Journal of Manufacturing Processes 64 (2021) 58–66

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

journal homepage: www.elsevier.com/locate/manpro

Drilling of CFRP-Ti6Al4V stacks using CO_2-cryogenic cooling

A. Rodríguez [a], A. Calleja [b], L.N. López de Lacalle [a,b], O. Pereira [a,*], A. Rubio-Mateos [c], G. Rodríguez [c]

[a] CFAA, University of the Basque Country (UPV/EHU) Parque Tecnológico de Zamudio 202, 48170 Bilbao, Spain
[b] Department of Mechanical Engineering, University of the Basque Country (UPV/EHU) Nieves Cano 12, 01006 Vitoria, Spain
[c] Tecnalia Research & Innovation. Parque Científico y Tecnológico de Gipuzkoa, Mikeletegi Pasealekua, 7, 20009 Donostia, Spain

ARTICLE INFO

Keywords:
CFRP
Ti6Al4V
Cryogenics CO_2
Stacks drilling

ABSTRACT

In the work here presented, liquefied CO_2 is used as cutting fluid for drilling CFRP-Ti6Al4V stacks as alternative to dry-drilling. Several tests were performed using dry-drilling technique, to compare this with the performance of CO_2 cryogenic cooling.

This work shows the feasibility of the proposed alternative, not only regarding technical issues but also environmental concerns. Results show that when CO_2 is used in drilling, hole diameter values diverge below 0.5 % from nominal values, tool tip temperature is drastically reduced, and surface integrity of CFRP layers are preserved. Drilling tool edges damage is reduced and so tool life extended. In short, dry-drilling process was notably improved by CO_2 assistance in comparison with dry drilling.

1. Introduction

All the aeronautical sector market predictions foretell that air traffic will continue a growing tendency, even after Covid 19. Hence, airplane manufacturing companies will need to persist in the effort to achieve productivity and quality in all manufacturing processes. The growth of air traffic over the past 20 years has been spectacular, and will continue in the future, particularly in the growing markets of the Far East. Aeronautical industry must accomplish several aspects regulated by European (recommendations of Clean Sky II program and from the Advisory Council for Aeronautics Research in Europe (ACARE)) and international rules, such as aircrafts general efficiency, reduction in noise and fuel consumption. Consequently a crucial role is played by materials in use in aircraft structures; around 50 % of the total aircraft weight is associated with airframe.

Thus, in the last ten years, to reduce aircraft structure weight, composite materials have taken increasing importance. In fact, 52 % of the total structure materials in Airbus A350 and 57 % of the primary structure of Boeing 787 are composites [1,2]. Carbon fiber reinforced polymer (CFRP) is the most used [3]. This composite is characterized by presenting lightweight, high strength, shape adaptability, and good fatigue resistance [4]. The composite is usually combined with Ti6Al4V in stacks shape [5], resulting in a new layered material that improves mechanical properties. On the other hand, combining material sheets in stacks is the easiest way of mounting/dismounting components during the repair/maintenance processes [6].

On the other hand, CFRP-Ti6Al4V stacks are fixed to aircraft body by bolted joints or rivets [7]. This fact implies that the primary machining operation applied to stacks is drilling [8]. Stacks dry drilling implies several difficulties, due to the different mechanical properties presented by each layer of material on one hand, and the absence of oil emulsions during the process in the other. In particular, in the case of CFRP layers, delamination is the main concern, which represents 60 % of all component rejections in manufacturing [9], delamination means some fibers pulled out, matrix melting or burning, or surface micro-cracks [10]. These problems are presented mainly at the drilling tool entrance and/or exit from the CFRP layers [11]. Nevertheless, CFRP also causes tool abrasive wear due to the hard and tough carbon fibers [12]. Otherwise, in Ti6Al4V drilling, the main problem concerns tool wear and life, due to Ti6Al4V has a low thermal conductivity that leads to tool cutting edges high temperature, which combined to its high chemical reactivity with tool materials implies a rapid tool wear. Titanium alloys chip and burr formation is complicated, often causing built-up adhesion layer on tool cutting edges [13]. Therefore, CFRP-Ti6Al4V stacks drilling is a process that presents risks and problems in both material sheets (composite and metal alloy) and tool, delamination in the former and

* Corresponding author at: University of the Basque Country (UPV/EHU), CFAA, University of the Basque Country (UPV/EHU) Parque Tecnológico de Zamudio 202, 48170 Bilbao, Spain.

E-mail address: octaviomanuel.pereira@ehu.eus (O. Pereira).

https://doi.org/10.1016/j.jmapro.2021.01.018
Received 27 March 2020; Received in revised form 13 January 2021; Accepted 13 January 2021
Available online 26 January 2021

wear on the latter.

Regarding the state of the art, several pieces of research analyzed stacks drilling performance. For example, in the work carried out by Xu et al., several cutting sequence strategies were carried out. In particular, the sequences used were firstly CFRP-Ti6A4V stacks and finally Ti6Al4V-CFRP stacks respectively, that is, the order of the stacks sheets changed. Besides, they also tested different kinds of sintered carbide drills (uncoated and coated) and diamond polycrystalline (PCD) ones. The results showed that in the case of Ti6Al4V-CFRP stack, tool tip achieved more temperature initially, and drilling thrust force was lower. Besides using the diamond coated drill, the heat generation was lower than using uncoated one [14]. In other work carried out by them, stack surface integrity was analyzed after being drilling with a 140° angle tip with carbide coated with TiAlN. The results showed that CFRP layers presented surface cavities due to fiber/matrix losses, and Ti6Al4V layers presented adhered material due to compressive tool loads [15]. On the other hand, Kuo et al. studied the effect of cutting speed and feed rate on the stacks surface integrity and tool life. In this case, the drill tool used was a tungsten carbide coated with diamond and two-stage point angle of 120°–180° with helix angle of 30°. The results showed that tool life did not exceed 30 holes, and a combination of lower cutting speed and intermediate feed implied minor adhesion effects on the hole surface [16].

Another characteristic to take into account when CFRP-Ti6Al4V stacks are machined is tools constitutive material. For example, PCD is the preferred one to deal with CFRP, whereas carbide tool is for machining Ti6Al4V [17]. This reasoning is based on the cutting temperatures; at high temperature PCD graphitizes and also reacts with Ti6Al4V appearing diffusion effect on the edge being not suitable to continue machining [18]. Then, using cutting fluid with this kind of stacks is a parameter to analyze. Kerrigan et al. analyzed the effect of different oil emulsions. In particular, oil emulsions at 40 %, 5 % and 8 % respectively, were studied during CFRP drilling using dry drilling as reference baseline; tool wear was reduced using oil emulsions in excess of 80 % [19]. From a technical point of view, the use of oil emulsions implies economic savings regarding tool costs. Nonetheless, in aeronautical workshops, the use of oil emulsions on CFRP can involve a risk of absorption of the cutting fluid by the CFRP layers [20]. Besides, from an ecologic point of view, the environmental footprint generated is unthinkable by current standards [21]. Drilling is frequently applied in semiautomatic manual stations, so coolant management is rather difficult. Consequently, looking for other alternatives to avoid the use of oil emulsions is a hot topic in research nowadays.

Therefore, the novelty of the work here presented stems from the idea of analyzing the eco-friendly lubricooling alternatives applied to CFRP-Ti6Al4V stacks to detect the more suitable technique. Based on this, cryogenic CO_2 cooling behavior was analyzed during drilling tests on CFRP-Ti6Al4V stacks with carbide tools coated with CVD (chemical vapor deposition) diamond. The results showed that the use of recycled CO_2 as cutting fluid implies a real improvement not only from an environmental point of view but also from a technical one.

2. Machining eco-friendly lubricooling techniques

In this section, with the aim of analyzing what is the more suitable eco-friendly technique to be applied as cutting fluid to CFRP-Ti6Al4V stacks, an analysis of their application in the literature to this kind of materials was carried out. Among the different alternatives for cutting fluids, minimum quantity lubrication (MQL) and cryogenic cooling are eco-friendlier processes. This was conclude based on the complete life cycle analysis (LCA) which was carried out by Pereira et al. In this research, the main lubricooling alternatives were analyzed from an environmental point of view, comparing its use with conventional oil emulsions. The results showed that MQL was the alternative to reduce the ecological footprint dramatically, and the use of cryogenic gases such as LN_2 or CO_2 also supposed a clear reduction [21]. Then in this section, these two lubricooling alternatives were analyzed to assist drilling process of stacks composed by CFRP-Ti6Al4V, MQL and cryogenic cooling respectively.

2.1. Minimum quantity of lubricant (MQL)

Minimum quantity lubrication implies the consumption of cutting oil at very low flow rates ranging between 10 and 100 mL/h [22]. In addition, it is possible to use biodegradable oils with MQL devices. In this line, a work carried out by Zhao et al. presented a set of surfactant-selection guidelines that can be used to design bio-based semi-synthetic metalworking fluid (MWF) microemulsions as a

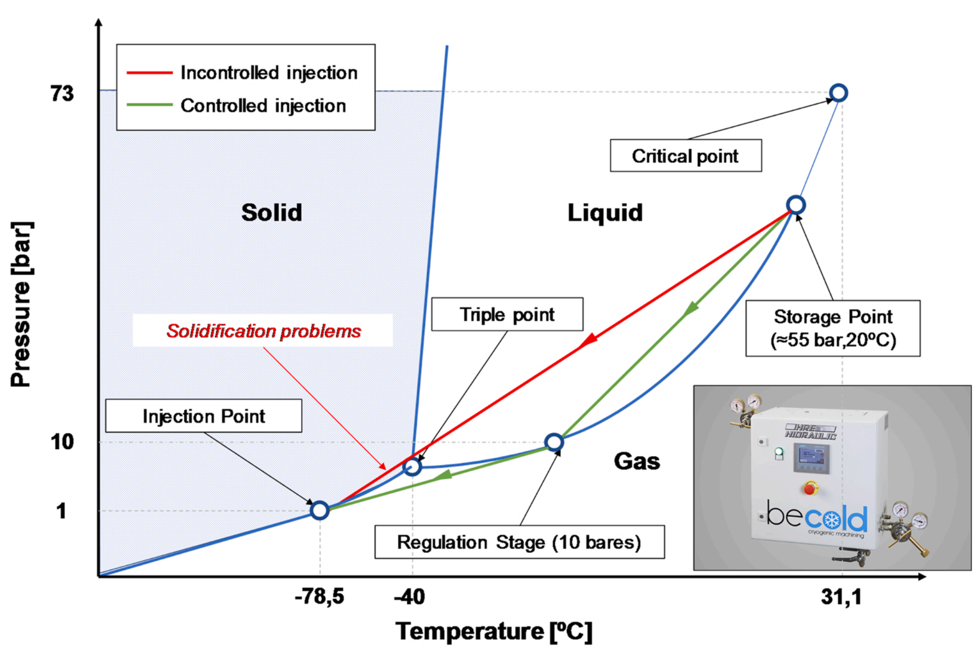

Fig. 1. CO_2 injection equipment and applications; green line is the right one (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

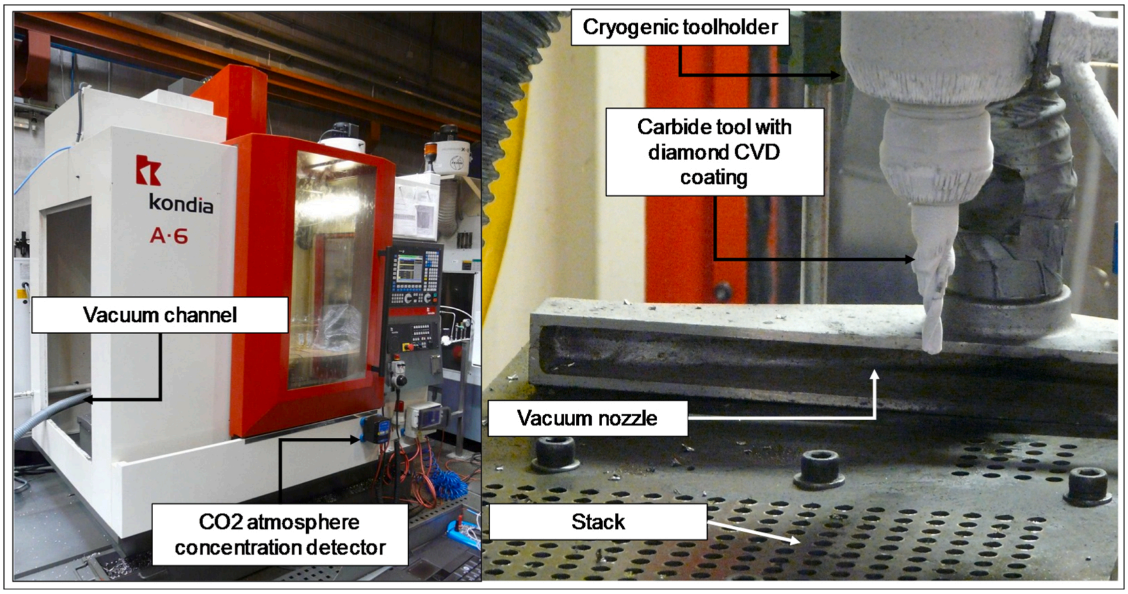

Fig. 2. Experimental setup for CFRP-Ti6Al4V drilling.

renewable alternative to conventional petroleum formulations [23]. The flow rate reduction is achieved by pulverization of biodegradable oil (microparticles) by Venturi's effect [24]. In this way, a thin film of oil can be injected between the tool-chip interaction zone with better lubrication performance than that obtained with oil emulsions, and with greater thermal stability [25]. MQL presents a better penetration of oil microparticles in the tool-chip interface in comparison with other techniques. In fact, Clarens researching group demonstrated the enhanced penetration of MQL into the cutting zone based on a derivation of the Navier–Stokes equation and the Reynolds equation for lubrication and applied to an orthogonal cutting geometry under steady-state conditions [26]. Besides, MQL causes practically produces clean chips easy to be recycled, while increasing the industrial hygiene of the workshops. In the literature, two types of research can be found in which CFRP composite and CFRP-Ti6Al4V stacks were machined using MQL, respectively. The first one with CFRP composite, the cutting forces increased in comparison with the use of oil emulsions; thus, although oil emulsions demonstrated better results regarding CFRP surface integrity, MQL was still comparable, and in addition the environmental footprint was reduced [27]. In this work about CFRP-Ti6Al4V stacks drilling, the results showed that higher thrust forces were registered in comparison with dry machining, perhaps due to the clogging effect of CFRP chips between hole surfaces and drill flutes. Besides, with dry machining delamination defects were lower [28]. Therefore, the use of MQL was not a suitable technique for this kind of material and it was disregarded.

2.2. *Cryogenic cooling*

Another alternative with a high degree of feasibility is cryogenic cooling. This technique presents a good cleanliness degree to be applied on medical and aerospace manufacturing sectors. Cryogenic refrigeration used liquefied gas at very low temperature as a cutting fluid. Generally, by cost and applicability, liquid nitrogen (LN_2) or liquefied carbon dioxide (CO_2) are used. The former advantage is that it reaches -196 °C when it is evaporated. However, because it must be stored at −198 °C in isolated reservoirs, it is continually boiling in the reservoir, which means that there is a constant loss of gas. Therefore CO_2, despite reaching −78 °C once injected, is positioned as the best option when used industrially [29], it is stored only under pressure and produces as a disposal gas from other industrial processes. From an environmental point of view, CO_2 is a recycled gas derived from a primary process; that is, the environmental neutrality is similar to LN_2 [30]. On the other hand, patent by Skerlos et al. proposed a method for lubricating a metal workpiece during a metalworking process includes delivering supercritical carbon dioxide combined with oil microparticles to the workpiece during the metalworking process [31].

However, due to CO_2 physical characteristics, it needs an injection device to make possible its use as a cutting fluid. In particular, "dry ice" formation inside pipes and channels in which is going to pass through is the central function of the injection system. In this line, the authors developed a "plug & play" device. This injection system is characterized by maintaining the CO_2 over the triple point, avoiding "dry ice" formation before being injection in the cutting zone. In Fig. 1 is shown a CO_2 diagram phase, in which is explained how it works.

In the case of cryogenics applied to drilling either single composites or stacks, LN_2 was used mainly. Thus, regarding CFRP, a research carried out by Basmaci et al. showed that the control of the cutting temperature provided by nitrogen avoided the crystal transition of the composite matrix, obtaining higher quality surfaces in comparison with dry machining [32]. This behavior was also obtained in other work carried out by Giasin et al., in which LN_2 coolants improved surface roughness in S2-Glass fibre-Al2024T3 stacks over dry conditions by up to 44 % [33]. In the case of Impero et al., this cooling technique in CFRP-Ti6Al4V stacks implied a thrust force and torque reduction, allowing the increase of drilling cutting speed [34]. However, in this research, CFRP surface integrity was not taken into account. This issue was analyzed by Xia in two researches, in which the use of LN_2 increased both thrust force and torque, leading to higher risk of delamination [35, 36]. The delamination effect was also studied by Khanna et al. in other work; The main conclusion was that delamination is caused by the CFRP hardening due to the very low LN_2 temperature [37]. Then, LN_2 is not a real solution to be applied in industrial workshops.

On the contrary, CO_2 cooling capacity is lower, but its injection pressure is higher than LN_2. Moreover, the higher injection pressure implied a cushion effect at the interface tool-material, which reduces friction [38]. Therefore, CO_2 opens a new way of drilling in which both surface and tool integrity can be preserved.

Recent works about drilling were focused on the relationship between burrs height, delamination length, process power consumption and the diameter of two-step drill bits [39], or about the stack drilling layers sequence. So, drilling from titanium to CFRP leads to higher magnitudes of the composite cutting temperatures [40]. However composite delamination risk increases too much. It is better starting the drilling operation on composite, being the titanium alloy sheet a clear

Table 1
Cutting conditions.

Material	Thickness [mm]	Feed per tooth (f_z) [mm/z]	Cutting speed (V_c) [m/min]	Strategy
CFRP	8	0.025	70	Continuous drill
Ti6Al4V	10.4	0.025	15	Peck drilling (step 0.5 mm)

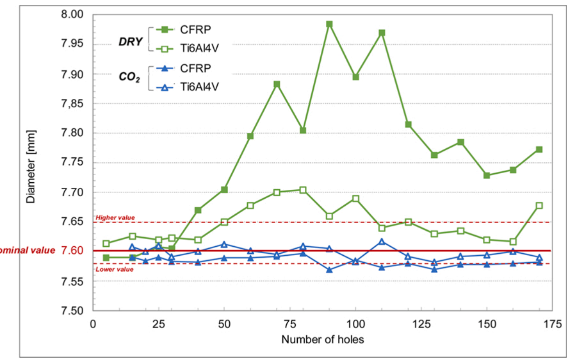

Fig. 3. Diameters obtained after drilling CFRP-Ti6Al4V stacks.

back support.

Therefore, an analysis of CO_2 behavior under industrial conditions is needed to achieve an efficient drilling process and to eliminate harmful coolants.

3. Experimental setup

In order to test CO_2 cryogenic cooling, stacks composed by a layer of CFRP (Carbon fiber, resin de Epoxy cured to a 180 °C, pre-impregnated W3T-182-42-F263-27, tensile strength: 525 MPa, tensile modulus: 53–59 GPa) on another one of Ti6Al4V (aged state) were drilled. The reason because stacks were chosen instead of single CFRP composites was to replicate industrial conditions in the aeronautical sector.

Tests were carried out in a Kondia A6 machining center, spindle up to 12,000 rpm and 15 kW, provided with an aspiration system to absorb chips and dust generated during drilling. Dry condition and CO_2 as cutting fluid were tested. The CO_2 injection was through the tool core by means of internal channels; a rotating tool holder developed by Laip S.A. was used to allow CO_2 being introduced into the tool internal channels. Stop test criterion was to carry out 160 consecutive holes. This value was established based on current aeronautical industrial requirements. Drills used were carbide tools coated with diamond CVD (10,000 $HV_{0,05}$), with a diameter of 7.6 mm, cutting edge angle (tip angle *2Kr*) of 135°, and provided with internal coaxial channels. CVD diamond is pure diamond formed as interconnected diamond microcrystals with no binder.

During testing, tool tip temperature was measured with an Impac® infrared camera just after each hole was completed, and spindle power consumption was monitored with a Vydas™ UPC-E-12 V measurement unit. Besides, tests were stopped each 10 holes for checking hole diameters were measured with a Mitutoyo™ interior micrometer. Also, adhesion of Ti6Al4V on the drill cutting edges with a Nikon™ SMZ-2T microscope was checked each 4 stops (40 holes). Finally, once the tests were finished, burrs height formed in the Ti6Al4V layer was measured with a Leica™ DCM-3D confocal microscope, and representative images were obtained with the aim of looking for burns at the CFRP hole edges with a Nikon™ SMZ-2T microscope. The experimental setup and cutting conditions are shown in Fig. 2 and Table 1, respectively.

4. Results

In this section, the results obtained during the tests carried out are gathered. Fig. 3 shows diameter evolution during the 160 holes. Values for both material sheets, and for dry and CO_2 machining are shown respectively. As can be seen, in both materials, when using CO_2 cooling, obtained diameters are closer to the nominal value along all the test evolution in comparison with dry drilling, being between 7.571 mm and 7.599 mm for CFRP layer and 7.621 mm and 7.586 mm for Ti6Al4V ones. Taking the nominal diameter (7.6 mm) as reference, these values imply hole diameter deviations between −0.38 % and −0.004 % for CFRP holes and between 0.28 % and −0.18 % for Ti6Al4V ones. In the case of dry machining, the diameter value deviations increase, presenting a significant volatility. In this case, in the CFRP layer, values are between 7.59 mm and 7.98 mm, and in the Ti6Al4V one between 7.612 mm and 7.703 mm, that is, diameter value deviations are between −0.13 % and 5.08 % for CFRP holes and 0.15 % and 1.35 % for Ti6Al4V ones. Then, the use of CO_2 implies diameter values more accurate, being the difference below 0.5 % than machining with dry conditions, in which the diameter value deviations can achieve 5 %. Besides, using dry conditions, in CFRP layer between the holes number 80 and 120 presents high variability and after the hole number 110 the hole diameters decrease. This is phenomenon is related with Ti6Al4V material stuck to the secondary edge of the tool. Then, depending of the amount of Ti6Al4V adhered, it modifies the diameter of the tool and therefore the

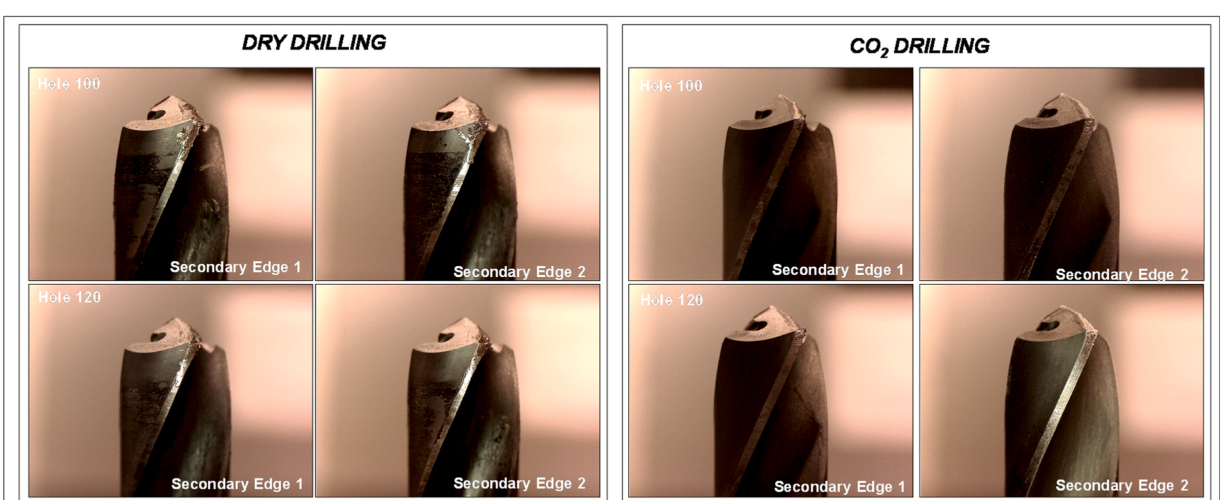

Fig. 4. Adhesion phenomenon on drill secondary edge.

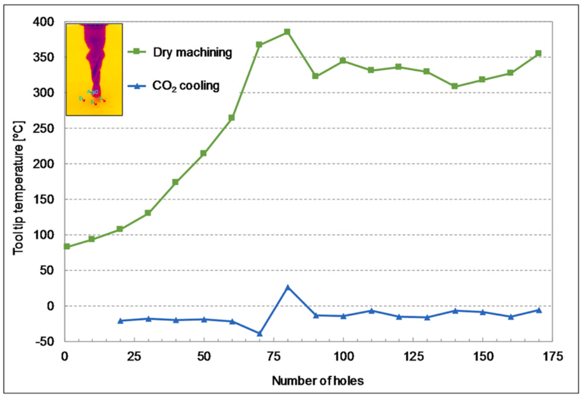

Fig. 5. Tool tip temperature just after drilling a hole CFRP-Ti6Al4V stacks.

hole diameter obtained. However, using CO_2 as cutting fluid this adhesion phenomenon is not presented which implies that the difference between the first and last hole is slight lower due to the mechanic wear of the tool secondary edge. In Fig. 4 is shown the drill secondary edges after carrying out the holes number 100 and 120 with both techniques, respectively.

This improvement is related with the strict cutting temperature achieved with the use of CO_2 as cutting fluid which avoids possible thermal expansions of both tool and workpiece. In fact, as shown in Fig. 5, when using CO_2, tool tip temperature is maintained constant, around 0 °C in the range between -38 °C and 26 °C. However, under dry conditions, temperature grows exponentially during the first 80 holes until being stabilized at ≈325 °C. It should be noted that this growth and subsequent stabilization also occurs in minor degree during the use of CO_2 as cutting fluid. This is mainly because tool coating layer in the edge disappears, and material is easily adhered to tool edges. This phenomenon is shown in Fig. 6, which also explains why when CO_2 is used, tool edge remains sharper compared to dry machining.

On the other hand, regarding Ti6Al4V burrs height, it appears in this layer because is below CFRP one, being the last layer before finishing the drilling process. The values can be seen in Fig. 7 in which the reference was established based on the common value used in aeronautical sector. In both cases, dry and CO_2 machining, burr exceed the reference value, being the most unfavorable case for dry machining. In the case of CFRP layers, the use of CO_2 implies the total absence of delamination, and neither burr nor burned areas after reaching the end of the test happens. The last holes (number 160) for drills using dry conditions and CO_2 ones are shown in Fig. 8. These phenomena are related with the cutting temperature, which is kept below 0 °C. Delamination is prevented because composite matrix becomes stiffer at low temperature, resulting in less cracks probability. Besides, it implies avoiding burned areas, just the contrary of the case of dry drilling; at dry conditions temperature usually achieve values over 300 °C. For instance, in Fig. 5 temperature reach 389 °C at the peak in hole 81. Therefore, the higher temperature, the higher probability of material defects and tool degradation.

Regarding machine spindle power consumption, Fig. 9 (a) shows the spindle power for the first and the last drilled hole, number 160. As it can be observed, the higher power consumption values can be due to the higher machining temperature variation caused by dry and CO_2. In particular, taking dry machining as reference, the use of CO2 implies in the first hole an increase of spindle power consumption of ≈50 %, which

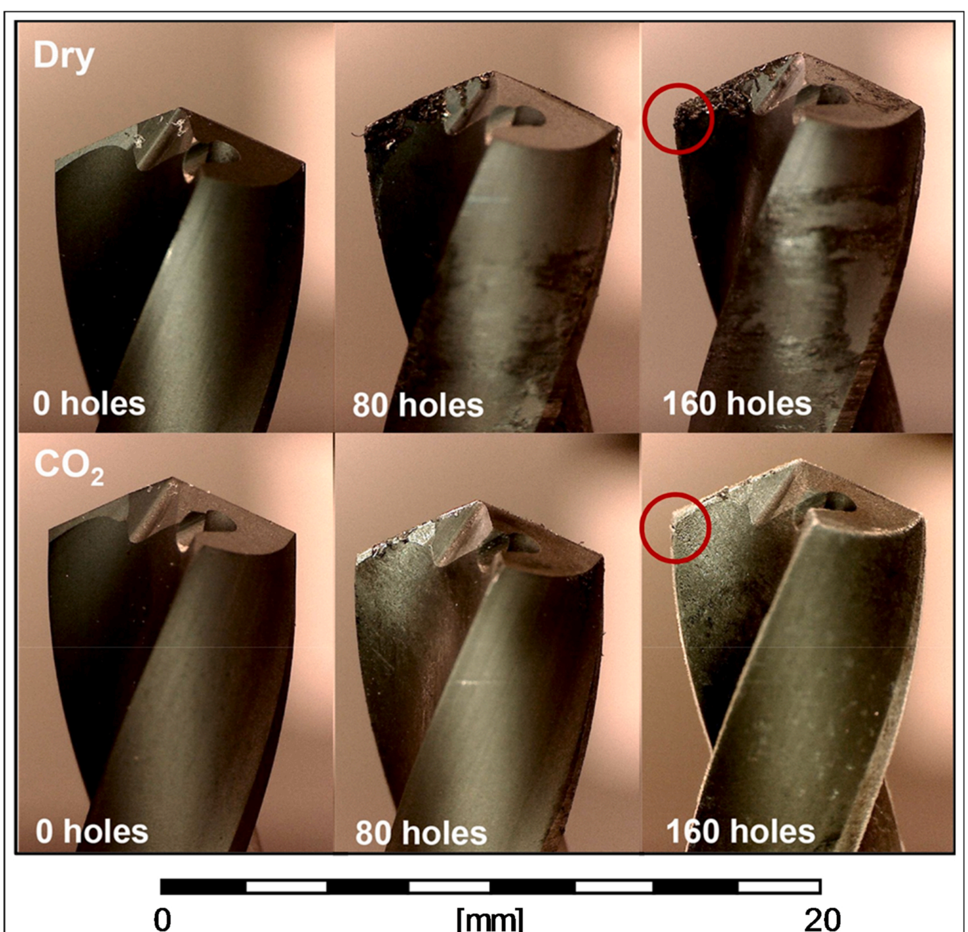

Fig. 6. Ti6Al4V adhesion evolution.

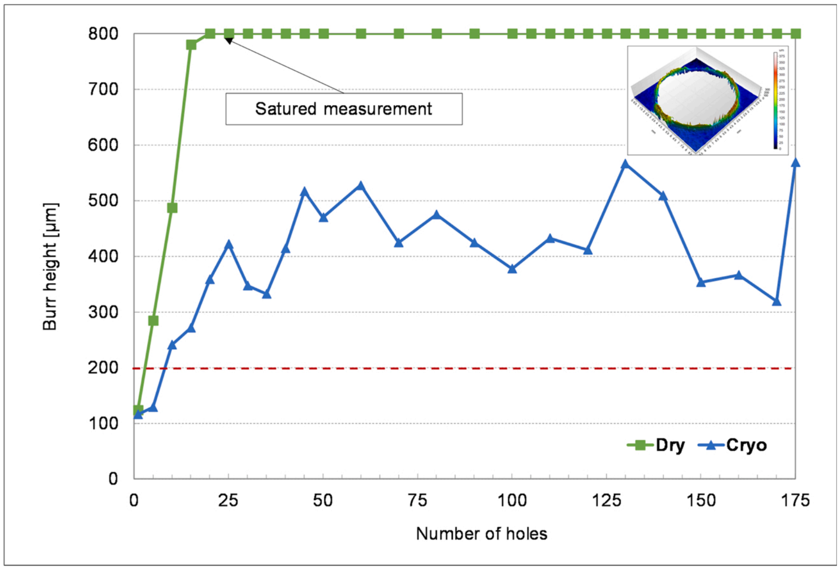

Fig. 7. Burr height obtained in Ti6Al4V layers.

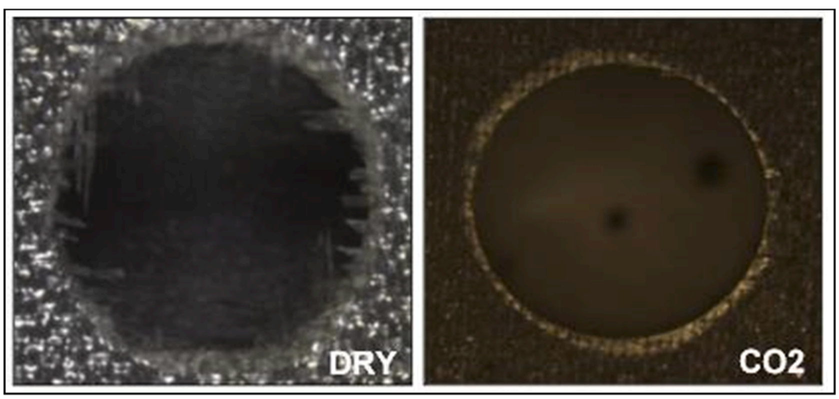

Fig. 8. Holes number 160 obtained with dry and CO_2, respectively.

is reduced along the testing process until being ≈24 % in the hole 160. This phenomenon is caused by both ductility decrease and fragility increase of the material when its temperature is reduced. This implies a reduction of the dislocation mobility of the material grains and therefore, torque increases and consequently the spindle power consumption. Nevertheless, CO_2 cutting fluid implied a more stable process as it can be seen in Fig. 9 (b), in which the first and last hole are compared using dry and cryogenics conditions, respectively. In fact, in the case of CO_2, there is not almost increase of the average consumption between the first hole and the 160, which is only of ≈0.5 %, but in the case of using dry conditions this difference increases until ≈23 %.

Finally, regarding tool wear, tool states after finishing the tests are shown in Fig. 10. In the cryogenics technique, tool after 160 holes presents a flank wear of 0.28 mm and 0.32 in each edge, respectively, but does not present adhered Ti6Al4V material due to the exhaustive control of the cutting temperature. Besides, on the secondary edge there is no evidence of burnt marks on the surface. On the opposite, when dry conditions are used, the tool is subjected to both high friction phenomenon and chemical diffusion without any cutting fluid assistance. In particular, friction mechanism takes relevance in the CFRP layer due to its abrasive nature. On the other hand, in the Ti6Al4V layer, chemical diffusion is the main wear mechanism due to the affinity between Ti6Al4V and tool materials. The combination of these effects causes adhesion, burn marks, and a flank wear of 0.31 mm and 0.35 mm in each edge. In case of comparing both techniques, it should be noted that the flank wear is similar but the drills present different behavior regarding adhesion phenomenon and burnt marks, being the CO_2 drilling the technique which avoid practically them and therefore, reduces the possibility of catastrophic tool failure.

5. Conclusions

In this paper, drilling performance using CO_2 as cutting fluid in CCFRP-Ti6Al4V stacks was studied. Tests were performed to compare dry machining with CO_2 to drill CFRP-Ti6Al4V stacks. The main conclusions obtained are the following ones:

- The use of internal cooling with CO_2 has a positive effect in drilling CFRP-Ti6Al4V stacks. Diameter values closer to nominal data are reached, particularly in CFRP layers, in which the tolerance obtained along the test is below 0.5 % approx.
- With CO_2, cutting temperature values are decreased drastically and maintained more constant along the test in comparison with dry drilling. In particular, no thermal damage is observed in the CFRP while the Ti6Al4V adhesion on the tool cutting edge does not occur at drill bit edges, even once the test stop criterion (160 holes) has been reached.
- It must be taken into account that when using cryogenic cooling, higher power consumption (associated with higher drilling torque) is generated. Undoubtedly this is related with the decrease in process

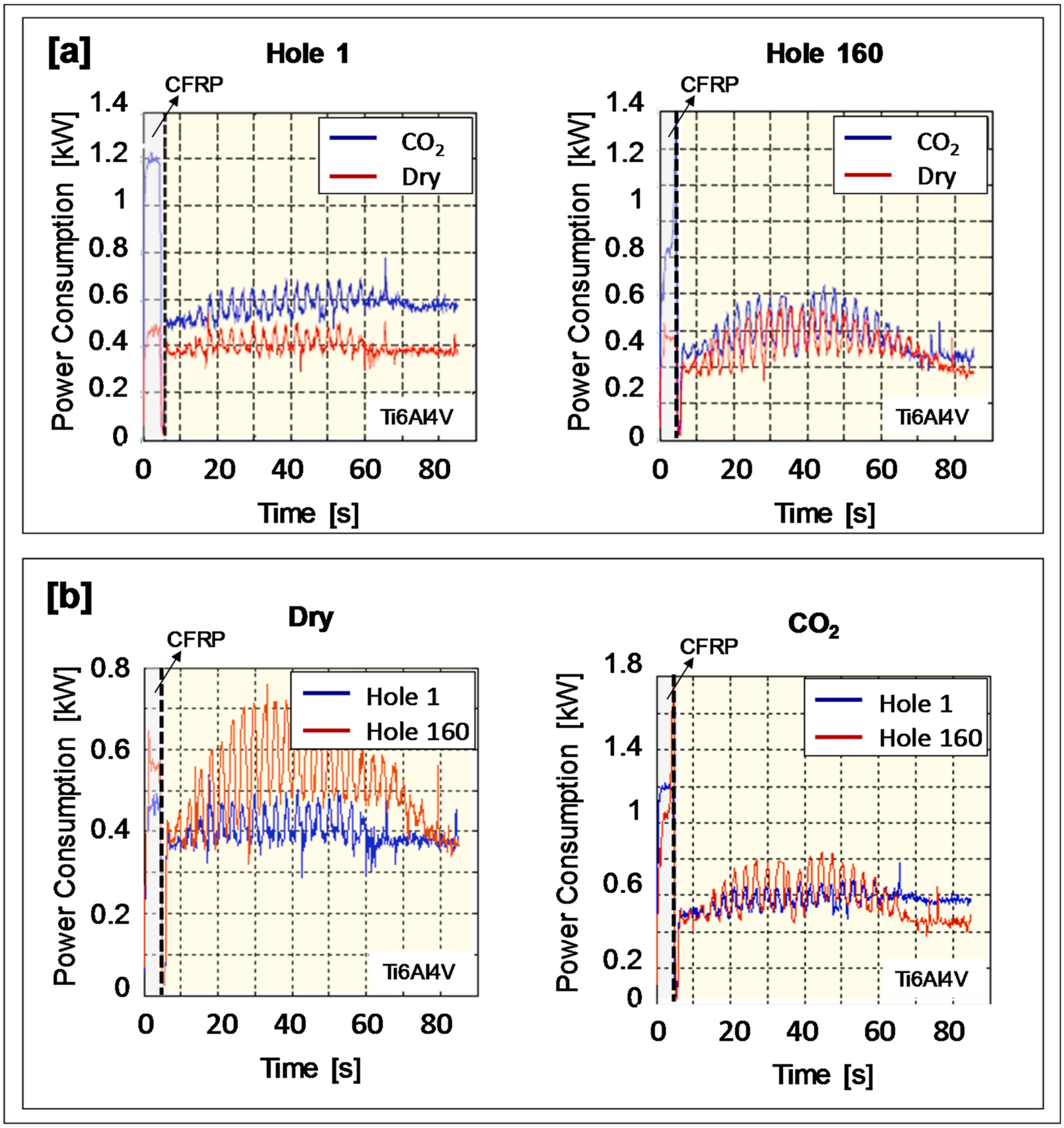

Fig. 9. Spindle power consumed during CFRP-Ti6Al4V drilling.

temperature. In particular, in the first hole the use of CO_2 as cutting fluid implies an increase of 50 % of power consumption in comparison with dry drilling. Nevertheless, this difference is reduced along the test until achieving 24 % in the last hole. On the other hand, when power consumed in the first and last hole of each test are compared, the use of CO2 implies an increase of 0.5 % and 23 % in case of dry milling. Thus, the use of CO2 as coolant implies obtaining a more stable process over time.

In short, from a technological point of view, the use of cryogenic cooling with CO_2 is presented as a feasible technique to be applied in industrial environments. Not only the surface integrity of the mechanized part is of vital importance, but also tool life plays a crucial role in determining the viability of the process. In particular, the use of CO_2 improves tool integrity in which adhesion and burnt phenomena are reduced. Besides, it's use implies achieving a more stable process in which power consumption variability along the drilling is also reduced and at the same time the variability of the hole diameter is reduced in comparison with conventional drilling process in which dry conditions are used. Therefore, the use of CO_2 implies a way of improving the drilling process of CFRP-Ti6Al4V stacks through an environmental respectful technique.

Declaration of Competing Interest

The authors report no declarations of interest.

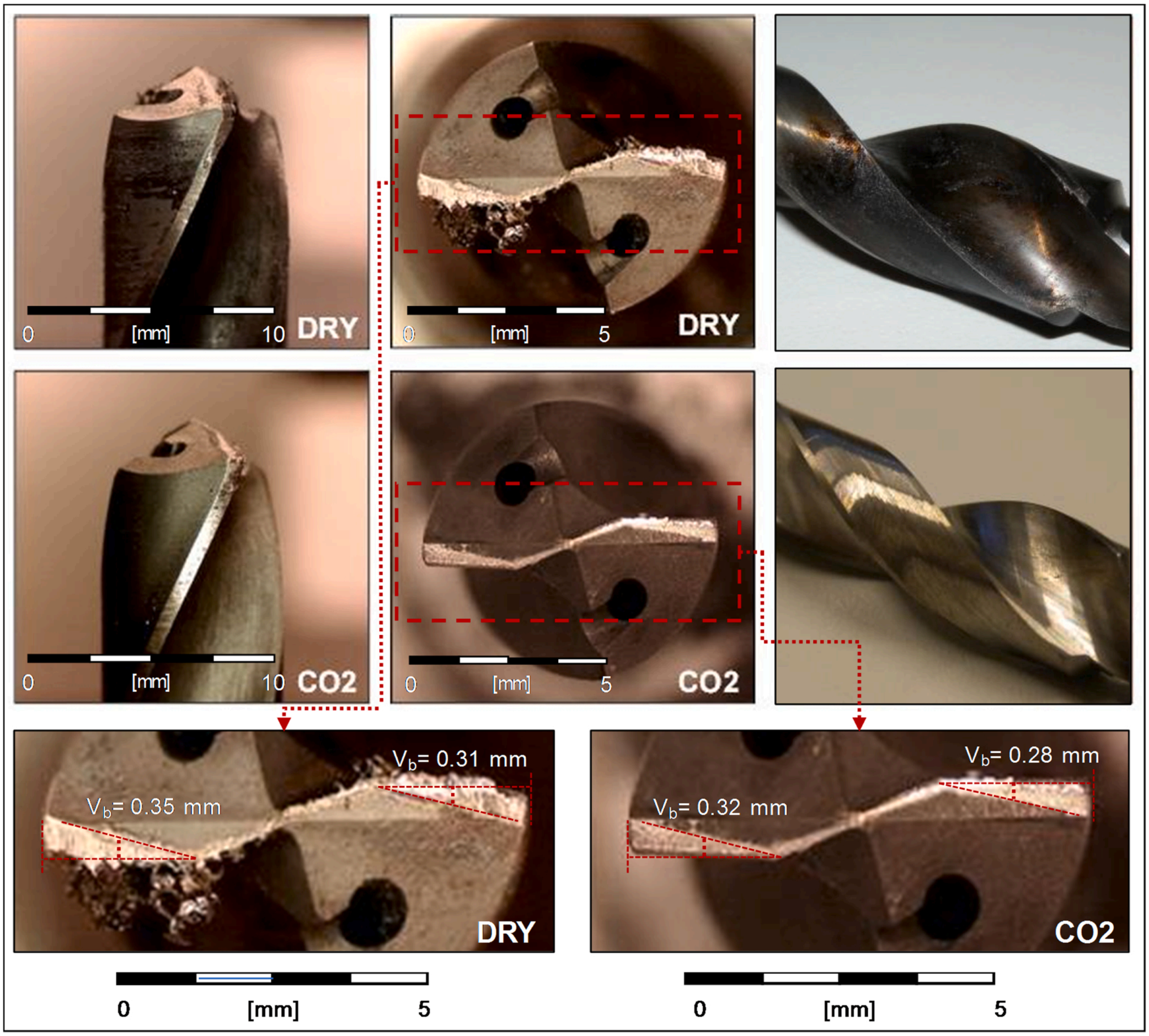

Fig. 10. Tool after finishing the tests: CO_2 avoids built-up edge and layers.

Acknowledgments

Thanks are addressed to Spanish ministry Project DPI2016-74845-R, to Basque government Project HAZITEK BeCool and Vice chancellor of innovation, social compromise and cultural action from UPV/EHU (Bizialab program from Basque Government). Authors are also grateful to Basque government group IT1337-19.

References

[1] Taking the lead: the A350 XWB. Airbus; 2009. http://www.eads.com/xml/content/OF00000000400004/7/19/41508197.pdf.
[2] Geng X, Liu Y, Shao Z, Lu Z, Zhang D. Delamination formation, evaluation and suppression during drilling of composite laminates: a review. Compos Struct 2019;15:168–86. https://doi.org/10.1016/j.compstruct.2019.02.099.
[3] Slamani M, Chatelain JF. Assessment of the suitability of industrial robots for the machining carbon-fiber reinforced polymers (CFRPs). J Manuf Process 2019:177–95. https://doi.org/10.1016/j.jmapro.2018.11.022.
[4] Tong L, Yu Q, Zhao XL. Experimental study on fatigue behaviour of butt-welded thin-walled steel plates strengthened using CFRP sheets. Thin-Walled Struct 2020;147:1–12. https://doi.org/10.1016/j.tws.2019.106471.
[5] Pecat O, Brinksmeier E. Low damage drilling of CFRP/Titanium compound materials for fastening. Procedia CIRP 2014;13:1–7. https://doi.org/10.1016/j.procir.2014.04.001.
[6] Shyha IS, Soo SL, Aspinwall DK, Bradley S, Perry R, Harden P, et al. Hole quality assessment following drilling of metallic-composite stacks. Int J Mach Tools Manuf 2011;51:569–78. https://doi.org/10.1016/j.ijmachtools.2011.04.007.
[7] Xu J, El Mansori M, Voisin J, Chen M, Ren F. On the interpretation of drilling CFRP/Ti6Al4V stack using the orthogonal cutting method: chip removal mode and subsurface damage formation. J Manuf Process 2019;44:435–47. https://doi.org/10.1016/j.jmapro.2019.05.052.
[8] Zitoune R, Krishnaraj V, Almabouacif BS, Collombet F, Sima M, Jolin A. Influence of machining parameters and new nano-coated tool on drilling performance of CFRP/aluminium sandwich. R. Composites: Part B 2012;43:1480–8. https://doi.org/10.1016/j.compositesb.2011.08.054.
[9] Campos-Rubio Davim J, Abrao J. A novel approach based on digital image analysis to evaluate the delamination factor after drilling composite laminates. Compos Sci Technol 2007;67(9):1939–45. https://doi.org/10.1016/j.compscitech.2006.10.009.
[10] Haeger A, Schoen G, Lissek F, Meinhard D, Kaufeld M, Schneider G, et al. Non-destructive detection of drilling-induced delamination in CFRP and its effect on mechanical properties. Procedia Eng 2016;149:130–42. https://doi.org/10.1016/j.proeng.2016.06.647.
[11] Gaugel S, Sripathy P, Haeger A, Meinhard D, Bernthaler T, Lissek F, et al. A comparative study on tool wear and laminate damage in drilling of carbon-fiber reinforced polymers (CFRP). Compos Struct 2016;155:173–83. https://doi.org/10.1016/j.compstruct.2016.08.004.
[12] Faraz A, Biermann D, Weinert K. Cutting edge rounding: an innovative tool wear criterion in drilling CFRP composite laminates. Int J Mach Tools Manuf 2009;49:1185–96. https://doi.org/10.1016/j.ijmachtools.2009.08.002.
[13] Xu J, Li C, Chen M, Mansori M, Davim JP. On the analysis of temperature, surface morphologies and tool wear in drilling CFRP/Ti6Al4V stacks under different cutting sequence strategies. Compos Struct 2019. https://doi.org/10.1016/j.compstruct.2019.111708.
[14] Xu J, Mansori M, Voisin J, Chen M, Ren F. On the interpretation of drilling CFRP/Ti6Al4V stacks using the orthogonal cutting method: chip removal mode and

subsurface damage formation. J Manuf Process 2019;44:435–47. https://doi.org/10.1016/j.jmapro.2019.05.052.

[15] Kuo CL, Soo SL, Aspinwall DK, Thomas W, Bradley S, Pearson D, et al. The effect of cutting speed and feed rate on hole surface integrity in single-shot drilling of metallic-composite stacks. Procedia CIRP 2014;13:405–10. https://doi.org/10.1016/j.procir.2014.04.069.

[16] Park KH, Beal A, Kim D, Kwon P, Lantrip J. Tool wear in drilling of composite/titanium stacks using carbide and polycrystalline diamond tools. Wear 2011;271:2826–35. https://doi.org/10.1016/j.wear.2011.05.038.

[17] Pan W, Ding S, Mo J. Thermal characteristics in milling Ti6Al4V with polycrystalline diamond tools. Int J Adv Manuf Technol 2014;75:1077–87. https://doi.org/10.1007/s00170-014-6094-y.

[18] Kerrigan K, Scaife R. Wet vs dry CFRP drilling: influence of cutting fluid on tool performance. Procedia CIRP 2018;77:315–9. https://doi.org/10.1016/j.procir.2018.09.024.

[19] Turner J, Scaife RJ, El-Dessouky HM. Effect of machining coolant on integrity of CFRP composites. Adv Manuf Polym Compos Sci 2015;1:54–60. https://doi.org/10.1179/2055035914Y.0000000008.

[20] Pereira O, Rodríguez A, Fernández-Abia AI, Barreiro J, López de Lacalle LN. Cryogenic and minimum quantity lubrication for an eco-efficiency turning of AISI 304. J Clean Prod 2016;139:440–9. https://doi.org/10.1016/j.jclepro.2016.08.030.

[21] Pereira O, Martín-Alfonso JE, Rodríguez A, Calleja A, Fernández-Valdivielso A, López de Calle LN. Sustainability analysis of lubricant oils for minimum quantity lubrication based on their tribo-rheological performance. J Clean Prod 2017;164:1419–29. https://doi.org/10.1016/j.jclepro.2017.07.078.

[22] Zhao F, Clarens A, Murphree A, Hayes K, Skerlos SJ. Structural aspects of surfactant selection for the design of vegetable oil semi-synthetic metalworking fluids. Environ Sci Technol 2006;40(24):7930–7. https://doi.org/10.1021/es061418l.

[23] Kumar-Sharma A, Kumar-Tiwari A, Rai-Dixit A. Effects of minimum quantity lubrication (MQL) in machining processes using conventional and nanofluid based cutting fluids: a comprehensive review. J Clean Prod 2016;127:1–18. https://doi.org/10.1016/j.jclepro.2016.03.146.

[24] Astakhov VP. Ecological machining: near dry machining. Mechanics of machining: FEM simulation machining. 2009. p. 195–223. https://doi.org/10.1007/978-1-84800-213-5_7.

[25] Wang S, Clarens AF. Analytical model of metalworking fluid penetration into the flank contact zone in orthogonal cutting. J Manuf Process 2013;15(1):41–50. https://doi.org/10.1016/j.jmapro.2012.09.015.

[26] Helmy MO, El-Hofy MH, El-Hofy MH. Effect of cutting fluid delivery method on ultrasonic assisted edge trimming of multidirectional CFRP composites at different machining conditions. Procedia CIRP 2018;68:450–5. https://doi.org/10.1016/j.procir.2017.12.077.

[27] Xu J, Ji M, Davim JP, Chen M, El-Mansori M, Krishnaraj V. Comparative study of mínimum quantity lubrication and dry drilling of CFRP/titanium stacks using TiAlN and diamond coated drills. Compos Struct 2019. https://doi.org/10.1016/j.compstruct.2019.111727.

[28] Pereira O, Urbikaín G, Rodríguez A, Fernández-Valdivielso A, Calleja A, Ayesta I, et al. Internal cryolubrication approach for Inconel 718 milling. Procedia Manuf 2017;13:89–93. https://doi.org/10.1016/j.promfg.2017.09.013.

[29] Pereira O, Rodríguez A, Barreiro J, Fernández-Abia AI, López de Lacalle LN. Nozzle design for combined use of MQL and cryogenic gas in machining. Int J Precis Eng Manuf Technol 2017;4:87–95. https://doi.org/10.1007/s40684-017-0012-3.

[30] Skerlos S.J., Hayes K.F., Clarens A.F. Metal working lubricant formulations based on supercritical carbon dioxide US Patent 7,414,015, 2008.

[31] Pereira O, Rodríguez A, Ayesta I, Barreiro J, Fernández-Abia A, López de Lacalle LN. A cryo lubri-coolant approach for finish milling of aeronautical hard-to-cut materials. Int J Mechatron Manuf Syst 2016;9(4):370–84. https://doi.org/10.1504/IJMMS.2016.082872.

[32] Basmaci G, Yoruk AS, Koklu U, Morkavuk S. Impact of cryogenic condition and drill diameter on drilling performance of CFRP. Appl Sci 2017;7:667. https://doi.org/10.3390/app7070667.

[33] Giasin K, Ayvar-Soberanis S, Hodzic A. Evaluation of cryogenic cooling and minimum quantity lubrication effects on machining GLARE laminates using design of experiments. J Clean Prod 2016;135:533–48. https://doi.org/10.1016/j.jclepro.2016.06.098.

[34] Impero F, Dix M, Squillace A, Prisco U, Palumbo B, Taglia F. A comparison between wet and cryogenic drilling of CFRP/Ti stacks. Mater Manuf Process 2018;12:1354–60. https://doi.org/10.1080/10426914.2018.1453162.

[35] Xia T. Investigation of drilling performance in cryogenic drilling on CFRP composite laminates. Theses and Dissertations – Mechanical Engineering. 2014. 36, https://uknowledge.uky.edu/me_etds/36.

[36] Xia T, Kaynak Y, Arvin A, Jawahir IS. Cryogenic cooling-induced process performance and surface integrity in drilling CFRP composite material. Int J Adv Manuf Technol 2016;82:605–16. https://doi.org/10.1007/s00170-015-7284-y.

[37] Khanna N, Desai K, Sheth A, Larsen JO. CFRP machining on indigenously developing cryogenic machining facility: an initial study. Mater Today: Proc 2019;18:4598–604. https://doi.org/10.1016/j.matpr.2019.07.434.

[38] Klocke F, Sangermann H, Krämer A, Lung D. Influence of a high-pressure lubricoolant supply on thermo-mechanical tool load and tool wear behaviour in the turning of aerospace materials. Proc. IMechE Part B: J. Eng Manuf 2010;225:52–61. https://doi.org/10.1177/09544054JEM2082.

[39] Zhen-yuan J, Chong Z, Fu-ji W, Rao F, Chen C. An investigation of the effects of step drill geometry on drilling induced delamination and burr of Ti/CFRP stacks. Compos Struct 2020. https://doi.org/10.1016/j.compstruct.2019.111786.

[40] Jinyang X, Chao L, Ming C, El Mansori M, Davim JP. On the analysis of temperatures, surface morphologies and tool wear in drilling CFRP/Ti6Al4V stacks under different cutting sequence strategies. Compos Struct 2020. https://doi.org/10.1016/j.compstruct.2019.111708.