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6th CIRP Conference on Surface Integrity

Surface Quality in Dry Machining of CFRP Composite/Ti6Al4V Stack Laminate

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Abstract

The present work deals with the effect of drilling parameters on the surface quality of CFRP composite/Ti6Al4V stacks. The assembly of the carbon fiber composite and metallic materials is often carried out by means of the adhesive and autoclave joining. To analyze the effect of the composite/metallic interface on the surface quality, several drilling experiments have been performed for different drilling conditions; spindle speed, feed rate and drilling sequence are particularly investigated. Surface integrity, delamination process and cutting forces were considered as the main output responses to analyze the machining quality. SEM images and 3D topography of the machined surfaces were carried to assess the surface quality of specimens. Thus, this study aims to provide in-depth understanding of drilling and the effect of assembly method on the machinability of CFRP/Ti stacks.

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Keywords: CFRP/Ti; delamination; surface integrity

1. Introduction

Given their high performance, composite/metal hybrid materials have become one of the most popular structural materials used in high-tech sectors such as aeronautics and aerospace over the last decade. This statement is attributed to the fact that these materials offer good damage tolerance, excellent fatigue and corrosion resistance, and a high strength-to-weight ratio. Thus, structural parts provide improved flexural rigidity and overall mechanical properties [1, 2]. The manufacturing of this type of structural parts often requires drilling operations. However, the machining of composite/metal hybrid materials is a real challenge due to the heterogeneous properties of each component and their poor machinability. Composites exhibit anisotropic behavior and abrasive nature, which can lead to poor surface quality [3, 4]. Metals such as titanium have a low thermal conductivity which leads to high heat generation and premature tool wear during machining [5]. Thus, after the stack drilling, it is possible to

observe defects specific to the stack itself such as differences between the diameters measured in each material or damage related to the evacuation of metal chips or delamination of the inter-material interface [6–8]. The superposition of these defects systematically degrades the mechanical performance of the structures during their in-service. The degradation mechanisms that appear when drilling long carbon fiber and polymer matrix composites have been identified with the help of tests and experimental observations. Regarding the delamination at the hole entrance, according to the findings of, Hocheng et al. [9] and Tsao [10] the helix of the drill tends to tear off the first ply, the upper plies are pulled upwards by the action of the cutting face, while the lower plies are held in place by the downward action of the drill core. On hole exit, Hocheng et al. [9] show that the remaining unmachined thickness becomes thinner and thinner and the deformation resistance of the remaining plies decreases. The axial load of the tool then becomes greater than the interlaminar bonding force and delamination occurs. According to Konig et al. [11], a pull-out

is a loss of a piece of fiber or matrix caused by a shear stress on the cutting edge. Cavities are created on the wall of the hole. The circularity defect is related to the anisotropy of the material. An elliptic hole shape is formed when drilling CFRP composite, this defect is due to the elastic deformation of the fibers before brittle shear failure.

During drilling Ti6Al4V titanium alloy, the contact between the effective part of the tool and the machined material generates a very extreme mechanical and thermal phenomena. This zone is the place of important plastic deformations and intense friction at the tool-material contact zones [12]. The work of Li et al. [13] on the morphology of dry drilling chips shows that, from a certain depth, roughness of the hole wall depends on the resistance to evacuation generated chips that folds on itself and scratches the wall of the hole. Furthermore, during drilling operation, a burr is created at the hole exit by an accumulation of plastic deformations under the tip of the drill and by the rupture of the displaced material when the limit stress is reached. The location of the breaking point gives its shape [14]. However, when drilling composite/metal stacks, other damage types were found in addition to the above-mentioned induced damage. Park et al [15] studied the effect of Ti phase on the hole size of CFRP phase during the drilling process of CFRP and CFRP/Ti stacks. They found that the machining quality is decreased due to tool wear, which also leads to larger hole size. Furthermore, when drilling from CFRP to Ti phase, chip removal of the titanium causes extreme damage in the CFRP phase. Brinksmeier et al. [16] found that scratches appear at the surface wall of the composite. The hot titanium chips evacuate into the flutes, they create helical grooves in the surface and thermally degrade the resin. Moreover, the presence of titanium microchips embedded in the wall causes serious damage to the quality of the finished part. Xu et al. [6] covered the critical role of the drilling sequence in shaping the surface morphology of the drilled hole and subsurface defects. They found that Ti-CFRP sequence promotes lower drilling forces, improved surface roughness, less diameter errors, decreased Ti burr extents and improves the drilled hole wall surface quality due to the avoided Ti chip evacuation problems.

The works mentioned above helped to understand the main issues encountered when machining CFRP/Ti6Al4V with a focus on the induced damage. However, the influence of the joining method of composite and metal parts have not been studied knowing that this interface is a high delamination risk zone [17].

Therefore, the aim of this paper is to make a sensitivity analysis of the input parameters (Cutting speed V_c , feed rate f , cutting sequence, joining method and the composite type) on the outputs in terms of machining forces, dimensional accuracy, surface integrity and finally hole quality.

2. Experimental Setup

The drilling tests were performed on a composite metal stack CFRP/ Ti6Al4V which is composed of one plate of annealed Ti6Al4V alloy and one T300/914 CFRP laminate (made from 125 μm CFRP thickness ply). Three configurations of CFRP composite/ Ti6Al4V specimens provided by “Applications

Composites” Company were adopted for the investigation of drilling operation:

- PUDC: Ti6Al4V alloy sheet assembled using adhesive with one unidirectional (UD) carbon/epoxy T300/914 prepreg with a fiber orientation of 0° ,
- PUDA: Ti6Al4V alloy sheet assembled using autoclave joining method with one unidirectional (UD) carbon/epoxy T300/914 prepreg with a fiber orientation of 0° ,
- PMD1: Ti6Al4V alloy sheet assembled using autoclave joining method with one multidirectional (MD) carbon/epoxy T300/914 prepreg with the following stacking sequence $[45^\circ/-45^\circ/0^\circ/90^\circ]_s$.

Each stacked material is composed of two plates (metallic and composite) of 4 mm thickness. The geometric dimensions of the specimens for the drilling tests are 300x150x8 (mm). The main geometrical characteristics of the CFRP/Ti6Al4V are presented in Table 1. The corresponding mechanical properties are shown in Table 2.

Table 1. Geometrical characteristics of the used CFRP/Ti6Al4V stack

Designation of the specimen	Fiber orientation of the CFRP phase	Assembly method with the Ti	Dimension (mm)
PUDC	0°	Adhesive	300x150x8
PUDA	0°	Autoclave joining	300x150x8
PMD1	$[45^\circ/-45^\circ/0^\circ/90^\circ]_s$	Autoclave joining	300x150x8

Table 2. Mechanical properties of the used CFRP/Ti6Al4V stack

Ti6Al4V alloy	
Tensile strength σ_b (MPa)	900-1160
Elongation δ (%)	8
Density ρ (kg/m^3)	4430
Young's Modulus E (MPa)	113000
Poisson's ratio ν	0.342
Thermal expansion coefficient α_T ($^\circ\text{C}^{-1}$)	9.1×10^{-6}
Thermal conductivity λ ($\text{W}/(\text{m}\cdot^\circ\text{C})$)	7.0
T300/914 CFRP	
Longitudinal stiffness E1 (MPa)	136600
Transversal stiffness E2 (MPa)	9600
Shear modulus G12, G13, G23 (MPa)	5220
Poisson's ratio ν	0.29
Density ρ (kg/m^3)	1578

The drilling tool used to conduct the drilling tests is a standard uncoated solid carbide drill bit ISO references: 452.1-0417-044A0-CM H10F with cutting diameter of 4.17 mm, two main cutting edges, a short 0.11 mm length chisel edge, a small helix angle of 20° and a point angle of 135° .

The machining tests were carried out on three-axis high-speed machining REALMECA RV-8 SP under the dry cutting conditions. This machine was instrumented for the needs of the study to measure the thrust forces F_z . The measurement system consists of a piezoelectric Kistler dynamometer type 9129AA

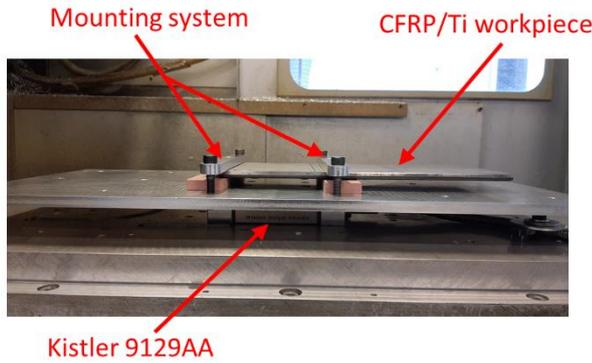


Fig. 1. Set-up of drilling tests

connected to multichannel charge amplifier type Kistler 5070A. The specimens were fixed to a table by means of two bars and two lateral clamping systems. The whole assembly is attached to the Kistler dynamometer which is mounted on the machining station table (figure 1). During the drilling tests, the adopted cutting variables were the cutting speed V_c , feed rate f and cutting sequence CFRP→Ti and Ti→CFRP, the used cutting conditions are summarized in Table 3. A full factorial experimental method was performed in order to investigate all the level of the variables, each experimental condition was repeated 3 times to provide reliable results. The tool wear was monitored during the drilling process, the observations enabled to make 24 holes with a single tool while minimizing the effect of tool wear. In total 288 holes were drilled, and the average result was reported. After drilling, hole entry and exit damages and interface delamination were investigated using a numerical microscope Keyence VHX-1000. The external diameters were measured for the three repetitions and an average value is given. In addition, damage mechanisms in the drilled surface were identified using a scanning electron microscope (SEM) JEOL 6010LA.

Table 3. Summary of the used cutting conditions for drilling CFRP/Ti6Al4V stack.

Cutting speed V_c (m/min)	Feed rate f (mm/rev)	Cutting sequence
15, 30, 45, 65	0.03, 0.06, 0.09, 0.12	CFRP→Ti Ti→CFRP

3. Results and discussion

3.1. Drilling forces

To address the parametric effects on the thrust force when drilling hybrid CFRP/Ti stacks, figures 2 and 3 show the obtained mean force evolution in terms of different specimens when drilling from composite to titanium. As shown in figure 2, the cutting force on blue curve is much higher for the PMD1 specimen where the multidirectional CFRP is used. On the other hand, the cutting forces are lower for PUDC and PUDA specimens where unidirectional CFRP is used. In addition, the thrust forces generated in the titanium phase are higher than those recorded in the composite phase. The cutting speed has a lower effect on thrust force in both phases and in either specimen. In contrast, the increase in the tool feed results on the increase in the thrust force (figure 3). The observation

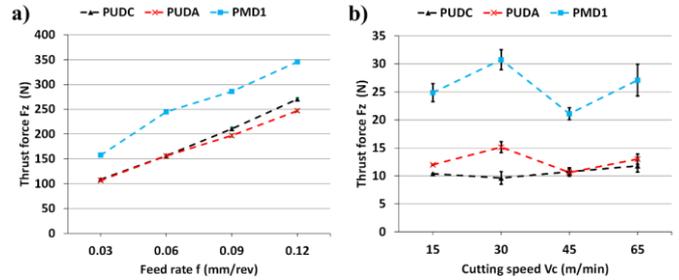


Fig. 2. Evolution of thrust force versus cutting speed ($f = 0.03$ mm/rev, and CFRP-Ti sequence) (a) in Ti phase; (b) in CFRP phase

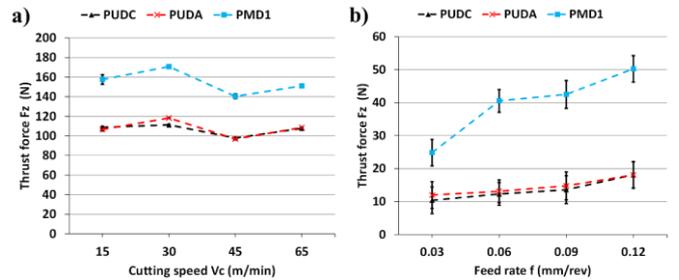


Fig. 3. Evolution of thrust force versus feed rate ($V_c = 15$ m/min and CFRP-Ti sequence) (a) in Ti phase; (b) in CFRP phase

aligns well with the experimental results of [18] when drilling composite/titanium stacks. This can be explained by the increase in volume of the released material as f increases, resulting in the elevating of the cutting forces. Moreover, the figures show that multidirectional CFRP (PMD1) promotes much higher forces in both phases than unidirectional CFRP. This is due to the enhanced strength in both longitudinal and transversal direction in a multidirectional CFRP in contrast of a unidirectional CFRP which results in cutting resistance for chip breakage. These findings show a good agreement with the work of Bonnet et al.[19].

3.2. Delamination analysis

In CFRP composite, delamination is one of the most frequent types of failure due to their relatively low inter-laminar strength. When drilling CFRP/Ti stacks in both sequences we will assess its damage in the entrance and exit of the hole by using the delamination factor F_d based on the maximum diameter. The F_d is defined as the ratio of the maximum diameter (D_{max}) of the delamination area to the nominal hole diameter (D_{nom}), as given by Equation (1)

$$F_d = \frac{D_{max}}{D_{nom}} \quad (1)$$

Figure 4 shows the parametric effects on drilling-induced damage in the hole exit (Ti→CFRP) and entrance (CFRP→Ti) with respect of different specimens. Feed rate has a highly positive effect on the extent of damage especially in UD-CFRP than MD-CFRP. It is noticeable that cutting speed doesn't have much impact on damage unlike feed rate f that has a predominant role in affecting the drilling-induced damage. For some previous studies [6, 7, 20] when drilling CFRP composite, it was usually observed that the damage is much higher in the exit hole, since it depends on the

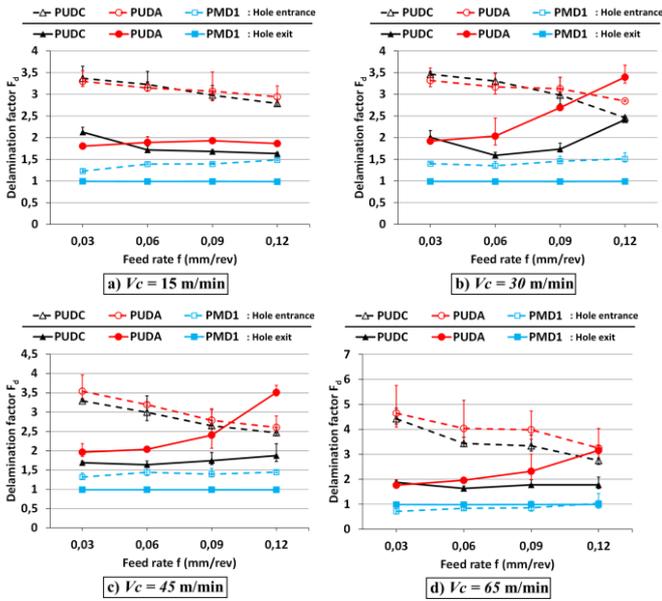


Fig. 4. Evolution of delamination factor versus feed rate when drilling in both sequences and for (a) $V_c = 15$ m/min; (b) $V_c = 30$ m/min (c) $V_c = 45$ m/min (d) $V_c = 65$ m/min

thrust force of the drill (F_z) coupled with the cutting speed as well as the tool shape and wear state. However, in this study, the observation of the delamination factor (at least for f ranged between 0.03 to 0.09) shows that this defect is much more important in the entrance than at the exit. Such different observations can be explained by the fact that in addition to delamination usually observed on the hole entrance caused by the thrust forces exceeding the interlaminar bond strength between the plies, a more severe damage is caused by the forces applied by the Ti chips pull out layers at the entrance of the hole. Moreover, CFRP fiber orientation may influence drilling induced damage as shown in figure 5. The delamination factor in PUDC and PUDA specimen is more accentuated unlike PMD1 that shows no damage neither in hole entrance nor hole exit due to the anisotropic nature of MD-CFRP that resists more to the feed

3.3. Hole wall quality analysis

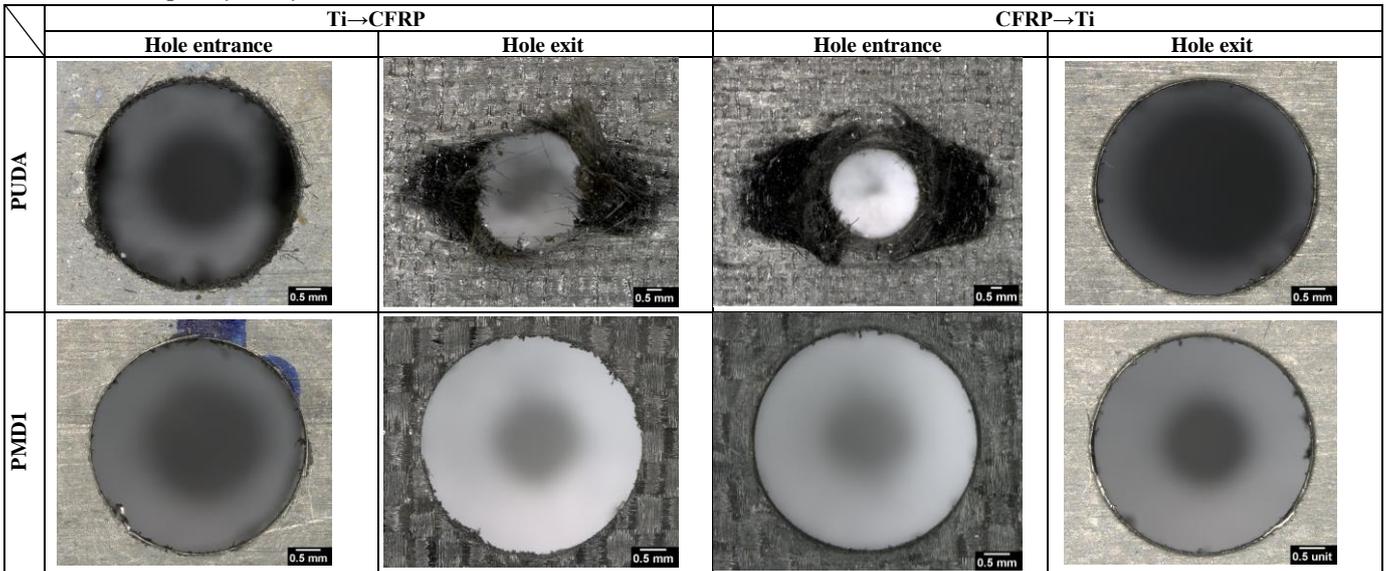


Fig. 5. Hole edge morphologies when drilling in both sequences and for $V_c = 15$ m/min; $f = 0.03$ mm/rev

Surface inspection is a good indicator of wall damage, tool wear and cutting conditions. Figure 6 shows a center across cut off drilled holes. It is obvious that when using the drilling sequence of CFRP→Ti the diameter and roundness of CFRP phase are larger than Ti phase regardless on the used cutting speed V_c . This can be mainly explained by the scratching effect of Ti chips on CFRP surface when evacuating the hole, and by the scratching and delamination effect caused by the adhered Ti chips on the tool when rotating out of the hole. Moreover, using Ti→CFRP sequence, the heat produced in the Ti phase increases the temperature of the tool and when it enters in contact with the composite, a thermo-mechanical damage is produced, and a burnt ring of resin is formed in the Ti wall. These observations are in good agreement with the results of An et al. [7].

Figure 7 shows a close-up visual inspection of the interface zone. This region is usually more vulnerable to drilling conditions, hence making the interface a very weak zone according to [18] findings. As seen from this figure, the drilled CFRP surface in either CFRP→Ti or Ti→CFRP cutting sequence is much rougher than the machined Ti surface due to the predominant brittle fracture chip separation mode. The key damage forms in the drilled CFRP hole surface are found to be fiber/matrix crack, delamination, and fiber pull-out, while for Ti hole surface the principal damages are re-deposited chip material and feed mark. The assembly method between composite and titanium plates affects the behavior of the interface. As can be seen in figure 7, the autoclave joined specimen (PUDA) promote less delamination, approximately up to 30% less than the adhesive assembled specimen (PUDC). This is because PUDA are directly using the epoxy resin to bond with the Ti phase, unlike PUDC that shows more delamination at the interface zone because it uses a third part to create a link and transfer the efforts between the phases. In addition, compared to Ti → CFRP, CFRP → Ti sequence generates severe fiber/matrix crack in CFRP area and especially in the interface region in both PUDC (up to 147 μ m for the CFRP→Ti sequence vs 76 μ m for the Ti→CFRP) and

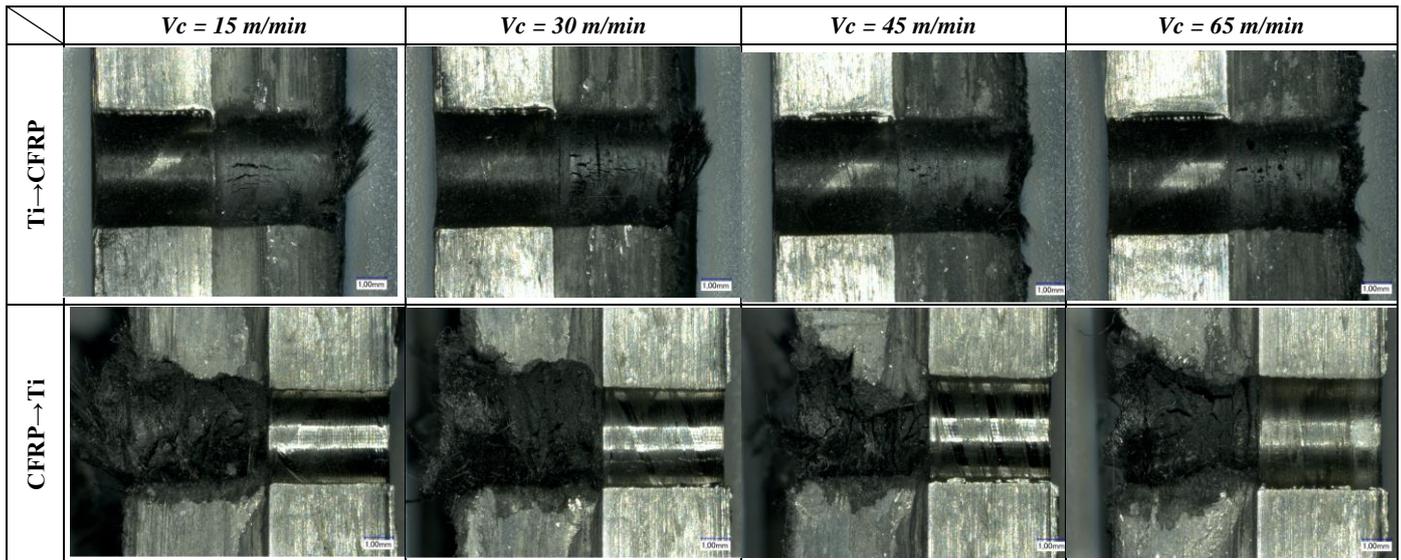


Fig. 6. Hole wall morphologies of drilled PUDC specimen in both sequences and for $f = 0.09$ mm/rev

PUDA (up to 108 μm for the CFRP \rightarrow Ti sequence vs 53 μm for the Ti \rightarrow CFRP) where delamination is significantly caused by Ti chip evacuation phenomena as discussed previously. In contrast, no delamination nor fiber/matrix crack is observed in PMD1 specimen due to the anisotropic nature of the composite which reinforces the interface region and roughs the plies, hence preventing the laminate from breaking under tool load. Moreover, the damage promoted in CFRP surface directly affects its hole dimension and roundness which further affects the hole-making accuracy of CFRP/Ti stacks. This phenomenon coincides with observations of the SEM image shown in figure 8. It can be seen the severe damage in CFRP

surface wall. As described previously, this is due to Ti chip evacuation effect and Ti chips adhered to the rotating tool when it pulled out from the workpiece. According to previous studies [21, 22], the most critical configuration when cutting a long fiber composite configuration, is the one where the angle between the fibers and the cutting direction is 90 or less than 0. In this configuration, material removal is initiated by a mode I opening that progresses along the fiber axis, followed by secondary break up to the free edge following the fiber shear. Significant defects can then propagate into the material, as the fibers become detached from the matrix. Hence, it can be acknowledged the existence of a link between decohesion of fiber/matrix in the CFRP phase and the appearance of delamination in the inter material interface. Indeed, the propagation of the crack that starts from the composite surface towards the interface results in delamination. This assumption is based on the analogy of crack propagation in coated tools, as the stress generated by the workpiece in the surface tool enhances crack propagation up to the interface between the coating and the substrate which causes delamination [23, 24].

4. Conclusion

This work has presented a sensitive experimental study on drilling CFRP composite/Ti6Al4V stacks by analyzing the input parameters (Cutting speed V_c , feed rate f) on the outputs in terms of machining forces. Therefore, allowing the display of full extent of the defects generated during the drilling of the studied stacks. Through this study, the effect of drilling sequence, assembling method and CFRP type on affecting damage mechanisms has been emphasized and can be summarized as follows:

- Thrust force analysis shows that PMD1 generates higher forces than PUDA and PUDC because of the anisotropic nature of the MD-CFRP that comes from alternating several fiber orientations which makes it more resistant to breakage.
- Damage in hole entrance (CFRP \rightarrow Ti) is more significant compared to the hole exit (Ti \rightarrow CFRP) because of the Ti chip removal. Moreover, as expected

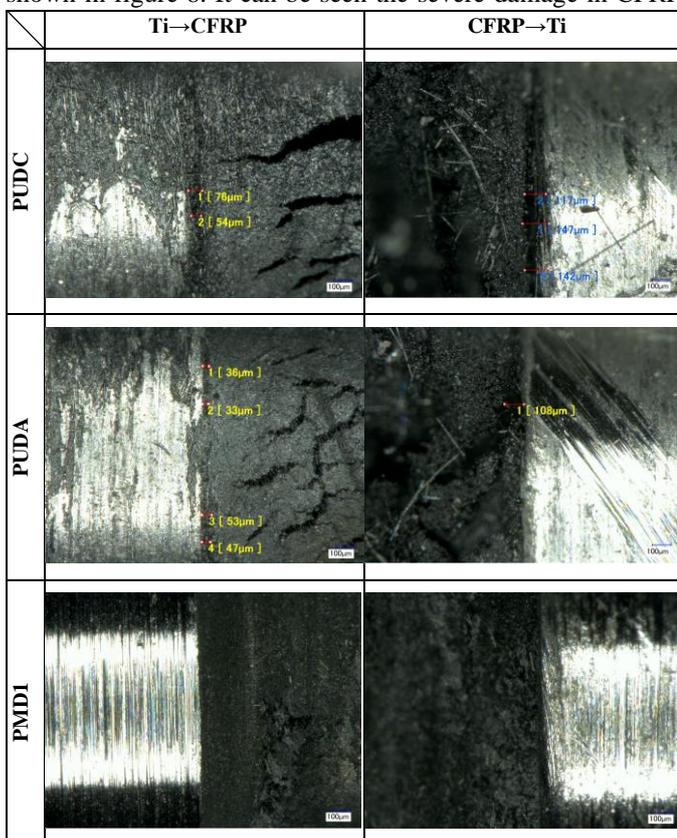


Fig. 7. Interface morphologies when drilling in both sequences and for $V_c = 15$ m/min; $f = 0.12$ mm/rev

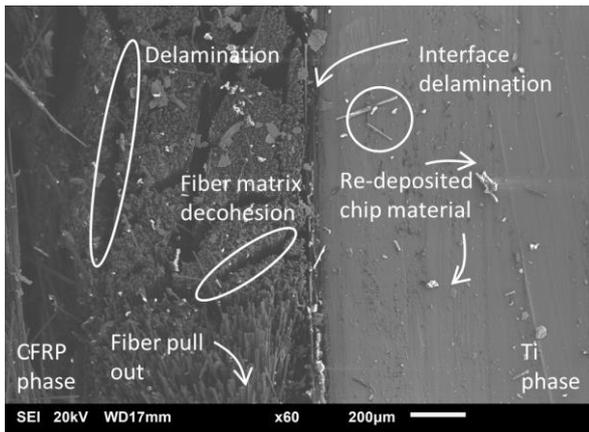


Fig. 8. SEM image of drilled PUDC hole wall morphology near the interface zone in CFRP→Ti sequence for $V_c = 65$ m/min and $f = 0.12$

PMD1 specimen show no visible signs of damage.

- Drilling sequence has a great effect on hole wall quality and diameter roundness. Ti→CFRP drilling sequence has less effect on diameter roundness and produces smoother cuts than CFRP→Ti sequence.
- Assembly method between composite and titanium is also, a parameter to be taken into account during the manufacturing as shown to have a direct link to delamination.
- Finally, a potential link between damage in CFRP phase and delamination i.e., the propagation of fiber/matrix crack can propagate to the interface and follow the shear direction which causes delamination.

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