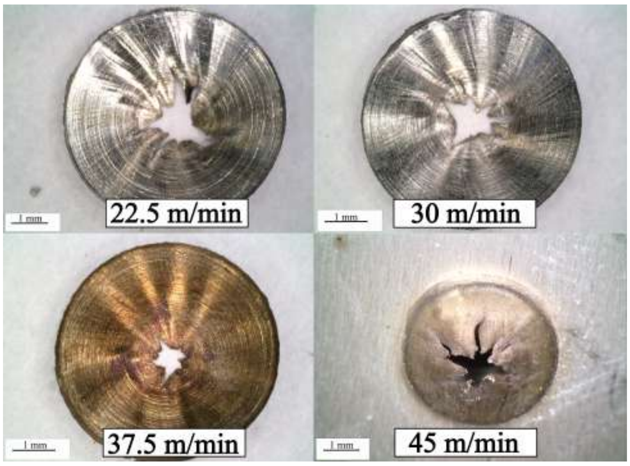


Fig. 6. Holes exit caps at 0.025 mm/rev.

## 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 double 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 globally 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 results tend to oscillate between similar tests, especially for a cutting speed of

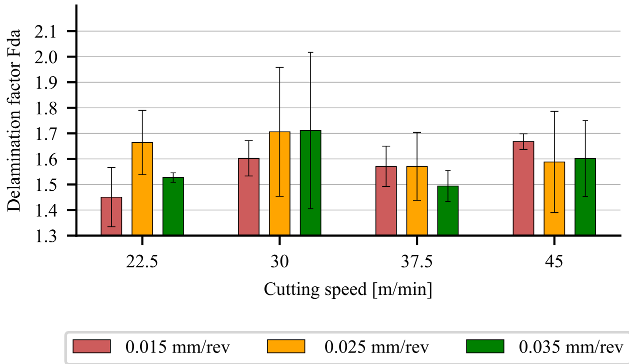


Fig. 7. Delamination factor $F_{da}$ measurements.

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 |

30 m/min. The global expected trends of delamination increase with feed due to the thrust force associated rise are not noticed [16]: average delamination results goes from 1.5 to 1.7 at 0.025 and 0.035 mm/rev.
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 (which is the case for metallic drilling). However, it is shown by ANOVA [17] that unlike metals, FRP and especially GFRP specific cutting forces do not significantly depend on cutting speed but only on chip thickness (and so on feed for drilling). This means that increasing the cutting speed in GFRP layers does not affect thrust force and will not tend to decrease delamination factor.

## 3.3. Exit burrs

Exit burr height measurements values are given in Fig. 8, lower height values of 0.29 mm are observed for 0.035 mm/rev and 22.5 m/min cutting parameters. It is important to note that due to the weak 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, which explains why burrs height measurements at this cutting speed were not possible to carried out. 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

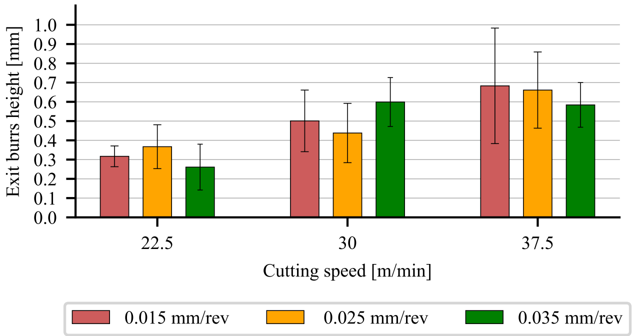


Fig. 8. Exit burr height measurements.

constant and depends on the given cutting speed : increase of feed from 0.015 to 0.025 mm/rev decreases height from 0.31 to 0.26 mm and 0.68 to 0.58 mm for cutting speed of 22.5 and 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*

Comparative diagrams between diameter and nominal diameter measurements are given in Fig. 9 and Fig. 10 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. Furthermore, 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 have been obtained for 30 m/min cutting speed, repetability of the tests is more critical than at lower cutting speeds, as shown by the average standard deviations of 0.024 mm for 22.5 m/min against 0.062 mm for higher cutting speed 30 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 respective 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, feed influence seems to increase differences for low cutting speed (22.5 m/min) but the rise is less steeper when the latter increase 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 be prefered because of the stability of the measurements.

Fig. 11 and Fig. 12 show roundness measurements for respectively GFRP and AISI 304 layers. As previously, deviations are higher on glass fiber than on stainless steel plates, both minimal values of 0.043 mm and 0.017 mm are 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. Hypothesis such as a natural frequency of the robot encountered remains 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 with exception of the highest 45 m/min speed for which results decrease.
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.

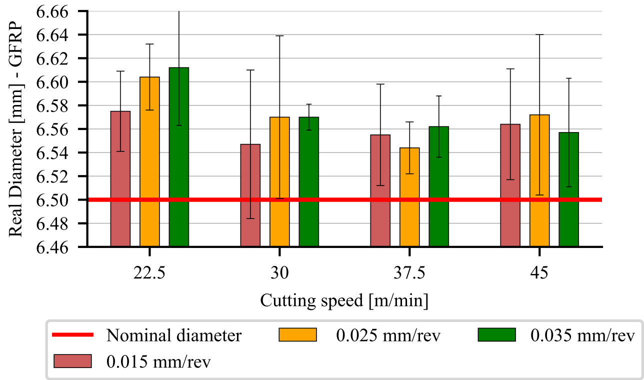


Fig. 9. Real diameter [mm] of GFRP holes.

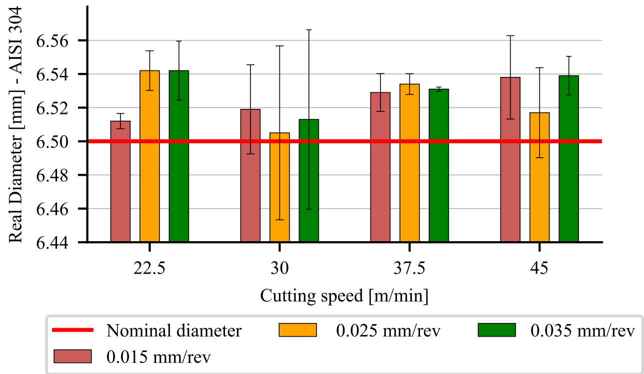


Fig. 10. Real diameter [mm] of AISI 304 holes.

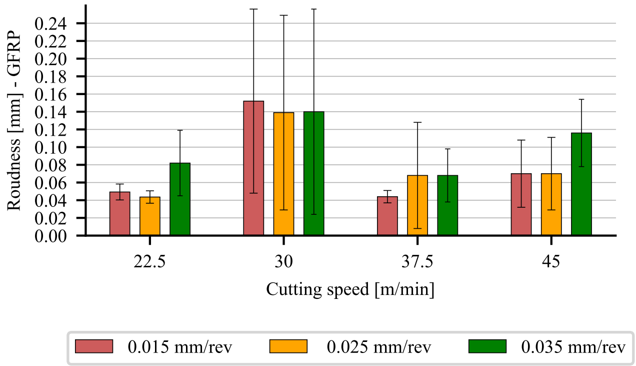


Fig. 11. Roundness [mm] of GFRP holes.

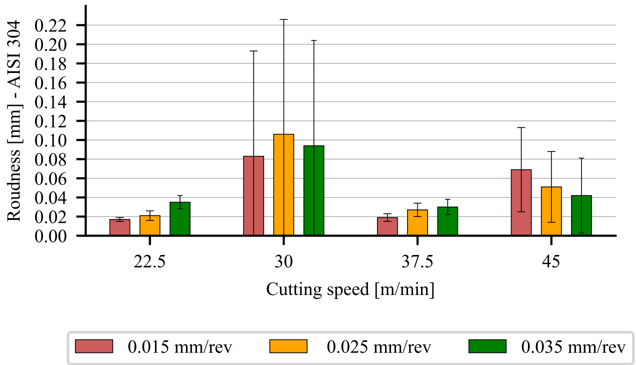


Fig. 12. Roundness [mm] of AISI 304 holes.

### 3.5. *Surface roughness*

Fig. 13 provides results of arithmetic roughness measurements of AISI 304 holes, lower values of 0.61 µm are observed at the lower cutting conditions (22.5 m/min and 0.015mm/rev). It clearly appears that at constant low feed (0.015 mm/rev), measurements are widely increasing with cutting speed : average 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 double from 0.78 to 1.43 µm when the cutting speed is doubled from 22.5 to 45 m/min.

As previously explained, GFRP measurements did not followed ISO 4288 and additonally, due to encountered problems with GFRP holes caused by poor surface conditions and the presence of uncut fibre obstructing the stylus movement and measurements, some holes could not be measured and graphs expressing the overall trends can not be provided. However, when it was possible values between 4 and 10 µm were measured on holes, global average values of 5.93, 6.56, 6.50, 5.95 µm were obtained for the respective 22.5, 30, 37.5 and 45 m/min cutting speeds.

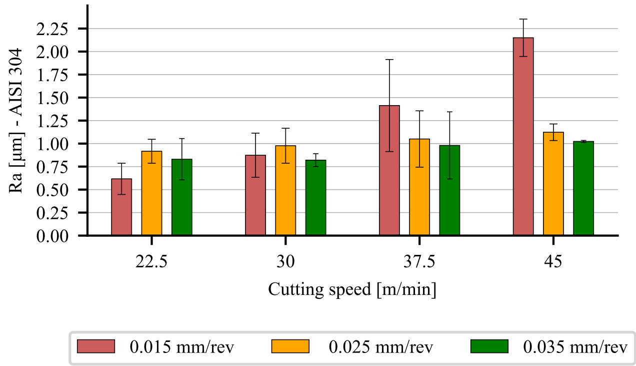


Fig. 13. Ra [$\mu m$] measurements on AISI 304 holes.

## 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 drastically 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 global unsteady conditions with respect to 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 of evaluate the potential gains of using carbide tools on hole quality criteria as well as on cutting parameters (potential productivity gains from the increase of the cutting parameters).

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