Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 00 (2024) 000–000

www.elsevier.com/locate/procedia

7th CIRP Conference on Surface Integrity

Effect of Cutting Conditions on Surface Integrity when Robotic Drilling of Aluminum 6082-GFRP Stacks

Thomas Beuscart[a,b], Pedro-José Arrazola[b], Noémie Tinel[a,c], François Ducobu[a]

[a]*Machine Design and Production Engineering Lab, Research Institute for Science and Material Engineering, UMONS, Belgium*
[b]*Escuela Politécnica Superior de Mondragon Unibersitatea, Loramendi 4, 20500, Mondragon, Spain*
[c]*Ecole Nationale Supérieure de Mécanique et d'Aérotechnique, E.N.S.M.A, 1, Avenue Clément Ader, 86960 Futuroscope Cedex, France*

* Corresponding author. : *E-mail address:* thomas.beuscart@umons.ac.be

Abstract

Six-axis robots are increasingly employed in manufacturing due to their excellent volume on cost ratio and extensive reach, facilitating the machining of large components, including those made of composites. However, this enhanced volume on cost ratio often compromises rigidity. This study investigates the effect of cutting conditions on surface integrity and robotic drilling forces when machining Aluminum 6082-GFRP stacks using 6 mm solid carbide drills and a 6-axis Stäubli TX200 robot. Two distinct drill geometries are assessed in various drilling sequences. Feed rate emerges as a pivotal parameter affecting drilling forces and hole quality. Comprehensive testing encompasses a range of feed rates and drilling strategies in both individual materials and stack sequences. The analysis includes cutting forces and hole quality, considering surface integrity and standard quality indicators such as delamination, arithmetic roughness, and burr height. The research seeks to propose optimal cutting conditions, specifically feed rate and cutting speed, essential for advanced industrial applications. These conditions ensure hole quality and surface integrity, which is particularly important for riveting processes and ensuring effective sealing.

Keywords: Drilling, Robot, Aluminium, Composite, Surface integrity ;

1. Introduction

The ever-evolving requirements of contemporary manufacturing have propelled the assimilation of advanced materials and automated procedures. In order to address these perpetual demands for cost-effective productivity in the composite manufacturing industry, particularly in finishing operations like trimming and drilling (which is the most commonly employed operation [1], principally for riveted assemblies), 6-axis robots appear to present the ideal solution owing to their high volume-to-cost ratio.

Furthermore, metals continue to be commonly used in composite structures, typically in assembly zones or strategically to provide structural reinforcement. These hybrid regions, often referred to as "stacks," are also frequently subjected to drilling operations. However, the limited stiffness of robots, coupled with the complexity of drilling bimaterials due to their differing natures (requiring distinct cutting conditions, tool geometries, etc.), currently results in relatively poor process control. Indeed, numerous defects that compromise the use of robots can potentially arise [2], [3]: vibrations leading to bad hole quality, tool breakage or premature wear, subpar surface conditions, defects such as delamination in FRP composites, or the creation of burrs or thermally affected zones in metals. The current state of robotic drilling, in fact, reveals subpar outcomes in terms of surface integrity, tool performance, and dimensional tolerances [4].

Surface integrity is a key variable to control and to ensure a good hole quality, especially for riveting [5]. This is why extensive research has already been conducted on surface integrity and drilling quality of conventional stacks using Cartesian-axis CNC machines [6], [7]. This article aims to show that the control of cutting forces is a key factor in optimizing hole quality and surface integrity. To address the question of the current industrial feasibility of the process, this article aims to provide a comparative study on the quality of robotic drilling, specifically focusing on the surface integrity of drilling Aluminum 6082-GFRP stacks. To achieve this, two carbide tools with differ-

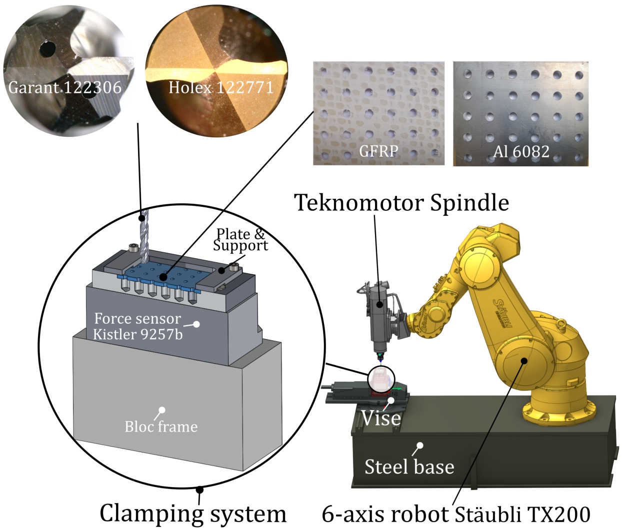

Fig. 1. Schematic of the experimental setup

ent geometries were tested on various material configurations (aluminum and GFRP alone, as well as stacks in both possible sequences) under selected cutting conditions (cutting speed and feed rate). Finally, this article proposes optimal cutting parameters based on cutting force analysis and surface integrity assessments.

2. Experimental procedure

2.1. Experimental Setup

The entire experimental equipment used during the tests is depicted in Figure 1. To accomplish this, a 6-axis Stäubli TX200 robot with a maximum payload of 130 kg and a maximum reach of 2.603 m was employed. It was mounted on a steel base considered as perfectly rigid. A Teknomotor spindle with a power of 7.8 kW and a maximum speed of 24,000 RPM was connected to the end of the robot to perform machining operations. The entire system was controlled by a Stäubli controller working at a frequency of 1000 Hz, the communication frequency between the robot and the controller is 500 Hz. A hydraulic vise holding the clamping system for the drilling plates was positioned in the robot's recommended working area (which gives an axial compliance of 2 μm). This vise allowed rigid clamping of the clamping system. The clamping system itself consisted of an aluminum block for attaching the Kistler 9257b force sensor. A support block was screwed onto the sensor, which had the exact inprint of the drilled plates to clamp them in a completely rigid manner.

The drilled materials were aluminum 6082 plates with a thickness of 5 mm for the metallic part. The GFRP part was extracted from 4 mm thick plates designed for aerospace applications. These plates were made of epoxy resin combined with 800 g/m² bidirectional woven roving fiberglass. The design aimed to achieve a fiber volume fraction (V_f) of approximately 45%, which corresponds to placing 1 roving per millimeter of thickness. The GFRP plates were then obtained by injection

Table 1. Geometrical drill description

Parameter	Holex	Garant
Reference	122771_6	122306_6
Drilled material spec.	Universal	Aluminium Alloys
Composition	Solid Carbide	Solid Carbide
Coating	AlTiN-Si	DLC
Diameter [mm]	6	6
Point Angle [°]	135	135
Helix Angle [°]	33	15
Half Web Thickness [mm]	0.5	0.65

molding at ambient pressure and underwent a curing cycle of 2.5 hours at 40°C, 2.5 hours at 60°C and 2 hours at 75°C to polymerize the material. Note that a gel coat was applied to the mold to facilitate demolding and prevent surface defects. All plates were cut to the desired dimensions (80x100mm) by guillotine cutting to avoid any undesirable thermal degradation. The stacks were finally obtained by adhesive bonding at room temperature.

Given the hybrid nature of the stacks and the limited tools and recommendations available, two different tool selection strategies were adopted. Table 1 provides the references and characteristics of these tools. The first strategy was to opt for a universal Holex 122771 solid carbide tool, which, due to its geometry and AlTiN-Si coating, is suitable for drilling a wide range of metals and composites. Furthermore, as it has been recommanded by previous studies [4], it may be important to select the tool based on the most challenging material in terms of cutting forces and temperature, which is aluminum in this study. Therefore, a Garant 122306 drill with a Diamond-Like Carbon (DLC) coating designed for drilling aluminum alloys was chosen. It should be noted that the reverse strategy of selecting tools adapted for GFRP is not possible on stacks with metal because the tools geometry and coating are not adapted to metals which often lead to severe tools breakage [4] (due to high cutting force and temperatures reached). The drill diameter was set at 6 mm for practical reasons; this is one of the most commonly used diameters in aerospace for riveting [5]. furthermore, larger drill diameters can lead to excessive cutting forces and overreach the maximum load of the robot.

2.2. Cutting Strategies

To determine optimal cutting parameters and various implementation strategies (such as drilling order and cutting conditions), initial drilling tests were conducted using two tools on different materials. Table 2 summarizes the ranges of cutting conditions tested on the two distinct materials. It is important to note that the tests were conducted dry for practical reasons and as per industrial choice (to preserve GFRP and robot integrity). These conditions were selected based on two criteria: firstly, to test the widest possible range of conditions, and secondly, to ensure material integrity and consider factors such as adverse effects of increased temperature on cutting speed and the robot's maximum allowable load on feed rate. Cutting forces were eval-

Table 2. Cutting conditions used for drilling Separate Materials

	Material	
	Al 6082	GFRP
f [mm/rev]	0.05 – 0.1 – 0.15	0.05 – 0.1 – 0.15
v_c [m/min]	50 – 80 – 100 – 125 – 150 – 175 – 200 – 250 – 300 – 350	45 – 50 – 55 – 60 – 65 – 70 – 75 – 80

Table 3. Cutting conditions used for drilling of stacks (Al-GFRP or GFRP-Al)

Condition n°	Stack Al – GFRP or GFRP - Al			
	Al 6082		GFRP	
	f [mm/rev]	v_c [m/min]	f [mm/rev]	v_c [m/min]
1	0.05	50	0.05	50
2	0.05	150	0.05	50

uated in advance using FEM-analytical hybrid models, allowing a reliable estimation of these forces [8]. It was found that feed rates below 0.15 mm/rev limited the maximum forces to 500 N, which was a target value not to be exceeded. This allows to prevent bad effects of excessive static deflection on the robot.

Finally, tests on Al-GFRP stacks were conducted in both directions based on the best conditions selected from the initial tests. Table 3 summarizes the conditions used for the stacks. The first condition (f = 0.05 mm/rev and v_c = 50 m/min) represents the best compromise found after the initial tests. The second condition is mixed: this consist of the recommanded best cutting conditions given by the tool's manufacturers for the two distinct materials.

It is noteworthy that each of the conditions mentioned and tested in Tables 2 and 3 was replicated three times. Furthermore, tool integrity underwent thorough verification following each test iteration. To mitigate any potential impact of initial tool wear on the experimental outcomes, the tools were replaced after every 30 holes for the initial tests on separate materials and after every 3 holes for the subsequent tests on the stacks.

2.3. Measurements

A set of associated measurements was conducted both in situ and post-tests. The instruments and measurements performed are as follows:

- Cutting force measurements were taken in situ using the Kistler 9257b force sensor. The measurements were then analyzed and post-processed using Dynoware 3.3.2.0 software. To eliminate noise from the process, the forces were low-pass filtered at a frequency equivalent to twice the tool's rotation speed.
- All optical measurements (hole shape, delamination, wear, and chip analysis) were conducted using the Dino-lite AM7013MZT digital microscope.
- Arithmetic roughness measurements (R_a) were performed using the Diavite DH-6 specialized roughness measurement instrument and analyzed using Diasoft software version 3.1.9.

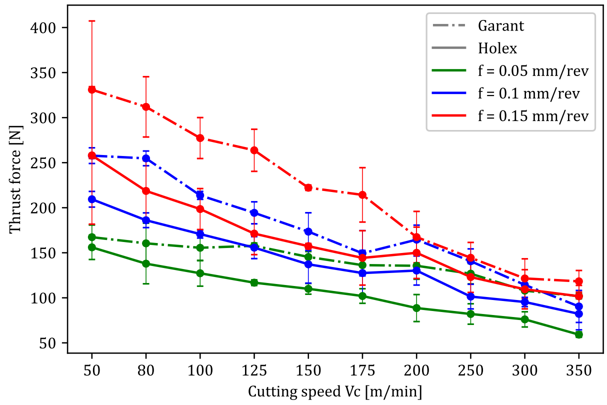

Fig. 2. Experimental thrust force (RMS values) during drilling on Aluminium 6082

3. Results and Analysis

3.1. Robotic Drilling on Aluminium 6082

As previously explained, separated tests were conducted on Aluminium 6082 and GFRP plates across a wide range of cutting conditions (see Table 2). The thrust force measurements obtained during drilling in Aluminium 6082 are depicted in Figure 2. The observed trends are as follows:

- The thrust forces increase linearly with feed rate, ranging from 59 to 331 N (RMS values), validating the safety assumptions made in setting the cutting conditions.
- Aluminium exhibits greater sensitivity to thermal softening than work hardening at high deformation rates, as evidenced by the decreasing thrust forces with cutting speed.
- The universal tool Holex generates lower thrust forces compared to Garant tools, despite the latter being coated for aluminum. This is primarily due to their more aggressive geometry and notably the helix angle (directly proportionnal to the cutting rake angle). This flat helix angle is designed to facilitate chip evacuation and subsequently high feed rates, but this configuration results in elevated cutting forces.

The analysis of cutting forces is crucial in understanding the factors contributing to improved surface integrity, especially in the context of flexible machines like robots. For clarity, the following results are illustrated using data from the Holex tools, but it's essential to note that the trends remain consistent for the Garant tools. As evident in Figure 3, which displays various observable defects, surface integrity and hole quality are significantly influenced by the cutting conditions. It's evident that surface defects correlate directly with feed rate and cutting force intensity. Additionally, a tool-tip slipping phenomenon, resulting from the robot's lack of rigidity, manifests at the entry point of the material. This is observed as an eccentricity (Δ) at the hole's entrance, as depicted in the right image of Figure 3. Figure 4 shows these eccentricites measurements Δ as a function of the cutting conditions used. The hypothesis of tool-tip

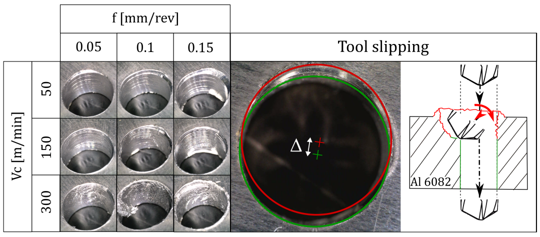

Fig. 3. Surface defects on Aluminium 6082 plates (Holex tool)

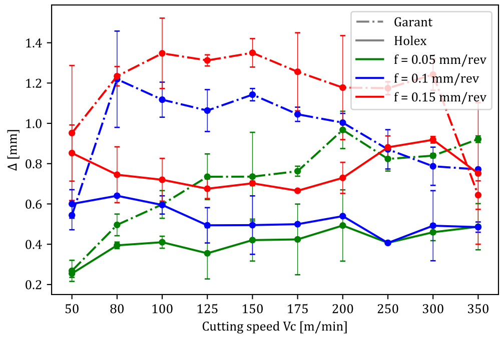

Fig. 4. Hole Entrance Eccentricity Measured on Aluminium 6082

sliding due to overall robot rigidity and potential tool deflection at the material entry point is confirmed by the dependence on feed rate and thrust forces highlighted in the graph. To protect tool integrity and ensure the best possible surface integrity by minimizing this offset, it's necessary to limit forces by employing low feed rates and mitigate dynamic effects induced by high spindle speeds.

These surface defects related to robot rigidity are directly influenced by feed rate. This is shown in Figure 5, illustrating the axial 1D profile measurement on the hole walls at a fixed cutting speed (v_c = 150 m/min). Fluctuations leading to shape errors are clearly observable during hole profile measurements. These fluctuations, attributed to robot vibrations, are approximately 10 μm at the lowest feed rate (f = 0.05 mm/rev). The straight and relatively consistent profile at low feed rates gives way to increasing fluctuations, primarily near the hole entry, where fluctuations measure around 40 and 60 μm, respectively. In addition to these shape errors, roughness indicators R_a and R_t, representing arithmetic and total roughness, respectively, are also directly impacted by changing cutting conditions. Figure 6 illustrates the evolution of arithmetic roughness measurements with varying cutting conditions and tools used. The following observations emerge:

- The minimum arithmetic roughness measurements R_a are 0.41 ± 0.13 μm for the universal Holex tool and 1.42 ± 0.45 μm for the Garant tool. These values correspond to quality classes N6 and N7 following ISO 1302, respectively, with associated total roughness values of 8.63 ± 3.4 μm and 22.8 ± 5.7 μm. Note that aeronautics norms typically mandate R_a within classes N7 - N8 for riveting applications [5].

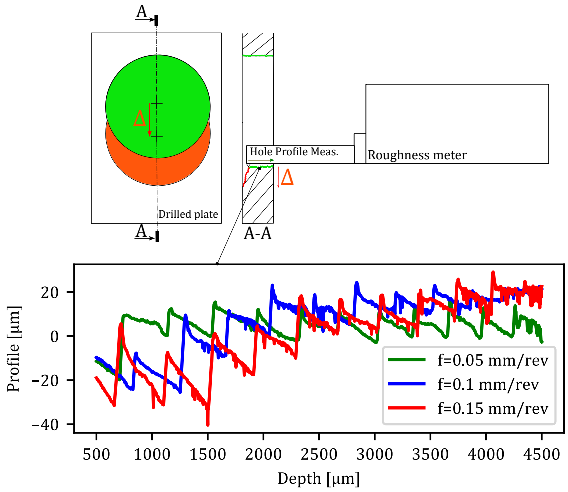

Fig. 5. Hole profile measurement on Aluminium 6082 (Holex tool) - v_c = 150 m/min

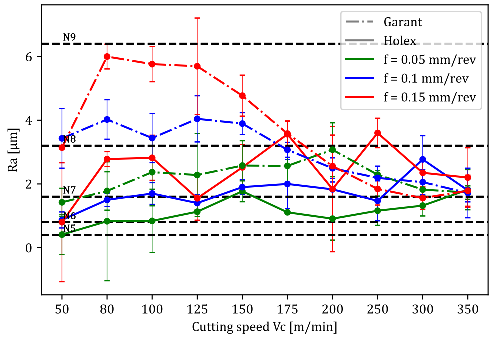

Fig. 6. Arithmetic roughness measurements on Aluminium 6082

- An increase in feed rate at a fixed cutting speed results in a proportional increase in arithmetic roughness, affirming the dependence of roughness on cutting forces. This also explains the higher roughness values obtained with the Garant tools, where measured forces are higher. This underscores the importance of selecting appropriate cutting conditions, as incorrect parameters can yield bad quality classes like N9 or N10.
- Interestingly, roughness does not decrease with cutting speed, as it might be expected due to decreasing forces. This highlights the influence of dynamic effects associated with higher tool rotation speeds, potentially affecting the robot's vibrational behavior, including resonance phenomena.

Based on these observations, the optimal cutting conditions for robotic drilling in Aluminium 6082 are v_c = 50 m/min and f = 0.05 mm/rev.

3.2. Robotic Drilling on GFRP

The cutting forces obtained under various tested conditions in GFRP plates are presented in Figure 7. The level of force

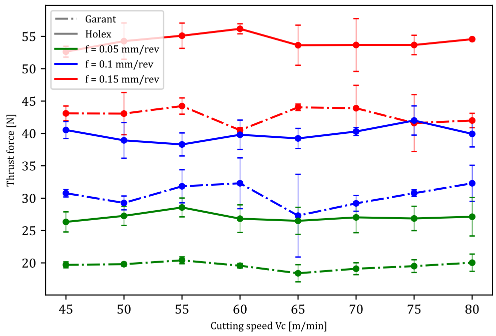

Fig. 7. Experimental thrust force during drilling on GFRP

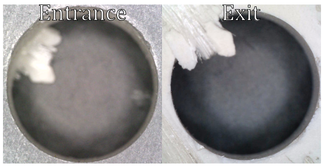

Fig. 8. Uncut fibers on GFRP plates

exerted (ranging from 20 to 55 N) is relatively low compared to the results obtained in metal plates. As expected, the force measurements indicate a direct dependency on feed rate, while cutting speed has no discernible impact on force evolution, this is due to the brittle nature of the material [8]. The following observations and conclusions were made based on the GFRP tests:

- The arithmetic and total roughness values are higher than those in metal plates. Given the low cutting forces and the minimal influence of cutting speed, it's challenging to establish clear trends. The average R_a measures on average 1.8 ± 0.8 μm with the Garant tool. The Holex tool results in average roughness R_a values of 2.5 ± 0.7 μm. These roughness values classify within quality class N9.
- The roughness profiles remain consistent, reflected in relatively stable total roughness values averaging 22 μm. No eccentricity is noted at the hole entrance, confirming the hypothesis that these phenomena is directly proportionnal to the thrust force exerced.
- Entrance and exit delamination defects are exceedingly limited, with the delamination factor F_d not exceeding 1.05. This delamination factor is computed as $F_d = \frac{D}{D_{nom}}$ [9], where D is the measured diameter and D_{nom} is the nominal diameter. However, Figure 8 reveals frequent occurrences of uncut fibers at the material's exit. The appearance of these defects does not seem to be correlated with cutting conditions or tool choice but rather with surface defects and incomplete impregnation of some fibers in the external roving.

In conclusion, GFRP exhibits limited sensitivity to cutting conditions, allowing for the selection of cutting conditions for Aluminium as common settings for Al 6082 - GFRP stacks.

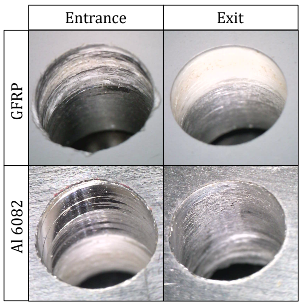

Fig. 9. Hole defects on stack plates

3.3. Robotic Drilling on Stacks

To precisely analyze the influence of cutting speed (v_c) on the Al 6082 portion, two different cutting conditions were chosen for the stack tests. The first condition, v_c = 50 m/min and f = 0.05 mm/rev, was assumed to be optimal based on tests on individual materials (Section 3.1). In addition to this, a second mixed condition was tested: v_c = 50 m/min and f = 0.05 mm/rev in GFRP and v_c = 150 m/min and f = 0.05 mm/rev in Al 6082. This mixed condition involved the application of two distinct cutting conditions as recommended by tool suppliers for drilling with common CNC machines. The objective was to potentially elucidate the factors influencing the selection of drilling conditions for robotic drilling as compared to conventional Cartesian-axis machines. Figure 9 illustrates the visual defects encountered in various sections of the stacks based on the chosen material sequence. Additionally, Figure 10 displays the 1D profile measured as a function of stack depth and material. Key observations include:

- Visually, the material at the entry exhibits lower quality compared to material drilled individually. In the case of GFRP, this is highlighted by delamination at the entry and aluminum deposits caused by the exit of aluminum chips, resulting in a more chaotic evolution in the 1D profile. In aluminum, this is reflected in the tool slipping effects observed previously.
- While the cutting forces measured in the stack tests were consistent with those observed in individual materials, two improvement phenomena are noteworthy for the material at the exit: there are no longer uncut fibers in GFRP, and the 1D profile measured in aluminum shows the disappearance of oscillations observed in the individual material (Figure 5). This leads to total roughness values below 10 µm (R_t), attributed to the presence of an entry material (GFRP) stabilizing the tool and mitigating vibration phenomena.

Figure 11 presents the evolution of arithmetic roughness (R_a) measurements as a function of stack sequence and tested cutting conditions. Cond. 1 and cond. 2 correspond respectively to the two cutting conditions tested and noted in Table 3. Furthermore, Figure 12 showcases the results of delamination measurements using the delamination factor F_d. It also displays the burr's height measured in Al 6082 at the entry and exit of the

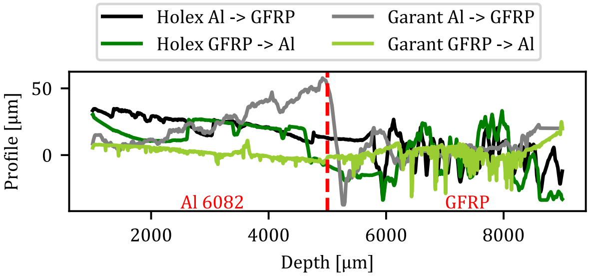

Fig. 10. 1D profile measurement on Al 6082 - GFRP stacks

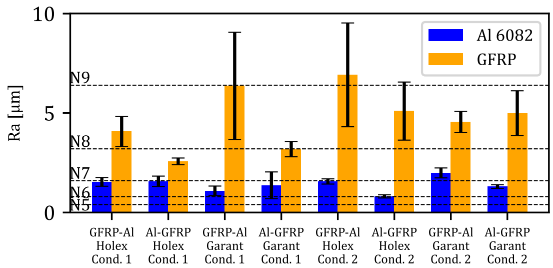

Fig. 11. Arithmetic roughness (R_a) measurement on stacks

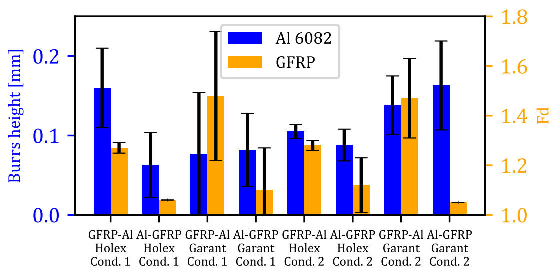

Fig. 12. Delamination factor (F_d) on GFRP and burrs height measurement on Al 6082

material, depending on the tested sequence. Key insights from these measurements include:

- Roughness values in the GFRP section are generally higher when using mixed conditions. Furthermore, as observed visually, surface states and roughness are better in the respective materials when placed at the exit. This can be attributed to material degradation due to the aluninium chip formation on GFRP and the tool slipping on aluminum.
- The Al-GFRP sequence with the Holex tool is the most favorable setup in terms of minimizing all measured parameters. It is possible to achieve an N8 class R_a for both materials, a near-perfect delamination factor (F_d) of 1.05, and an entry burr height of 0.07 mm.
- Results demonstrate that a N7 class R_a can be achieved in the Al 6082 section when placed at the entry with the Garant tool. However, this comes at the expense of hole quality in the GFRP section, which reaches bad surface integrity with an R_a in N10 class in this sequence and exhibits a F_d of 1.5 at the entry.

4. Conclusion

This study investigates the robotic drilling of Al 6082 - GFRP stacks using a Stäubli TX200 robot in its recommended configuration. The research highlights the critical role of cutting forces and robot stability, particularly influenced by the feed rate, in optimizing robotic drilling conditions and allowing to obtain similar quality than CNC drilling [6]. It reveals the lower importance of the coating on cutting forces and emphasizes the importance of selecting appropriate cutting parameters and tools in accordance with industrial tolerance standards [5].

For achieving the desired surface roughness in both metal and composite components, the study recommends utilizing the low cutting parameters v_c = 50 m/min and f = 0.05 mm/rev in combination with the universal tool. This combination consistently delivers an R_a of N8 class following ISO 1302 standards, allowing riveting applications, and effectively minimizing delamination at the exit (F_d = 1.05) and entry burr height (h = 0.07 mm). Furthermore, it is shown that by adapting drilling parameters to favorable conditions for the exit material, it is possible to enhance surface quality in this part. This allow to achieve an R_a of N7 class in Al 6082 region but reduces GFRP class to N10.

5. Acknowledgments

Authors acknowledge the funding of the MachStack project through conventions 1910097 (Region Wallonne), as well as ZL-2020/00606 and ZL-2021/00273 (Hazitek program).

References

[1] E. Brinksmeier, S. Fangmann, and R. Rentsch. Drilling of composites and resulting surface integrity. *CIRP Annals*, 60(1):57–60, 2011.
[2] Seong Hyeon Kim, Eunseok Nam, Tae In Ha, Soon-Hong Hwang, Jae Ho Lee, Soo-Hyun Park, and Byung-Kwon Min. Robotic Machining: A Review of Recent Progress. *International Journal of Precision Engineering and Manufacturing*, 20(9):1629–1642, September 2019.
[3] Alexander Verl, Anna Valente, Shreyes Melkote, Christian Brecher, Erdem Ozturk, and Lutfi Taner Tunc. Robots in machining. *CIRP Annals*, 68(2):799–822, 2019.
[4] Thomas Beuscart, Pedro-José Arrazola, Edouard Rivière-Lorphèvre, Paulo Flores, and François Ducobu. Hole quality analysis of AISI 304-GFRP stacks using robotic drilling. *Procedia CIRP*, 108:436–441, 2022.
[5] Jerzy Kaniowski. Comparison of Selected Rivet and Riveting Instructions. *Fatigue of Aircraft Structures*, 2014(6):39–62, June 2014.
[6] Redouane Zitoune, Vijayan Krishnaraj, and Francis Collombet. Study of drilling of composite material and aluminium stack. *Composite Structures*, 92(5):1246–1255, April 2010.
[7] N. Tamil Alagan, Nikhil Teja Sajja, Andreas Gustafsson, Enrico Savio, Andrea Ghiotti, Stefania Bruschi, and Rachele Bertolini. Investigation of the quality of Al-CFRP stacks when drilled using innovative approaches. *CIRP Journal of Manufacturing Science and Technology*, 43:260–272, July 2023.
[8] François Ducobu, Thomas Beuscart, Borja Erice, Mikel Cuesta, Bert Lauwers, and Pedro-José Arrazola. A mechanistic-finite element hybrid approach to modelling cutting forces when drilling GFRP-AISI 304 stacks. *CIRP Annals*, 72(1):69–72, 2023.
[9] Wen-Chou Chen. Some experimental investigations in the drilling of carbon fiber-reinforced plastic (CFRP) composite laminates. *International Journal of Machine Tools and Manufacture*, 37(8):1097–1108, August 1997.