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Investigation of the quality of Al-CFRP stacks when drilled using innovative approaches

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ABSTRACT

The usage of metal/composite stacks such as those made of aluminum alloy (Al) and carbon fiber-reinforced polymer (CRFP) has recently increased in the aerospace industry thanks to their high strength-to-weight ratio. As drilling high-quality holes in metal/composite stacks is still a challenge, innovative machining processes, such as ultrasonic vibration-assisted drilling and cryogenic drilling, have gained increasing attention for the part quality they promise. The feasibility of using the synergistic ultrasonic cryogenic drilling approach on Al/CFRP stacks is investigated for the first time, and the influence of the aforementioned innovative drilling approaches at varying feed in relation to the hole quality declined in terms of geometrical accuracy, surface roughness, delamination, and surface defects evaluated. The cutting forces are acquired as well. The obtained results show that, at increasing feed, the hole quality drastically worsens, nevertheless, it improves when applying innovative drilling technologies with respect to the standard one. Overall, ultrasonic cryogenic drilling carried out at the lowest investigated feeds represents the best drilling scenario thanks to the simultaneous application of ultrasonic vibrations, which enhances the surface finish as a consequence of the decreased contact between the workpiece and tool, and cryogenic cooling, which makes the surfaces harder.

Introduction

In recent years, carbon fiber-reinforced polymer (CFRP) and metal alloy sheets stacked together have been introduced in the transportation field, thanks to their superior properties such as impact, shear, tensile, and flexural strengths. As example, Al/CFRP and Al/CFRP/Ti stacks are already used in airplane wings and tails. To be assembled to other structures, these stacks need to be drilled, which can be challenging as a consequence of the different properties of the composite and the metal alloy that may significantly influence the cutting mechanism, possibly leading to poor accuracy and defects. For current industrial applications, acceptable tolerances for the hole diameter lie within 30 µm, which may be difficult to achieve in the case of poor-quality holes [1]. On the other hand, delamination is undoubtedly the most significant factor influencing the hole quality, which may lead to reduced structural integrity and load-carrying capacity of the part.

Cutting parameters play a role in determining the quality of the drilled holes. In the case of drilling Al/CFRP stacks, the higher the feed the higher the form error and surface roughness, as was observed by Zitoune et al. [2] and Shyha et al. [3]. Furthermore, the higher the feed the higher the delamination. When the feed was reduced, the area of delamination reduced, but when the feed exceeded a critical value, the area of delamination suddenly rose, as was pointed out by Devim and Reis [4]. Barik et al. [5] investigated the drilling of Al/CFRP stacks showing a decrease in delamination and hole surface roughness at increasing cutting speed and decreasing feed. The same experimental results showed that holes of higher quality were obtained in the Al at lower cutting speeds, whereas higher cutting speeds improved the hole quality in the CFRP.

Angelone et al. [6] demonstrated that drilling of Al/CFRP stacks at 90 m/min and 0.15 mm/rev resulted in holes closer to the nominal dimension, rounder, and smoother. However, if using a lower cutting speed and higher feed, delamination occurred, thus decreasing the hole quality. Shyha et al. [7] examined the hole quality of Al/CFRP/Ti stacks and reported that all the holes drilled by using a conventional flood coolant were undersized with the largest deviation of 14 µm,

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whereas holes drilled with a spray mist were oversized up to 6 µm. Furthermore, it was observed a significant reduction in the CFRP delamination, thanks to the support of the Al and Ti layers [8].

Soo et al. [9] reported that in CFRPs the feed increase improved the hole accuracy resulting in a diameter deviation of less than 15 µm from the nominal value. On the other hand, drilling at higher feed resulted in the delamination increase. Tsao and Chiu [10] showed a well-defined correlation between the thrust force and delamination in CFRPs, proving that delamination at the hole exit did not occur below a critical thrust force.

Ultrasonic drilling (UD) has been recently recommended as an effective cutting approach to decrease delamination at the hole exit compared to standard drilling (SD). Ultrasonic drilling is a non-conventional cutting method where the tool vibrates at high frequency, making the process discontinuous by changing the path of drilling [11]. Ultrasonic drilling was used by Amini et al. [12] to drill Al sheets in comparison to standard drilling: in the former case, no hole oversize was observed at the entry, and the exit burrs were reduced. Chang and Bone [13] studied the ultrasonic drilling of Al sheets and proved that the higher vibration frequencies reduced the burr width and height. Chern and Lee [14] examined the ultrasonic drilling of Al sheets and reported that the hole size, form, and surface roughness were improved at increasing vibration frequency and amplitude.

The ultrasonic drilling approach has been extensively used also in drilling CFRPs, focusing attention on its performance towards the hole exit delamination [8]. Dong et al. [15] conducted robotic rotary ultrasonic drilling on Al/CFRP stacks and proposed a theoretical model to predict the height of the burrs, showing a reasonable agreement with the experimental outcomes. Alejandro et al. [16] investigated drilling of CFRP/Ti stacks finding that, thanks to ultrasonic vibrations superimposition drillng, delamination was reduced by approximately 50% at lower cutting speed and feed. Wu et al. [17] studied the hole delamination in CFRPs when using ultrasonic drilling and reported that the feed increase resulted in higher delamination in standard drilling compared to ultrasonic one, whereas the spindle speed increase could hinder the delamination defect during both the drilling approaches. Geng et al. [18] carried out rotary ultrasonic elliptical machining on CFRPs, showing a reduction of 17% and 14% in the hole exit delamination and thrust force compared to standard drilling regardless of the adopted cutting speed and feed. Baraheni and Amini [19] carried out rotary on ultrasonic drilling CFRPs, observing the lowest thrust force and delamination when using the lowest cutting speed and lowest feed. Xu et al. [20] investigated the drilling process of multilayer carbon/epoxy composite-Ti6Al4V stacks under varying drilling strategies and parameters. Machining responses including drilling forces, temperatures, and hole quality were considered as output of the study. Regardless of the cutting speed, it was shown that ultrasonic drilling led to a reduction of the drilling thrust forces and temperatures for both the CFRP and titanium layers. As a consequence of that, standard drilling induced much rougher hole in the composite and higher amount of defects whereas the opposite situation was found by using ultrasonic drilling thanks to the formation of discontinuous metallic chips that reduced their mechanical abrasion and thermal degradation onto the composite hole surfaces.

In [21], UD coupled with forced air-cooling was designed and applied to investigate the tool wear in drilling of CFRP/Ti6Al4V stacks using uncoated twist drills. Results showed that, compared to standard and dry ultrasonic drilling, the proposed approach was efficient for reducing the tool wear in virtue of the interrupted contact between the cutting edge and the workpiece, the enhancement of the chip evacuation ability, and the cooling effect provided by the forced air.

In recent years, also cryogenic cooling (CD) has been increasingly used when machining difficult-to-cut materials, with the aim of reducing the material damage induced by the cutting process itself. Joshi et al. [22] reported a 25% decrease in surface roughness, but delamination and thrust force increased by 17% and 40%, respectively, when drilling CFRPs using cryogenic cooling compared to dry cutting at high cutting speed and low feed. On the other hand, Basmaci et al. [23] demonstrated that thrust forces and delamination were higher under cryogenic drilling of CFRPs than under dry conditions at low speed and high feed, whereas, at the same cutting parameters, higher surface quality and less tool wear were observed when using cryogenic cooling. Khanna et al. [24] stated that, when using liquid nitrogen as a coolant in drilling CFRP sheets, a 14–38% decrease in the hole surface roughness and a 5–68% increase in delamination were observed. Kannan and Pervaiz [25] reported higher cutting forces under cryogenic cooling compared to dry cutting when drilling CFRP sheets, but with a significant increase in the hole accuracy. Besides liquid nitrogen (LN_2), also liquid carbon dioxide (LCO_2) has gained attention as cryogenic cutting fluid able to remove heat from the cutting zone. However, while LN_2 extracts the heat form the cutting zone due to evaporation of the liquid phase, LCO_2 remove the heat after a sudden expansion due to the Joule-Thomson effect. This creates a two-phase flow where dry ice and gaseous CO_2 coexist, and the temperature reduction is achieved by the sublimation of the solid phase [26]. Rodriguez et al. [27] evaluated the feasibility of using LCO_2 to increase the hole accuracy and tool life when drilling CFRP/Ti6Al4V stacks. Results showed that the LCO_2 adduction assured higher hole accuracy compared to the dry case in terms of hole actual diameter, thanks to the reduction of the thermal expansions of both the tool and workpiece. Besides the hole quality, also the tool life benefitted from the LCO_2 adoption due to the reduction of adhesion and burnt phenomena.

The above-reported literature review shows a number of records dealing with the evaluation of the hole quality when drilling CFRP sheets and Al/CFRP stacks under different, but distinct, strategies, nevertheless the latter were never compared except in a previous study by the Authors [28], where ultrasonic and cryogenic drilling were compared, showing that the former was effective in reducing the thrust forces, hence delamination, while the latter was particularly efficacious in improving the hole accuracy in terms of cylindricity and perpendicularity.

On this basis, the purpose of the present paper is twofold: i) to investigate, for the first time, the combination of ultrasonic and cryogenic drilling as it may represent an innovative approach to increase the hole quality in Al/CFRP stacks, and ii) to extend the hole quality analysis, including also the evaluation of the surface texture and possible defects appearing on the borehole surfaces as a consequence of the adopted drilling strategy. This will give new insights about the performances of different drilling strategies, even when adopted in a combined manner. To this aim, drilling of Al/CFRP stacks was carried out at varying feed using various approaches, namely standard, ultrasonic, and cryogenic drilling, as well as the latter two combined together. The hole quality was assessed in terms of hole diameter, perpendicularity, cylindricity, surface roughness, and delamination factor using different characterization techniques, including optical microscopy, coordinate metrology, and stylus profilometry. Thrust forces were acquired as well during drilling to assess a correlation with the above-mentioned surface integrity parameters.

Materials and methods

Workpiece and cutting tool

The stacks used in this study are made of dissimilar materials and were provided by GKN Aerospace in Sweden. Specifically, a sheet of AA6082-T6 aluminum alloy is joined to a CFRP one, made of dry carbon fibre Sigmatex uniweaves and RTM6 epoxy resin. Uniweaves belong to non-crimp fabric and consist of carbon fiber yarns that are woven with thin and sparsely distributed weft yarns. E-glass yarns

Table 1
Mechanical properties of the AA6082-T6 [29].

Yield strength (MPa)	Ultimate Tensile Strength (Mpa)	Elongation at break (%)	Density (g/cm^3)
250	290	10	2.7

Table 2
Mechanical properties of the RTM6 epoxy resin.

Elastic Modulus (Gpa)	Ultimate Tensile Strength (Mpa)	Flexural modulus (Gpa)	Flexural strength (Mpa)
2.989	75	3.3	132

was alternated to 12 K Toho Tenax HTS40 F13 carbon fiber roving in the warp direction while a combi-yarn was used along the weft direction. The two sheets were stacked together using a commercial glue. The mechanical characteristics of the stack constituents are summarized in Table 1, Table 2 and Table 3.

The material was received in the form of a prism (230 mm height x 254 mm length x 9 mm thickness). The Al sheet is 5 mm thick and the CFRP sheet is made of 5 plies, each 0.8 mm thick, for a total thickness of 4 mm. Such kind of composite stacks are mostly used in aerospace applications such as in wings and, tails, thanks to their high strength and durability.

The drilling tests were conducted using the uncoated solid carbide tools shown in Fig. 1 whose specifications are reported in Table 4. Special drills devoted to machine composite, such as spur drills, were not considered in this study since they are not suitable for drilling hybrid stacks according to a previous literature study [30].

The tool typology was suggested by the tool manufacturer on the basis of its easiness in chip evacuation and lower tendency to the built-up edge development.

Drilling set-ups

The Al/CFRP stacks were drilled on the DMG™ Mori 635 V ecoline 3-axis milling machine shown in Fig. 2. The ultrasonic drilling system employed in the study includes an ultrasonic vibration amplitude horn, an ultrasonic generator, and a transducer. The resonant mode was used where the operational frequency was maintained constant at 21 kHz by varying the amplitude using ultrasonic power. The ultrasonic vibration amplitude, measured by means of a laser vibrometer, was equal to 5 ± 0.4 µm.

Fig. 3(a) shows the three types of motions along the Z-axis during ultrasonic drilling: ultrasonic vibration, spindle rotation, and feed motion were applied to the drill bit, whereas the workpiece was kept fixed. Fig. 3(b) illustrates the difference between the standard and ultrasonic drilling paths: during the former, the tool and workpiece are continuously in contact making the cutting continuous, whereas, during ultrasonic drilling, depending on the chosen drilling parameters, the contact can be discontinuous, making the cutting intermittent as a consequence of the tool vibration. The sinusoidal trajectory of the cutting tool is shown in Fig. 3(c), where A is the vibration amplitude, f the vibration frequency, and Z the tool displacement along the axial direction.

Table 3
Mechanical properties of the carbon fibre yarns.

Elastic Modulus (Gpa)	Ultimate Tensile Strength (Mpa)	Elongation at break (%)	Density (g/cm^3)
240	4400	7	1.77

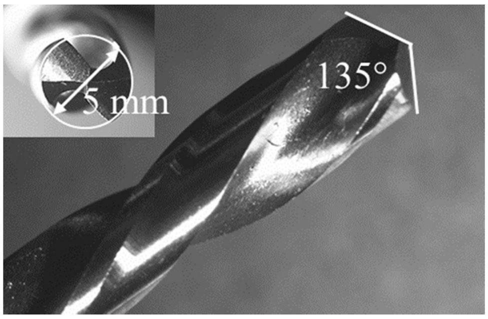

Fig. 1. Uncoated solid carbide tool used in the present study.

Table 4
Cutting tool specifications.

ISO code	B284D08000HPS
Type of tool	Uncoated solid carbide
Grade	KN15
Drill diameter (mm)	5
Drill shank diameter (mm)	6
Drill overall length (mm)	66
Flute length (mm)	28
Maximum drilling depth (mm)	20
Drill point length (mm)	0.923
Shank length (mm)	36
Point angle (°)	135

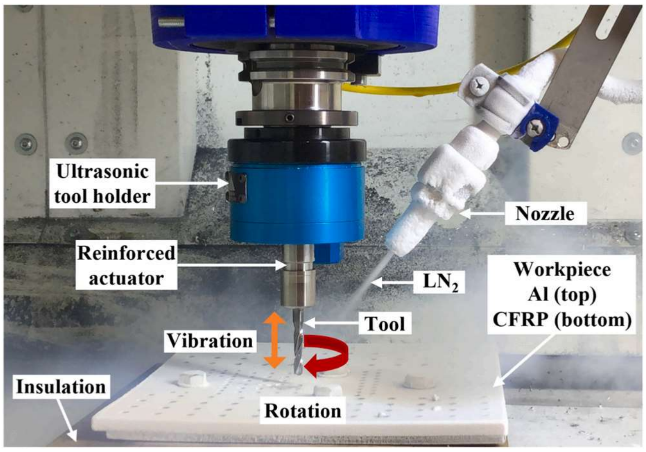

Fig. 2. Drilling setup with the ultrasonic and cryogenic drilling systems.

Fig. 2 also illustrates the cryogenic drilling setup, where the liquid nitrogen is stored in a dewar at the pressure of 24 bars and transferred, using an insulated pipe, to the cutting zone where a nozzle sprays it towards the cutting tool. The nozzle, named GMA 1010 F31B, has a diameter of 1.106 mm and is covered with a stainless steel body. The drill bit is exposed to cryogenic cooling during drilling as well as the Al/CFRP stack, which is tightly bolted to the machine table using a pocket-designed wooden plate. This wooden plate acts as a thermal insulator to preserve the load cell integrity and makes it possible to manufacture a through-hole with no support beneath. The workpiece is fixed in such a way that the Al sheet is on the top and the CFRP one on the bottom, so that the exit hole delamination can be evaluated. To prevent from coming into contact with the cryogenic coolant, the Kistler™ force sensor was installed at the center of the table, underneath the wooden plate. For more effective insulation, the dynamometric table was also surrounded by polystyrene thermoform panels.

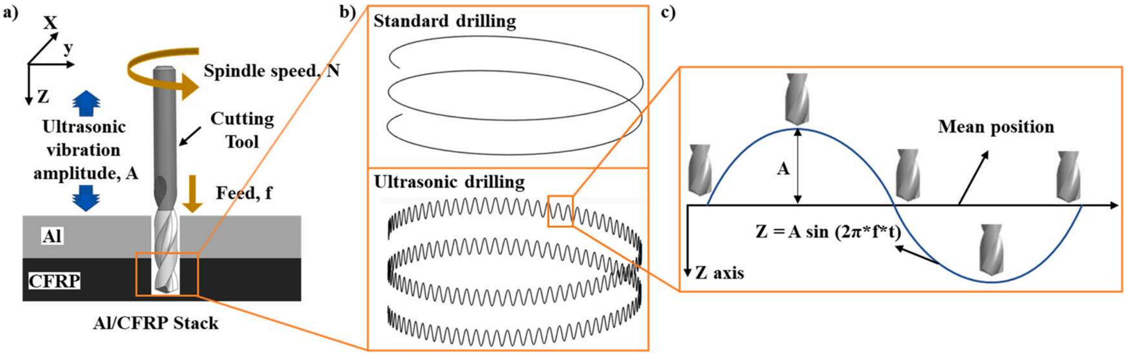

Fig. 3. (a) Scheme of the ultrasonic drilling process; (b) cutting paths during standard and ultrasonic drilling; (c) Sinusoidal trajectory of the cutting tool during ultrasonic drilling.

Drilling trials

Ultrasonic, cryogenic, and ultrasonic-cryogenic drilling trials were carried out, and their outcomes in terms of thrust force, hole geometrical features (diameter, cylindricity, and perpendicularity), hole surface texture parameters (R_a and P_t), and delamination factor were compared to those from standard drilling trials.

As it is customary when machining composites, standard and ultrasonic drilling were carried out under dry cutting conditions. Since the literature review indicated a more significant influence of the feed rather than of the cutting speed on the drilling performances, the latter was kept fixed equal to 60 m/min, while the former was varied using three levels, namely 0.05, 0.1, and 0.15 mm/rev. The nominal diameter of the hole to be drilled was 5 mm and the distance between two adjacent holes was set to a pitch distance of 10 mm to avoid any interference effect among subsequent holes.

The experimental plan of the drilling trials is reported in Table 5. A design of experiments (DOE) plan was prepared to vary the feed and drilling approach for a total of 12 experiments, and a randomized excel function was used for executing the experiments. For each cutting condition, three holes were drilled to evaluate the repeatability of the results. A new drill bit was used for each cutting condition to assume the tool wear was negligible. After drilling, the quality of the holes was inspected using the methods reported in the following section.

The thrust forces were acquired by using a Kistler™ force sensor and the acquired data were transferred to the data collector DAQ and later on processed using the Dynoware™ data processing software.

Analysis of the hole quality

The hole geometry was investigated by contact scanning coordinate metrology using a Zeiss™ Prismo Vast 7 coordinate measuring machine (CMM) with a ruby spherical probe tip of 2 mm diameter. The individual hole datum was defined by probing 8 points on the top surface around the hole in a circular pattern and a total of 4 circular sections per hole were acquired with a scanning speed of 0.5 mm/s at four different levels. For the Al, two sections were measured at distances of 1.5 and 3.5 mm from the top surface, whereas for the CFRP, two sections were at distances of 6.5 and 7.5 mm from the top surface. The least-squares cylinder diameter, minimum-zone cylindricity, and axis perpendicularity were determined from the scanned circles.

The surface texture of the hole was tested by stylus profilometry along the cylinder generatrix using a Zeiss™ TSK Surfcom 1400 A roughness tester with a stylus tip of 5 µm radius. The main measuring conditions are given in Table 6. After careful identification of the starting point of the profile on the CFRP side, profile portions corresponding to each material were considered, namely 0–4 mm for the CFRP sheet and 4–9 mm for the Al one. Each of the 3 holes was measured at 4 different locations (0°, 90°, 180°, and 270°) as shown in Fig. 4 for a total of 12 measurements. Profile surface texture parameters according to the ISO 4287:1997 standard were taken into consideration, namely the arithmetical mean deviation of the assessed profile (R_a) and the total height of the assessed profile (P_t). The latter was selected as indicator of the status of the adhesive layer between plies, while R_a was considered as baseline for comparison of the different processing conditions. Additional surface texture parameters, including the maximum height of the assessed profile (R_z), maximum profile valley depth (R_v), and bearing curve parameters (R_{pk}, R_k, R_{vk} according to ISO 13565–2:1996) were investigated, however not here documented because they provided similar trends to the selected ones for illustrating the machined part performances in terms of surface texture.

Further, the section of the drilled hole surfaces was investigated using a FEI™ QUANTA 450 Scanning Electron Microscope (SEM) with magnifications of 32X, 500X, and 1000X to verify the presence of possible surface defects.

The quantification of drilling-induced defects at the exit hole in CFRP was carried out by means of light optical microscopy (OM), placing the sample directly under the objective lens, without any specific metallographic preparation. As it will be demonstrated in §3.4, fibre fraying and tearings were the main defects found at the exit of the hole. The former refers to the presence of uncut carbon fibres residing in form of strips, whereas the latter to the removal of a piece of ply after drilling.

The optical microscopy images were analysed through the digital image processing software ImageJ™. To calculate the defects area the following procedure was adopted: i) the recorded image was

Table 5
Drilling parameters.

Cutting speed (m/min)	60
Feed (mm/rev)	0.05, 0.1 & 0.15
Hole type	Through
Drilling approach	Standard drilling, SD
	Ultrasonic drilling, UD
	Cryogenic drilling, CD
	Ultrasonic-cryogenic drilling, UCD

Table 6
Summary of main surface texture measuring conditions.

Total measurement length (mm)	8.5
Tilt correction	Flat mean line
Filter type	Gaussian
Nesting index / cutoff (mm)	0.25
Stylus type	90° cone, diamond
Stylus tip radius (µm)	5
Measuring force (mN)	0.75
Measuring speed (mm/s)	0.30

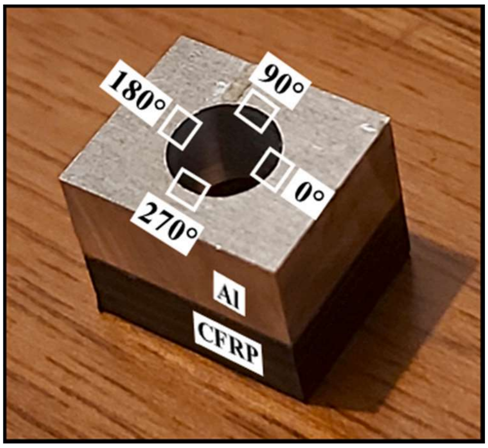

Fig. 4. Surface texture measurement spots.

transformed into a grey one, ii) a circle equal to the hole size was placed on the grey image to identify the measurement area, iii) an intensity threshold value was applied in order to identify the defect zone; iv) the defect zone was selected, and v) the defect area was calculated by counting the number of pixels. The main steps of the defect quantification procedure are shown in Fig. 5.

Then, the fibre frying factor (φ_{FF}) was introduced in accordance to [31] to quantify the burrs areas:

$$\varphi_{FF} = \frac{A_b}{A_{nom}} \tag{1}$$

where A_b is the area of the burrs, and A_b the nominal hole area.

The same procedure was applied to calculate the tearing factor (φ_T):

$$\varphi_T = \frac{A_t}{A_{nom}} \tag{2}$$

where A_t is the area of the tearing area.

Afterwards, both φ_{FF} and φ_T were combined to calculate the cumulative delamination factor (DF):

$$DF = \varphi_{FF} + \varphi_T \tag{3}$$

Results and discussion

Thrust force

Fig. 6(a) shows the evolution of the thrust force during drilling Al/CFRP stacks at varying drilling strategy and at the lowest feed, together with the schematic path of the drill bit. It is worth noting that similar thrust force evolutions were observed at the other investigated feeds, therefore they are not reported for sake of brevity.

In general, five zones can be highlighted in the thrust force evolution: i) the drill bit entry into the stack leading to the first sudden rise in the thrust force, ii) the full engagement of the drill bit into the Al layer, iii) the cutting of the interface between the Al and CFRP that is characterized by a mechanical resistance in between the ones of the Al and CFRP and leads to a force reduction, iv) the full engagement of the drill bit into the CFRP layer, and v) the drill bit exit from the CFRP leading to the final thrust force decrease. The forces for drilling the CFRP are two to three times lower than the ones for drilling the Al being the latter much more resistant.

Fig. 6(b) shows the very significant force oscillations when the CFRP is drilled, which can be ascribed to the interaction of the tool with the different composite layers it encounters [22]. The forces tend to decrease as the exit approaches due to the intense heat that develops and promotes the softening of the polymer matrix.

Fig. 7 reports the average values, purged of the transient ones, of the thrust force for the three repetitions with the standard deviation bars. Forces are reported separately for the Al and CFRP to allow a better comprehension of the recorded data. In the case of Al, ultrasonic drilling led to a reduction of the thrust force at the lower feeds (0.05 mm/rev and 0.1 mm/rev) with the respect of standard drilling, while an inverse trend was registered at the highest feed. This implies a lower efficiency of ultrasonic drilling at the highest feed since the chip breakage becomes more difficult as its thickness increases. On the contrary, the LN_2 application in cryogenic and ultrasonic-cryogenic drilling made the thrust forces increase drastically, according to several literature studies [32]. Compared to standard drilling, in the case of Al, cryogenic drilling led to a thrust force increase of 20%, 27%, and 23%, while ultrasonic cryogenic drilling of 29%, 27%, and 10% for feed of 0.05, 0.1, and 0.15 mm/rev, respectively.

Similar results were obtained when drilling the CFRP, since, compared to standard drilling, the thrust force increase during cryogenic drilling was 62%, 53%, and 45%, and during ultrasonic cryogenic drilling 67%, 62%, and 29% for feed of 0.05, 0.1, and 0.15 mm/rev, respectively. Again, the thrust force increase as a consequence of the temperature reduction promoted by cryogenic cooling is witnessed by several available literature studies [22,32,33]. Interestingly, regardless of the considered material, the application of ultrasonic vibrations led to a thrust force reduction when cryogenic drilling at the highest feed.

The recorded thrust forces when ultrasonic and standard drilling the CFRP can be considered statistically similar, except for the ones at the highest feed, where a 5% increase was registered for ultrasonic with the respect to the standard one. Ultrasonic drilling implies a discontinuous cutting resulting in a better chip evacuation from the tool rake face as well as a reduction of the contact area between the workpiece and the drill bit, thus leading to a reduction of the thrust force. Nevertheless, its efficiency is reduced at higher feed due to the increase of the chip cross section.

When drilling the Al, the higher the feed the higher the thrust force, as expected as a consequence of the higher uncut chip thickness and material removal rate (MRR). On the contrary, when

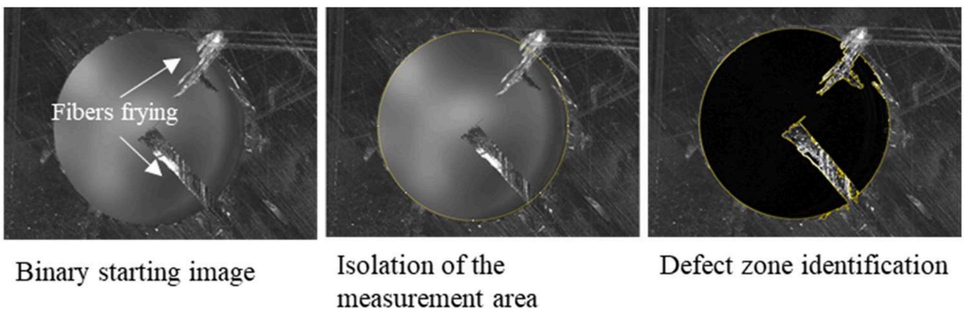

Fig. 5. Procedure for drilling-induced defects quantification.

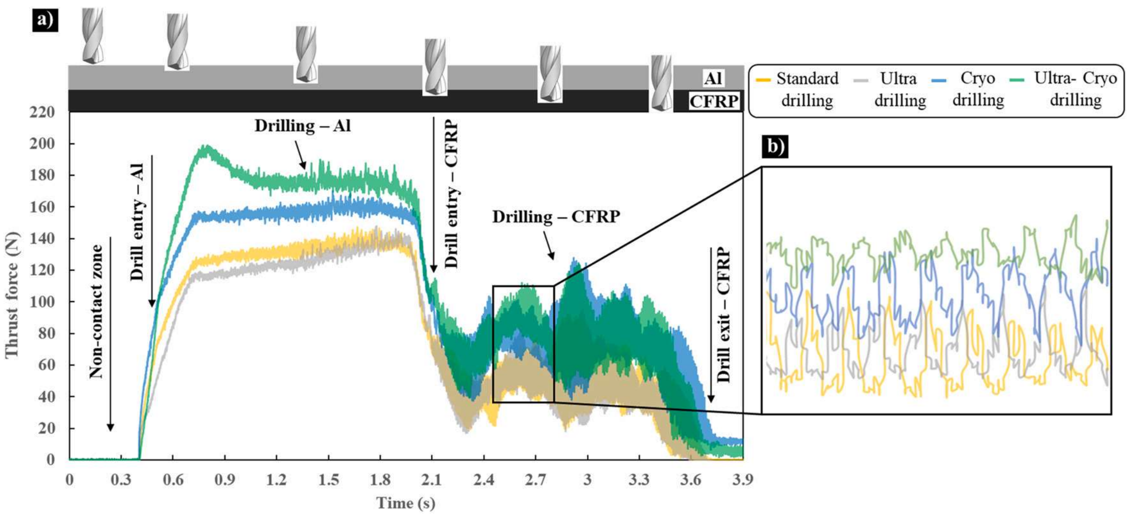

Fig. 6. (a) Thrust forces recorded at varying drilling strategy and f= 0.05 mm/rev; (b) Magnified view of the thrust forces recorded when drilling the CFRP.

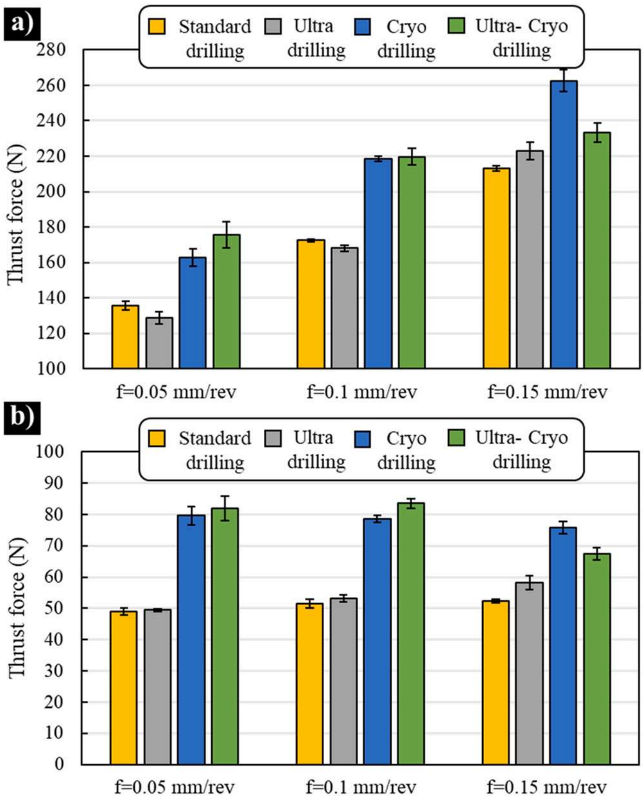

Fig. 7. Average thrust force at varying feed and drilling strategy for a) Al and b) CFRP.

drilling the CFRP, the feed did not provide the expected boosting in the thrust force, except in the ultrasonic drilling case. When carrying out standard drilling, the forces were similar regardless of the feed, while the cryogenic-assisted processes showed an almost inverse trend witht respect to ultrasonic drilling. At the highest feed, the thrust forces in cryogenic and ultrasonic cryogenic drilling decreased by 5% and 18%, respectively, when compared to the same values but at the lowest feed. Such anomalous behaviour can be ascribed to the peculiarity of the investigated stack composed by Al and CFRP. In general, an higher feed translates into: i) an increment of the MRR, and ii) an increase of the strain rate, which, in turn, translates into a flow strength enhancement, thus increasing the thrust force [33]. At the same time, an higher feed leads to a temperature increase and therefore a flow stress decrease.

Nevertheless, the temperature field arising in the CFRP as a consequence of drilling can be further increased by the heat conducted from the Al sheet, already heated by the cutting process: this amplifies the temperature effect provided by the drilling process in the CFRP, and as a consequence, mitigates the thrust force increase.

Dimensional accuracy of the drilled holes

As the Al and CFRP sheets are characterized by very dissimilar mechanical and thermal properties, their response to drilling in terms of hole dimensional accuracy can be quite different. Both undersized and oversized holes in both the materials can be produced, which can significantly affect the part in-service properties. The use of a screw or a rivet in an undersized hole can cause stresses on the hole walls, which may induce crack onset and propagation, resulting in component failure. Conversely, using an oversized hole for joining components may result in loose assembly and subsequent failure [34].

Fig. 8 shows the hole diameters in the Al and CFRP at varying feed and drilling strategy. It can be observed that all the holes are oversized compared to the nominal drill bit diameter (Ø5 mm), regardless of the feed and drilling strategy. Most of the literature records report that holes drilled in CFRPs are undersized because of the existence of uncut fibers and stress relaxation as a consequence of the mismatch between the coefficients of thermal expansion and elastic moduli of the stack materials [35].

On the contrary, the outcomes of this study proved that the holes drilled in CFRP are slightly oversized: such behavior may be ascribed to the stress relaxation arising as a consequence of the mismatch between the coefficients of thermal expansion and elastic moduli of the Al and CFRP [35]. On the other hand, the deviation from the nominal diameter in the case of the holes in Al is much higher, see Fig. 8(a). Ashrafi et al. [36] also showed that hole diameter in the Al was larger than in the CFRP, as the Al has a higher thermal expansion and lower modulus of elasticity compared to the CFRP.

Fig. 8(b) shows that, when drilling the CFRP, the minimum deviation from the nominal hole diameter was observed at the lowest and intermediate feeds in the case of ultrasonic drilling. Specifically, 0.04% and 0.07% reductions were obtained by adopting ultrasonic rather than standard drilling for f= 0.05 mm/rev and f= 0.1 mm/rev, respectively. This can be ascribed to the discontinuous cutting regime that leads to the formation of shorter and discontinuous chips

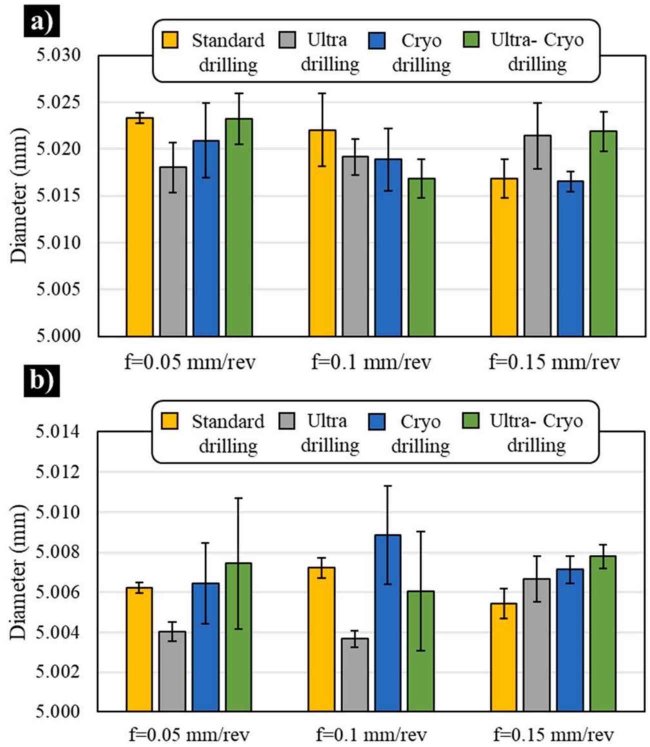

Fig. 8. Hole diameter at varying feed and drilling strategy for a) Al and b) CFRP.

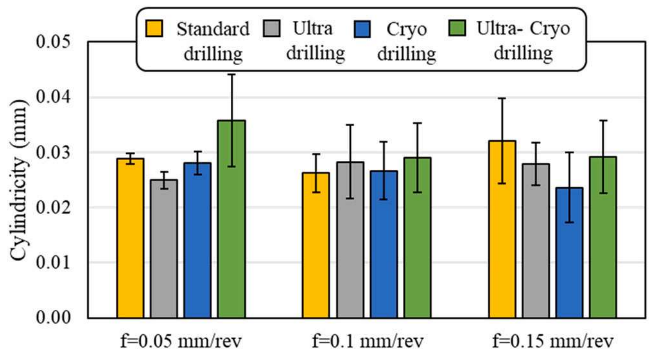

Fig. 9. Cylindricity at varying feed and drilling strategy.

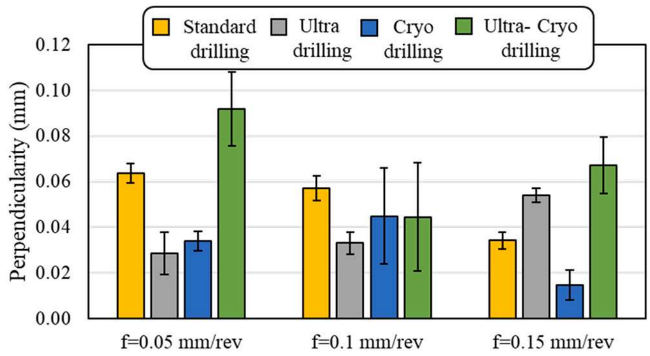

Fig. 10. Perpendicularity at varying feed and drilling strategy.

compared to standard drilling. Whereas, at the highest feed in ultrasonic drilling, the hole diameter increased presenting the same trend of the thrust forces. In the case of both the Al and CFRP, there is very little difference observed by increasing the feed, regardless the drilling strategy adopted.

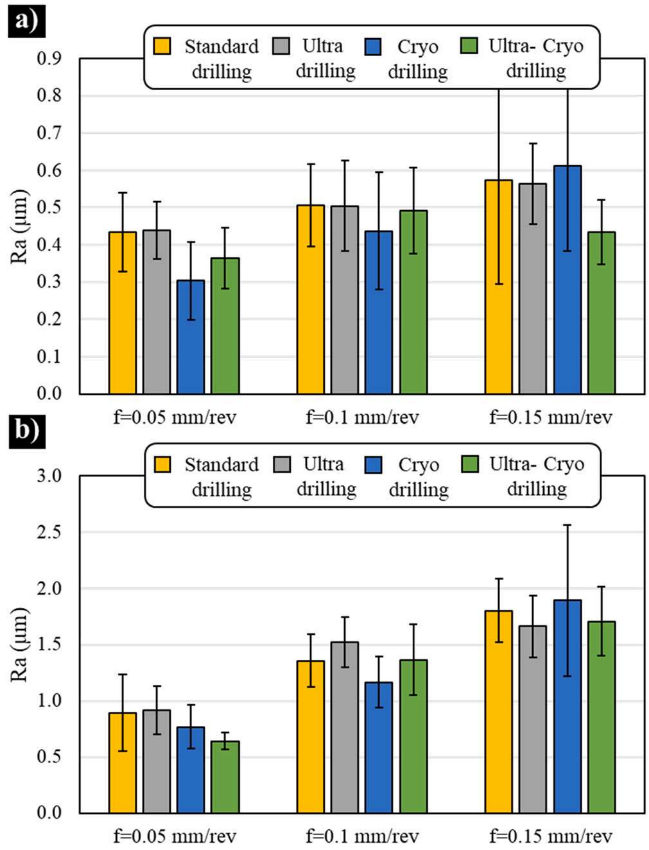

Fig. 11. Surface roughness at varying feed and drilling strategy for a) Al and b) CFRP.

Cylindricity is a global indicator of the form error, including both straightness along the drilled hole and roundness of each considered section. Fig. 9 plots the cylindricity with respect to the feed and drilling strategy. It is worth noting that, at the highest feed, the best performance is given by cryogenic drilling, showing a 26% reduction over the standard drilling strategy, which can be ascribed to the lowest cutting temperature. Whereas, at the lowest feed, ultrasonic drilling gives the best result, improving cylindricity of 14% over the standard strategy, thanks to the discontinuous cutting regime with reduced MRR.

Perpendicularity defines how a hole axis is oriented in relation to a given datum. It is one of the most common geometrical specifications used for the evaluation of hole quality in aerospace structures. Poor perpendicularity tends to minimize the contact between the hole wall and rivet, leading to a reduction of the part fatigue life. As seen in Fig. 10, the minimum hole perpendicularity was observed after cryogenic drilling at the highest feed and after ultrasonic drilling at the lowest feed. Specifically, the perpendicularity improvements settled to 99% and 55% for the former and latter technology over standard drilling, respectively. It is worth noting that the best performance is found under the same conditions as for cylindricity.

Surface texture of the drilled holes

Fig. 11 reports the values of the surface roughness parameter R_a at varying feed and drilling strategy, as measured on the hole walls in the Al and CFRP. In general, higher surface roughness values were obtained in the case of CFRP, since the drill bit was chosen as suitable for the Al. In addition, the presence of uncut fibre drastically increases the roughness values.

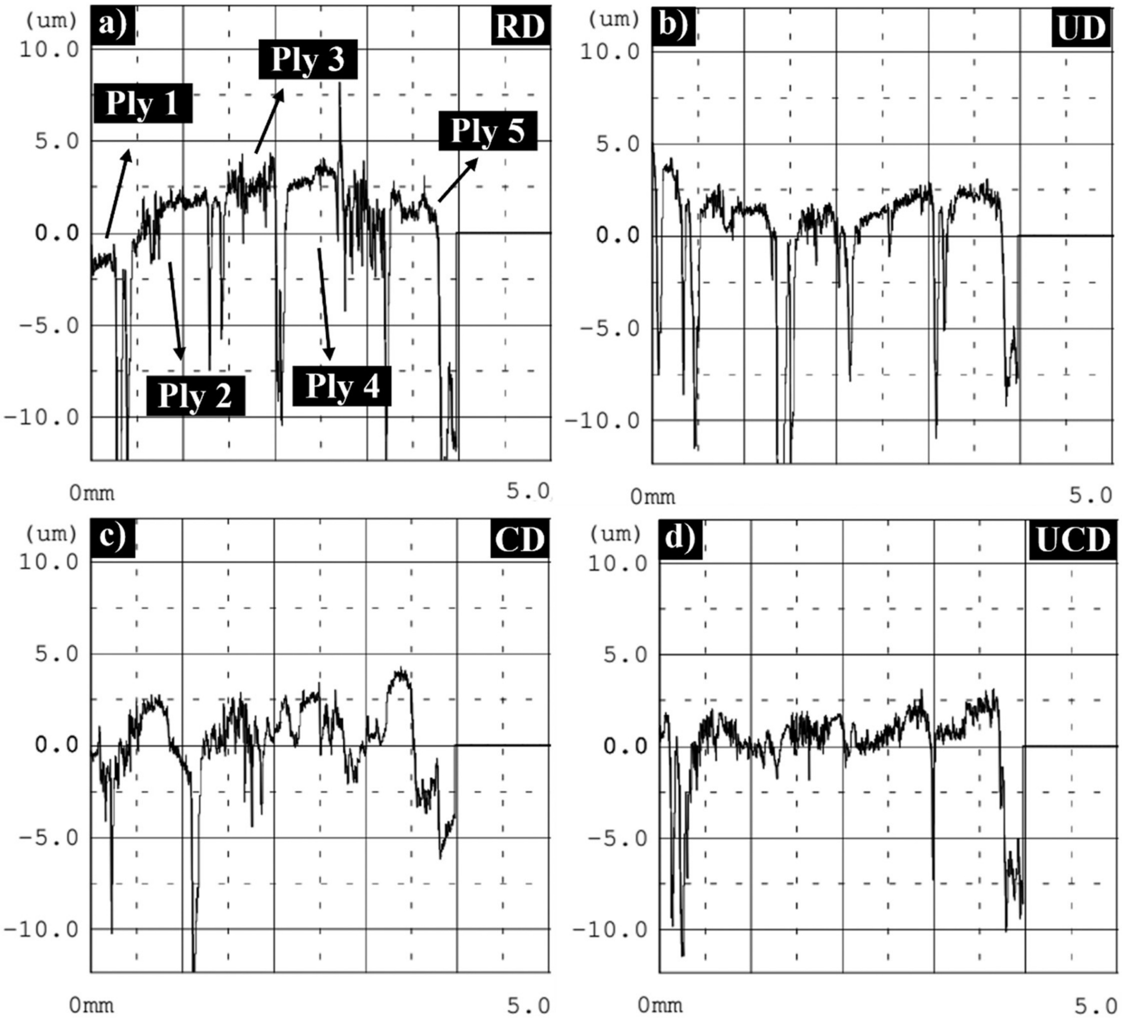

Fig. 12. Examples of primary profiles of the CFRP at varying drilling strategy and feed of 0.05 mm/rev.

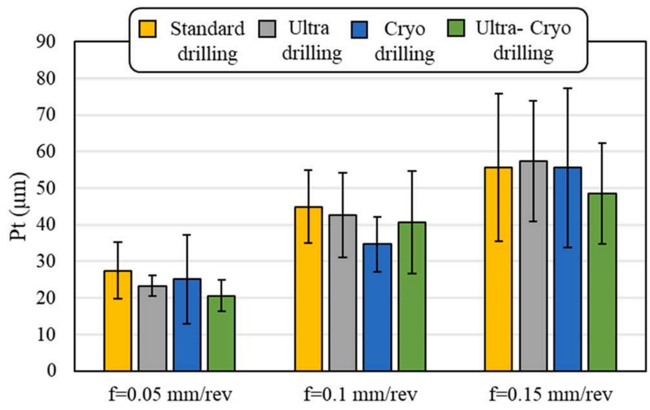

Fig. 13. Profile parameter values of the CFRP at varying feed and drilling strategy.

When drilling the Al at the lowest feed and by applying LN_2, as in the case of cryogenic and ultrasonic cryogenic drilling, R_a reduces compared to standard and ultrasonic drilling, up to 30%, as shown in Fig. 11(a). This is because the higher the feed the higher the cutting temperature that causes thermal softening and consequent material ductility increase. The latter upsurges the tool adhesion wear during drilling leading to an increase in the hole surface roughness [37]. On the contrary, when using cryogenic cooling, besides limiting the cutting temperature and therefore lowering the thermal softening, the formation of debris from the workpiece material is reduced, thus enhancing the surface quality [38].

In the CFRP, the feed has the primary influence on the surface roughness, whereas the other process conditions have a secondary influence. The feed increase leads indeed to an increase in the friction between the tool and CFRP that causes higher temperatures in the cutting zone and more fiber pull-out that gradually increases the surface roughness [39]. Fig. 11 (b) shows that the surface roughness reduces in the case of cryogenic and ultrasonic cryogenic drilling compared to the other strategies at the lowest feed. For f= 0.05 mm/rev, the roughness improvements settled to 14% and 28% for the cryogenic and ultrasonic cryogenic drilling strategies over the standard one. This improvement can be ascribed to the combination of the application of ultrasonic vibrations and cryogenic cooling, which induces a better chip removal mechanism [40]. In fact, ultrasonic vibrations can remove more easily the uncut fibre from the cutting zone, which, being more fragile as a consequence of the liquid nitrogen adduction, further tend to be more easily removed [41]. Fig. 13

Examples of unfiltered primary profiles after tilt correction are shown in Fig. 12 at varying drilling strategy and at the lowest feed for the CFRP. The CFRP used in this study was made of five plies, and the interface between the different plies can be appreciated by observing the primary profile, as it leads to a sudden large height variation at the interface. The P_t parameter, namely the vertical distance between the maximum profile peak height and the maximum profile

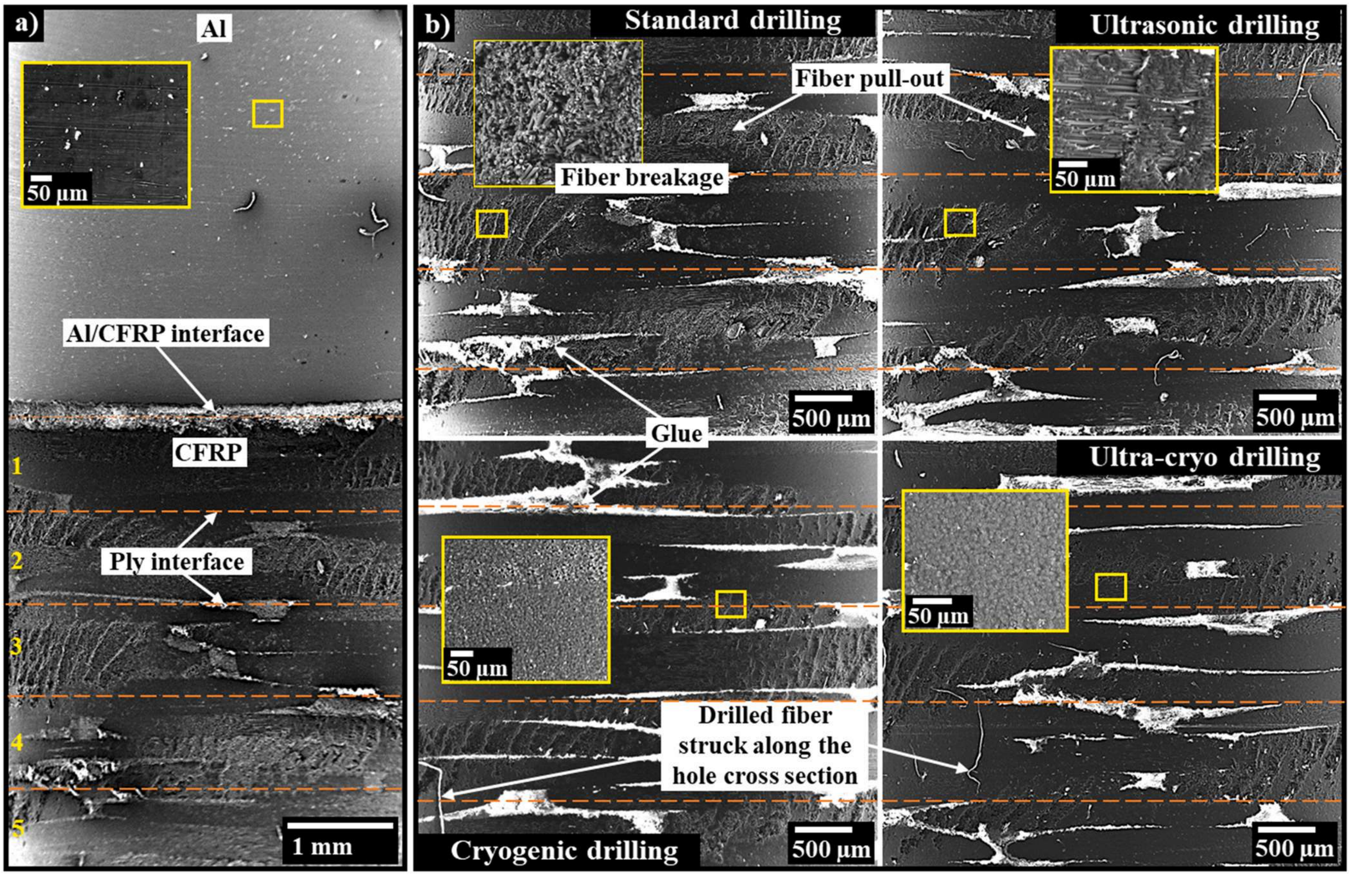

Fig. 14. (a) Hole surface after standard drilling at f= 0.15 mm/rev; (b) defects in the CFRP at varying drilling strategy and f= 0.15 mm/rev.

valley depth, was chosen as an indicator of the adhesive status after drilling [42]. The morphological aspect of the interface among different plies was also captured at SEM and it is visible in Fig. 14 for the highest feed.

In general, the feed has the highest effect, since, as the feed increases, the P_t values boost as well. This can be ascribed to the defects intensification caused by the lower interface resistance strength at elevated temperatures. Although at the highest feed similar P_t values were seen, an improvement in P_t was afforded at the lower feeds for ultrasonic-cryogenic drilling, where a 25% and 10% reduction was seen over standard drilling. This highlights the ability of cryogenic cooling of removing heat from the cutting zone, thus preventing the composite plies separation.

Further, in order to analyse the internal surfaces of the drilled holes, SEM analysis was performed to evaluate possible defects generated during drilling the Al/CFRP stacks at varying feed and cutting strategy.

As example, Fig. 14 (a) reports a secondary electron SEM image of the walls of the hole drilled in the Al and CFRP, where the interface among subsequent plies is highlighted by orange dotted lines. The main defects found on the Al layer of the composite stack is adhered material stacked to the hole's surface [43]. Such type of defect was present especially in standard and ultrasonic drilling, because of the lack of any kind of lubrication.

The CFRP shows the most critical surface, characterized by a high amount of defects like fibre pullout, fibre breakage, and glue residues smeared on the hole surfaces.

Typical cross-section areas observed at varying cooling strategy at the highest feed are shown in Fig. 14 (b). Only the highest feed is here reported, since it represents the worst condition, as the higher the feed the worse the machined surface. The white areas in the picture are associated to the presence of glue, while the black areas are the composite material, namely the matrix and fibres. It can be seen that defects are generally present, regardless of the cooling condition adopted for performing the drilling operations. Nevertheless, from the magnified images circled in yellow in Fig. 14 (b), it is evident that both the fibres and matrix material were smoothly cut when drilling under a cryogenic environment. This is a consequence of the ability of the cryogenic cooling to preserve the drill bit sharpness during machining, preventing the thermal softening of the composite matrix [40].

According to [22], at cryogenic temperatures, as the failure mode changes from bending rupture to shear fracture, the fibrous drilled composite material gets sheared and stuck along the drilled wall. Since the drilled fibres are along the hole walls, there is less rubbing induced by the chips, which, overall, helps in preserving the hole surface integrity.

Overall, the ultrasonic cryogenic drilling strategy leads to the best surface status among all the investigated conditions, thanks to the improved chip evacuation given by the ultrasonic vibration assisted cutting, besides the advantages derived from the cryogenic cooling.

Delamination features

Delamination can occur on both the top and bottom surfaces of the stack. In the present paper, delamination was evaluated solely at the exit because the Al sheet at the entrance appears free of defects, regardless of the cutting conditions.

Fig. 15 shows the optical microscope images of the exit delamination at varying feed and drilling strategy. Fibre fraying,

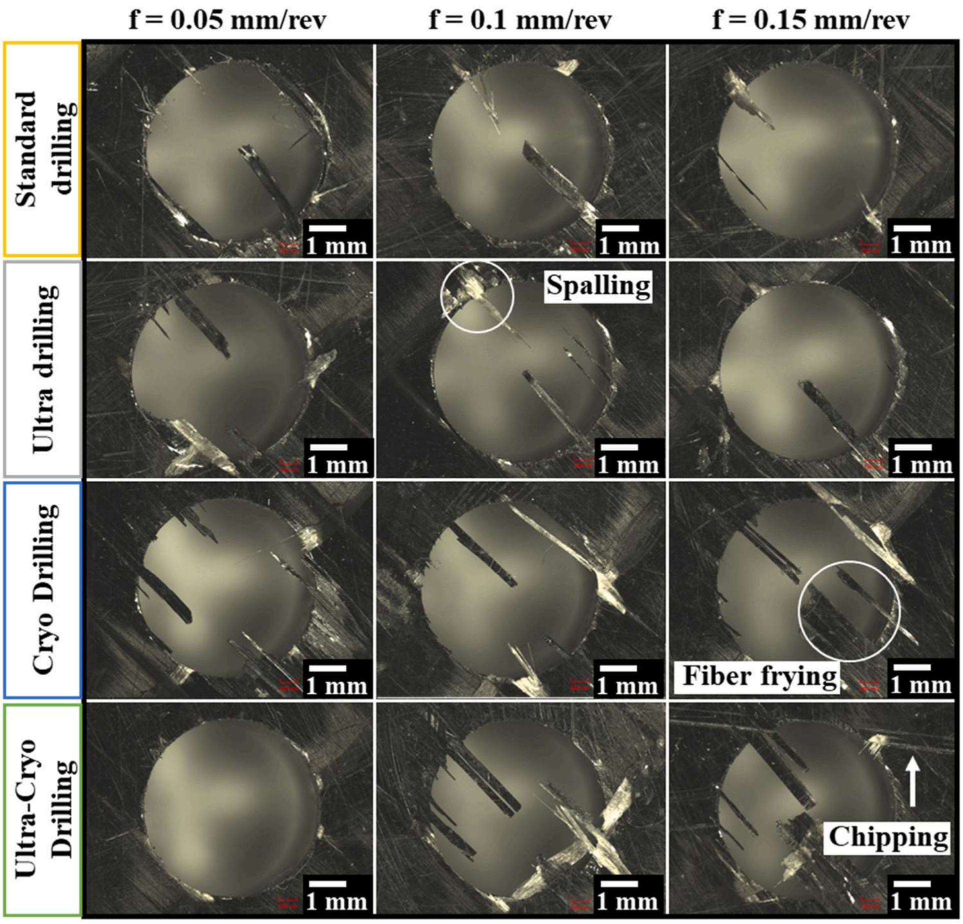

Fig. 15. Hole exit appearance at varying feed and drilling strategy.

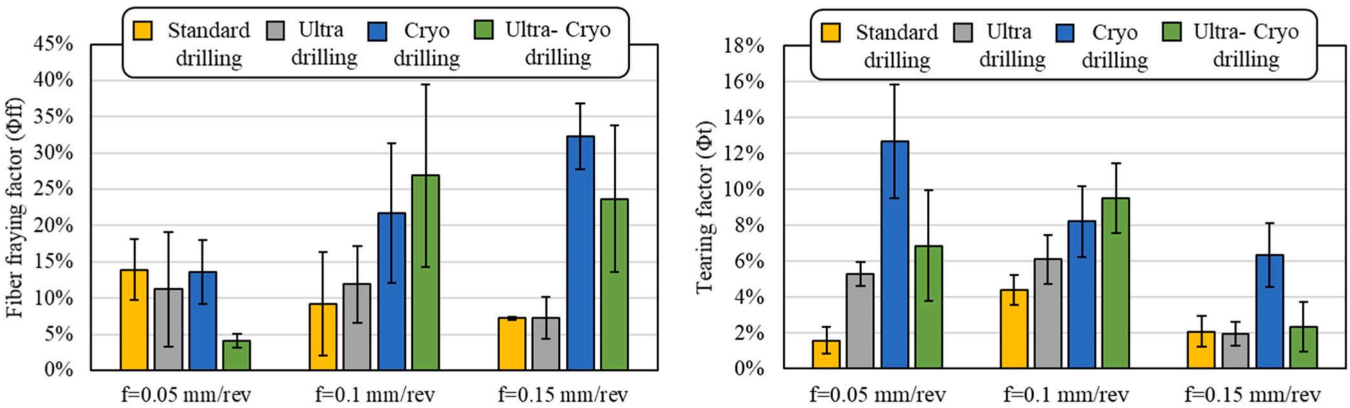

Fig. 16. Fibre fraying and tearing factor at varying feed and drilling strategy.

delamination and chipping were the main defects found at the hole exit on the CFRP side, as stated in § 2.4.

On the basis of Eqs. (1) and (2), both the fibre frying and tearing factors were calculated and the obtained results are presented in Fig. 16. As general consideration, the entity of the fibre frying is higher compared to the one of tearing, nevertheless they present almost the same trend.

Interestingly, when adopting both standard and ultrasonic drilling strategies a higher feed is not necessarily correlated to a higher density of defects at the hole exit, as it is reported in many literature records. This result is in accordance with the recorded thrust forces, which were comparable regardless of the feed at fixed cooling condition. In general, a higher amount of defects was registered when liquid nitrogen was applied as a coolant since the latter promotes an increase in the thrust force compared to dry drilling conditions like the standard and the ultrasonic ones [44]. Nevertheless, a peculiar behaviour can be highlighted in case of ultrasonic cryogenic drilling that presents an inverse relation with the thrust force. The maximum thrust force was indeed found during ultrasonic cryogenic drilling at the lowest feed, even if this is the condition that presented the lowest delamination, registering a 7% decrease in fibre frying compared to standard drilling. It is worth noting that these results match the ones of the surface roughness and surface defects. The reason behind this can be ascribed to the simultaneous

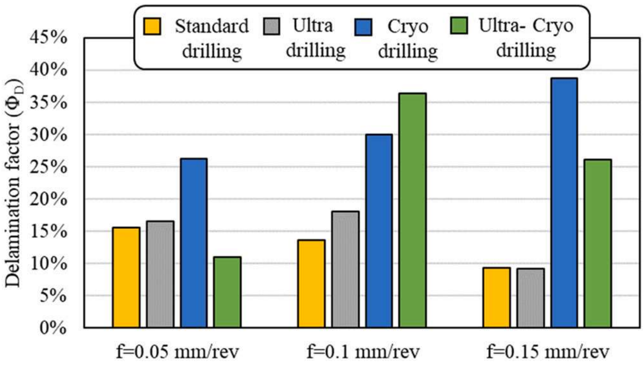

Fig. 17. Delamination factor at varying feed and drilling strategy.

application of ultrasonic vibrations (that implies less contact between the tool and composite) and cryogenic cooling (that makes surfaces harder), which, at the lowest feed, induces even less temperature increase.

Fig. 17 presents the delamination factor at varying feed and drilling strategy, which reflects the trend of the fibre frying factor.

Overall evaluation of the innovative drilling technologies performances

Fig. 18 (a), (b) and (c) summarize the overall performances analysis when drilling Al/CFRP stacks at f= 0.05, f= 0.1 and f= 0.15 mm/rev, respectively. In each graph, each analysis parameter is equally weighted. The best hole quality is achieved when the considered parameters locate at the farthermost layers, hence, the bigger the area beneath the curve the better the performance of a certain drilling strategy. It is worth noting that the thrust forces were not included in the calculation since they do not directly contribute to the achievement of the hole quality.

Fig. 18 (d) reports the area beneath the radar graph curves percentage variation with the respect to the standard drilling case, which was considered as the baseline. According to the results shown in Fig. 18 (d), ultrasonic cryogenic represents the best drilling strategy at f= 0.05 mm/rev, whereas cryogenic drilling shows the highest hole quality at f= 0.1 mm/rev and f= 0.15 mm/rev, respectively. Standard drilling always represents the worst case regardless of the feed.

More in detail, at the lowest feed, the combined approach ultrasonic cryogenic technology improves drillability of 13% and 12% over the ultrasonic and cryogenic stand-alone techniques, whereas a 49% increase is registered over standard drilling. At the lowest feed, ultrasonic cryogenic drilling is indeed particularly efficient in improving surface integrity characteristics in terms of delamination, surface defects and roughness characteristics over the other drilling strategies.

At the intermediate feed, the improvements given by the innovative drilling strategies are reduced compared to standard drilling, settling to 8%, 18% and 4% for UD, CD and UCD. In particular, cryogenic drilling outperforms the other drilling strategies in terms of surface roughness and profile parameters whereas ultrasonic drilling provides the best results in terms of hole accuracy.

Finally, at the highest feed, the cryogenic and ultrasonic cryogenic drilling strategies assure the best performances in terms of hole accuracy and surface finish, respectively.

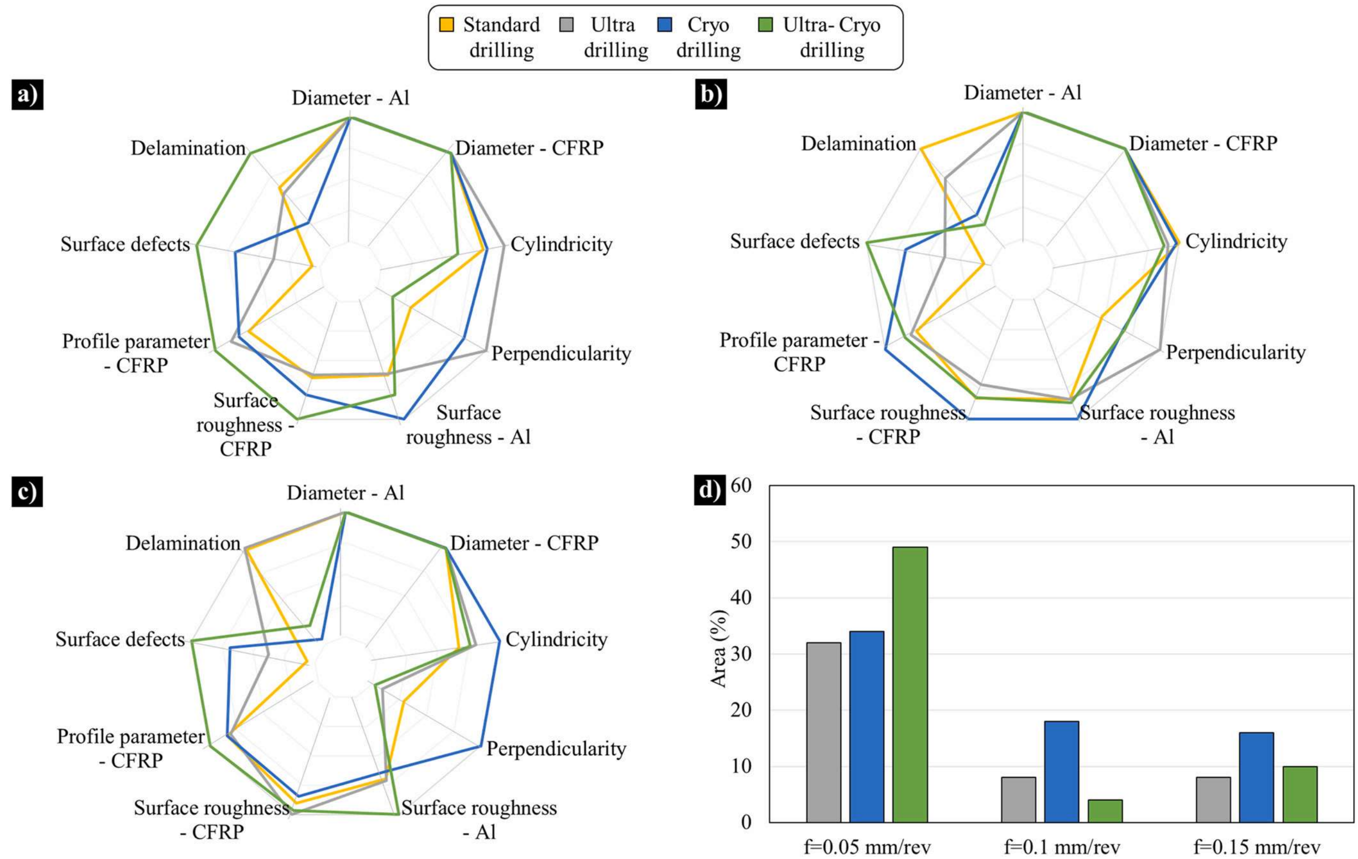

Fig. 18. Overall evaluation of the hole geometrical accuracy and surface integrity as a function of the drilling strategy at: (a) f = 0.05 mm/rev; (b) f = 0.1 mm/rev; (c) f = 0.15 mm/rev and d) area beneath the radar graph curves percentage variation with the respect to the standard drilling case.

The performances afforded by the innovative drilling strategies decreases at increasing feed, as the drilling becomes even more harder at increasing feed. Therefore, adopting a low feed to maximize the hole quality is suggested when drilling composite stacks.

Conclusions

The paper investigated the quality of Al/CFRP stacks when drilled using various drilling strategies. Ultrasonic drilling, cryogenic, and ultrasonic cryogenic drilling were evaluated against standard drilling for reference at varying feed. The drilled hole quality was evaluated in terms of hole diameter, cylindricity, perpendicularity, surface roughness, defects and delamination factor. The thrust forces were acquired as well during drilling to find a possible correlation with the hole quality. The following results can be highlighted:

With the respect of standard drilling, ultrasonic drilling helped in reducing the thrust forces, especially at the lowest feed. Regardless of the material of the stack and feed, the application of liquid nitrogen led to the thrust force increase. Compared to standard drilling, in the case of Al, cryogenic drilling led to an average thrust force increase of 23%, while ultrasonic cryogenic drilling of 22%. Similarly, for the CFRP, the average thrust force increase settled to 53% during both cryogenic and ultrasonic cryogenic drilling.

The hole diameters were less deviated from the nominal one in the CFRP than in the Al. For both the materials, ultrasonic drilling provided the least deviation over the nominal hole value. In the case of CFRP, the ultrasonic strategy was able to reduce the diameter deviations of 0.04% and 0.07% compared to the standard drilling strategy at f= 0.05 mm/rev and f= 0.1 mm/rev, respectively.

The hole cylindricity and hole perpendicularity were the lowest when adopting cryogenic drilling at the highest feed, showing a 26% and 99% improvement over the standard drilling strategy. Ultrasonic drilling showed the best performances at the lowest feed, enhancing the cylindricity and perpendicularity of 14% and 55% over the standard drilling technology.

In both the Al and CFRP, the cryogenic and ultrasonic cryogenic drilling strategies led to smoother surfaces at the lowest feed. The surface finish improved of 30% and 16% when drilling the Al by using cryogenic and ultrasonic cryogenic drilling at the lowest feed compared to standard drilling, respectively. Similarly, for the CFRP, 14% and 28% improvements were gained.

The higher the feed the higher the P_t values, but ultrasonic cryogenic drilling limited the P_t increase at lower feeds.

The fibre and matrix material of the composite were smoothly cut when drilling under a cryogenic environment, while standard drilling promoted a significant matrix smearing.

The delamination factor did not increase at increasing feed. Except in one case, the application of cryogenic cooling induced higher delamination factor, with the respect to the ultrasonic and standard drilling. Nevertheless, ultrasonic cryogenic drilling at the lowest feed assured the lowest delamination factor among all the drilling conditions.

The overall evaluation of the hole quality output evidences that ultrasonic-cryogenic, cryogenic drilling and cryogenic drilling represent the best drilling strategy at f= 0.05 mm/rev, f= 0.1 mm/rev and f= 0.15 mm/rev, respectively, while standard drilling always represents the worst drilling case.

On the basis of the overall evaluation of the hole quality, it can be highlighted that: i) innovative drilling strategies always perform better than the standard one; ii) the most adequate drilling strategy must be chosen on the basis of its interaction with the adopted feed; iii) low feed values are strongly suggested to maximize the hole quality; iv) the combined ultrasonic cryogenic drilling strategy can be particularly efficient if applied within the adequate parameter window, namely at low feed. The latter is ascribed to the advantages given by the simultaneous application of ultrasonic vibrations (that implies less contact between the tool and composite) and cryogenic cooling (that makes surfaces harder), which, at the lowest feed, induces even less temperature increase.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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