Milling of Stacks of Material Composed of Carbon Fiber Composites and Titanium Alloy for Aerospace

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Abstract

Carbon Fiber Reinforced Polymers (CFRP) composite materials are widely used today in the aerospace industry for their specific strength and stiffness, as well as their relative light weight, compared to metallic alloys. Even though composite parts are manufactured to near net shape, additional machining operations are required for assembly purposes, such as drilling to produce holes for screws, bolts or rivets. Unlike metallic materials, composite materials raise some specific problems during drilling, especially for stacks of material as CFRP over titanium plates. For this process, the machining conditions for both materials are incompatible. Damage in the form of delamination, cracks, and matrix burning is observed due to the evacuation of hot titanium chips, improper cutting conditions or tool wear. The production of titanium burrs at the tool exit is also an important issue. In this paper, an orbital milling process is proposed and optimized to generate holes by means of a milling tool being operated along a helical path into the workpiece. The objective of this study is to describe the effects of orbital milling on quality of holes in CFRP/titanium stacks and to propose key parameters and optimal cutting conditions for this process. It was found that the corner radius of tools and the helical step had a severe impact on the quality of holes. It was also found that different cutting conditions for each material as well as a finishing cycle at the end of the orbital milling cycle were required to produce best quality holes.

1. Introduction

Recent trends in the aerospace industry have seen increased use of composites and titanium alloys due to their exceptional mechanical properties. Composite materials are widely used not only for their higher specific properties (properties per unit weight) of strength and stiffness compared to metals, but also for their excellent resistance to fatigue and corrosion. Due to the dissimilar properties of titanium and CFRP, drilling parameters and drilling defects are very different in both materials. Surface delamination, thermal damage, fiber pull-out, and roughness variation along the hole are common defects encountered while drilling CFRPs (Abrao, 2007). For the titanium alloy, the most common defect is burr formation at the hole exit.

There are several factors affecting the extent of delamination in machining CFRP laminates. Wen-Chou worked on CFRP laminates, and found that increased delamination is related to tool wear, and that tool wear is related to machining temperature (Wen-Chou, 1997). Liu conducted a review of the literature and found that most of the studies examined show that increased delamination is related to greater feed rates (Liu, 2012). Hocheng et al. found, based on an analytic model, that delamination is directly related to thrust force (Hocheng, 2005). Another key factor in CFRP delamination is the tool geometry, as shown by Tsao in his study of step-core drills in CFRP laminates (Tsao, 2008). There are different approaches used to measure delamination. Faraz et al. propose a new criterion Fa based on a percentage of the delamination area and hole area, which avoids certain errors caused by fibers being pushed into and out of the hole, which could increase the delamination value (Faraz, 2009).

For titanium machining defects, Ramulu et al. found that burrs depend on cutting speed and feed rate. Under conditions of constant speed, the size of the burr decreases with an increase of the feed rate, while with a constant feed rate, the size increases with a cuting speed increase (Ramulu, 2001).

While multiple studies have examined the drilling of CFRP, only a few have been carried out on the CFRP/titanium stacks. Schulze mentioned that the advantage of orbital milling is that with it, damage in the workpiece is lower because process forces are directed towards the center of the workpiece. He also mentioned that different studies have found better quality holes using a helical milling-like process as compared to drilling (Shulze, 2011). Park et al. found that with the use of a metal bonded diamond core drill in CFRP laminates, hole delamination is improved (Park, 1995). Persson compared special tool geometries with dagger drills in CFRP with the KTH procedure, and found better results in hole quality and fatigue resistance (Persson, 1997). Yagishita found lower roundness using circular milling with a diamond coated drill bit (Yagishita, 2007). Finally, Brinksmeier showed that helical milling of Aluminum/CFRP/titanium composites leads to lower temperatures and lower forces compared to drilling. He also found that titanium chips do not cause temperature peaks on the CFRP surface, which improves surface quality, and lastly, he found that drilling CFRP laminates with a low cutting temperature is preferred over helical milling (Brinksmeier, 2002, 2011).

Regarding the cutting parameters used in machining these materials, a relatively high cutting speed (150-200 m/min) with a low feed rate (0.01 to 0.05 mm/rev) are recommended for drilling CFRP laminates in order to minimize delamination (Konig, quoted by Shyha, 2011), while low cutting speeds (10-30 m/min) with moderate feed rate (0.05-0.1 mm/rev) are recommended for machining titanium alloys, (Ramulu, quoted by Shyha, 2011).

This paper presents an approach to the helical milling of CFRP/titanium stacks, and focuses on CFRP surface delamination and titanium burr defects.

2. Methodology

The workpiece used was composed of CFRP and titanium plates. The CFRP was an autoclave-cured 24-ply laminate with a stacking sequence $[(90^\circ,-45^\circ,45^\circ,0^\circ,45^\circ,-45^\circ,45^\circ,-45^\circ,0^\circ,-45^\circ,45^\circ,90^\circ)]_s$ and 3.72 mm thick. The titanium plate was a 3.175 mm thick $TiAl_4V_6$. Tests were performed without lubrication, with a supporting back plate used to prevent the elastic deformation of the material. Holes were drilled using a 16x5 arrangement, with a distance of 15 mm between them, as shown in Figure 1, and tool wear was verified for every 5 holes. Holes were 6 mm in diameter, and were made with a 4 mm diameter tool. The tests were performed using a CNC machining center Huron K2X-10 with a Siemens SINUMERIK 840D controller. Holes were made with a Pocket cycle available within the controller. This cycle allows circular pockets to be made following a helical trajectory and a circular milling finishing pass at the bottom of the hole (Figure 2). The pocket cycle has different parameters which could be changed according to machining requirements.

The hole depth is defined by the _DP parameter, and was set at 1 mm below the bottom of the surface. The radius of the hole was set to 3 mm for the roughing sequence, while the finishing allowance was set by the _FAL parameter, with a 0.05-to-0.1 mm range. All machining components were set to up-milling mode. The axial feed rate was set by the _FFD parameter, while the circumferential feed rate was controlled by the _FFP1 parameter.

Finally, the helical step was set by the _DP1 parameter and the spindle speed configured before the controller started the cycle. Cutting forces were measured along the three axes components using a Kistler 9225B table. Individual testing was carried out, first with CFPR, and then with titanium. The optimized parameters found for each of the materials were then used to drill stacks by modifying the latter at the transition point between the two materials.

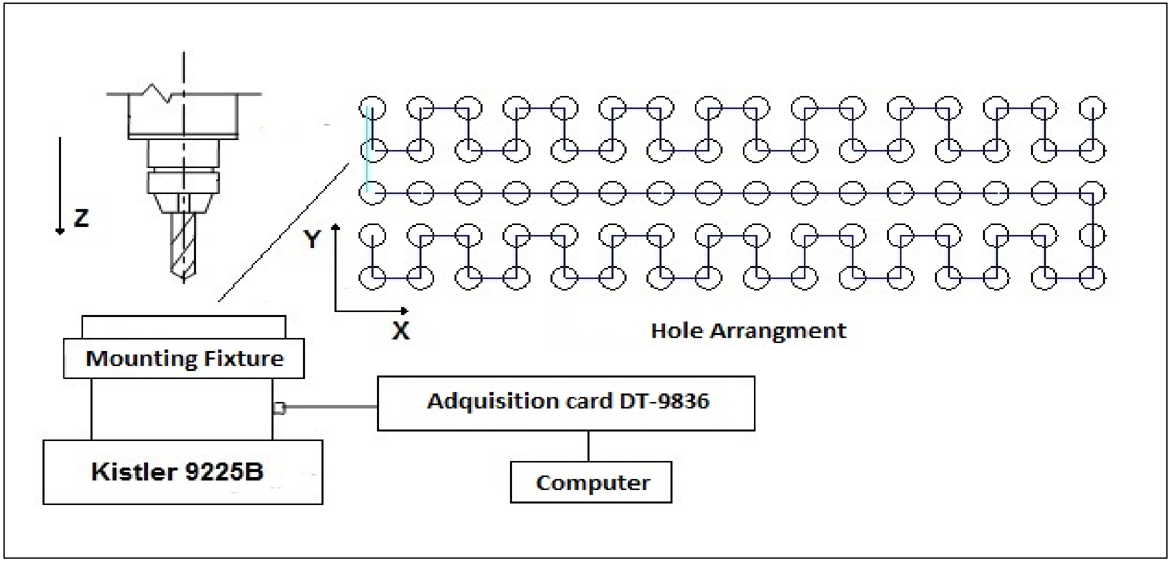


Figure 1. Experimental set-up

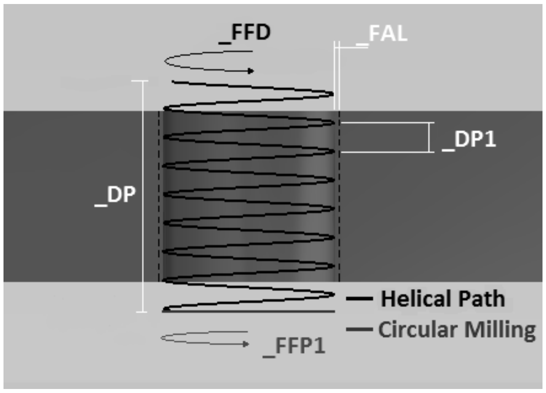


Figure 2. Parameters and tool path

Initial tests were performed with titanium alloy plates with a total of three different tools and a range of spindle speeds, axial feed rates, surface feed rates and helical steps, for two reasons: first, to select the more suitable tool for the testing, and secondly, to find the key parameters for the CNC controller cycle affecting the quality of the hole. The first tool tested (Type I, Figure 3) was a 4 mm diameter coated carbide drill bit, with four flutes, having a helix angle of 30° and a rake angle of 6°. The second tool tested (Type II) was a 4 mm diameter coated carbide drill bit, with four flutes, having a helix angle of 50° and a 0.5 mm corner radius. The third tool (Type III) was a 4 mm diameter coated ball end mill, with four flutes, having a helix angle of 20° and a rake angle of 6°. After preliminary tests, it was found that the most suitable tool to use for the rest of the study was the type I drill bit. We discuss the quality issues resulting from the preliminary tests for the three types of tools in the next section.

Following the preliminary tests, an optimization process, for the suitable tool, consisting of a design of experiments and an ANOVA analysis was performed to determine the factors, among those available with the cycle, that have a significant effect on the delamination of the CFRP laminate, on burr formation for the titanium plate, and on hole diameter for both materials. The influencing parameters were then varied in a study to find the best values, according to quality. This process was first performed for the titanium plates, alone, without a finishing cycle (Table 1). A total of 70 holes were machined to find appropriate axial feed rate and helical step values. Then, a study of the effect of the finishing tolerance was performed using the parameters shown in Table 2. The axial feed rate and helical step were kept constant with values equal to the best ones found in the previous study.

Following this process related to the titanium material, the optimization process was repeated for the CFRP laminates with the parameters shown in Table 3. As for the case of the titanium, a total of four tests were conducted, varying the finishing tolerance from 0 to 0.1 mm to study the finishing cycle influence on the quality of the hole, with the parameters shown in Table 4.

Finally, a total of 20 holes divided into four tests were performed within CFRP/titanium stacks. Ten holes were machined without the finishing cycle, and the rest with the finishing cycle. The machining tool was changed every 5 holes and tool wear was measured.

Figure 3. Tool types I, II and III

Table 1. Titanium Machining Test parameters							
Test	Cutting Speed [m/min]		Axial Feed Rate [mm/min]		Helical Step [mm]		Number of Holes Per Test
#	Min	Max	Min	Max	Min	Max	
1	40		120	180	0.2	0.3	10
2			180	240	0.2	0.4	
3			240	300	0.3	0.5	
4			300	360	0.5	0.6	
5			300	360	0.2	0.4	
6			360	420	0.2	0.4	
7			420	480	0.2	0.6	

Table 2. Titanium Finishing Test parameters								
Test	Cutting Speed [m/min]	Axial Feed Rate [mm/min]	Helical Step [mm]	Surface Feed Rate [mm/min]		Finishing Tolerance [mm]		Number of Holes Per Test
				Min	Max	Min	Max	
1	40	300	0.35	200	300	0.05	0.1	5
2				300	400	0.05	0.1	
3				200	300	0		
4				300	400			

Table 3. CFRP Machining Test parameters

Test	Cutting Speed [m/min]		Axial Feed Rate [mm/min]		Helical Step [mm]		Number of Holes Per Test
	Min	Max	Min	Max	Min	Max	
1	75	107	800	1000	0.25	0.5	10
2	107	138	600	800	0.25	0.5	
3	107	138	600	800	0.5	0.75	
4	75	107	800	1000	0.5	0.75	
5	75	107	800	1000	0.75	1	
6	107	138	600	800	0.75	1	

Table 4. CFRP Finishing Test parameters

Test	Cutting Speed [m/min]	Axial Feed Rate [mm/min]	Helical Step [mm]	Surface Feed Rate [mm/min]		Finishing Tolerance [mm]		Number of Holes Per Test
				Min	Max	Min	Max	
1	138	800	0.7	200	300	0.05	0.1	5
2				300	400	0.05	0.1	
3				200	300	0		
4				300	400			

Table 5. Cutting parameters CFRP/Titanium stacks

Material	Axial feed rate [mm/min]	Cutting Speed [m/min]	Helical Step [mm]
Titanium	300	40	0.35
CFRP	800	138	0.7

All parameters were kept in the same order to visualize the finishing cycle and tool wear influence on the results (Table 5). To measure the delamination, only the defects on the first plies of each side of the composite were considered, and the factor Fa was used, as proposed by Faraz et al. (Faraz, 2009). Areas were measured using the ImageJ software, as shown in Figure 4. This software allows the measurement of the area in pixels of different contours in any image. Burr height was measured with a Mitutoyo electronic height gauge at four positions around the circle, and the average for each hole was taken. Finally, a Mitutoyo Coordinate Measuring Machine was used to measure the hole diameter. It was measured in eight positions in the periphery of

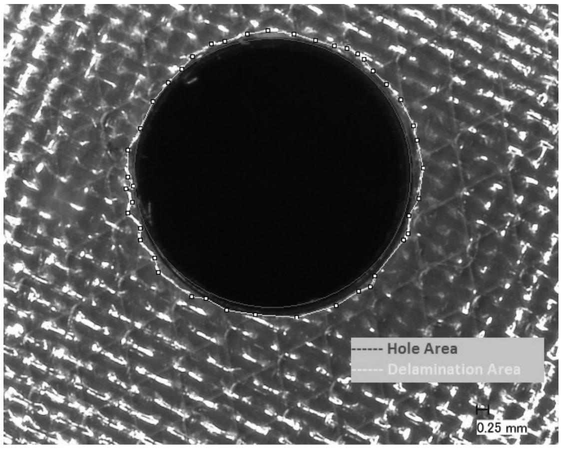


Figure 4. Delamination measurement

the hole, separated by 45 degrees at three different heights: 0.5 mm from the surface, 0.5 mm from the bottom, and in the middle of the hole. Figure 5 shows the measuring configuration for the CFRP/Titanium stacks.

3. Results

3.1. Key factors in the process

A total of three different tool geometries were used at the beginning of this experiment. Burr formation was the only criterion used to select the tool, and it was found that drill bits with a corner radius produced burrs in the titanium alloy. Tool geometry without a corner radius was capable of producing holes without burr formation, and was therefore used for all the remaining tests. Initial tests also showed that the circular milling feed rate did not have an influence on the quality of the hole, and was set at a value of 250 mm/min for the rest of the experiment. Finally, the optimization process allowed us to find a cutting speed of 40 m/min, capable of producing holes in the titanium alloy without burr formation, and which, consequently, was used for the rest of the tests.

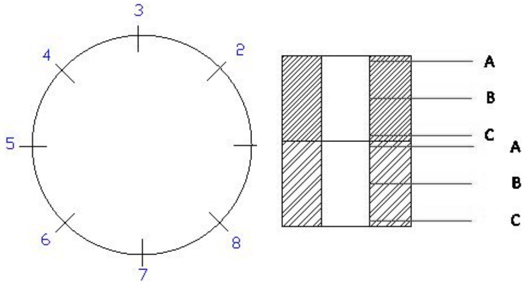
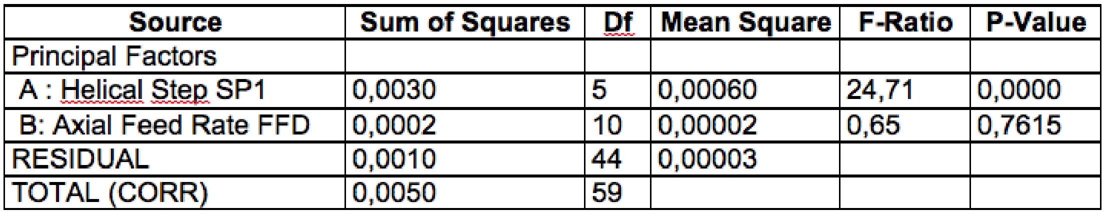


Figure 5. Diameter measurement

3.2. Titanium Alloy Plates

The ANOVA analysis for the titanium plates revealed no significant influence on the burr height by the axial feed rate or helical step. However, the same analysis also revealed that the helical step had an influence on the hole diameter; when the helical step was increased, the hole diameter also increased, as shown in the table showing the ANOVA results (Figure 6). The axial feed rate does not show an influence on the hole diameter. As burr formation was not present, optimal parameters were selected to obtain a closer value of the nominal diameter. As shown in the Box-and-Whisker Plot (Figure 6), the helical step that would produce a hole diameter near the value of 6 mm is located between a value of 0.3 to 0.4 mm, which is why 0.35 mm was selected as an optimal value for the helical step. Moreover, as shown in the same figure, the axial feed rate that would produce a value closer to the 6 mm diameter was situated between 300 and 360 mm/min, and 300 was selected as it presented less variability in results.



Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Principal Factors					
A : Helical Step SP1	0,0030	5	0,00060	24,71	0,0000
B: Axial Feed Rate FFD	0,0002	10	0,00002	0,65	0,7615
RESIDUAL	0,0010	44	0,00003		
TOTAL (CORR)	0,0050	59			

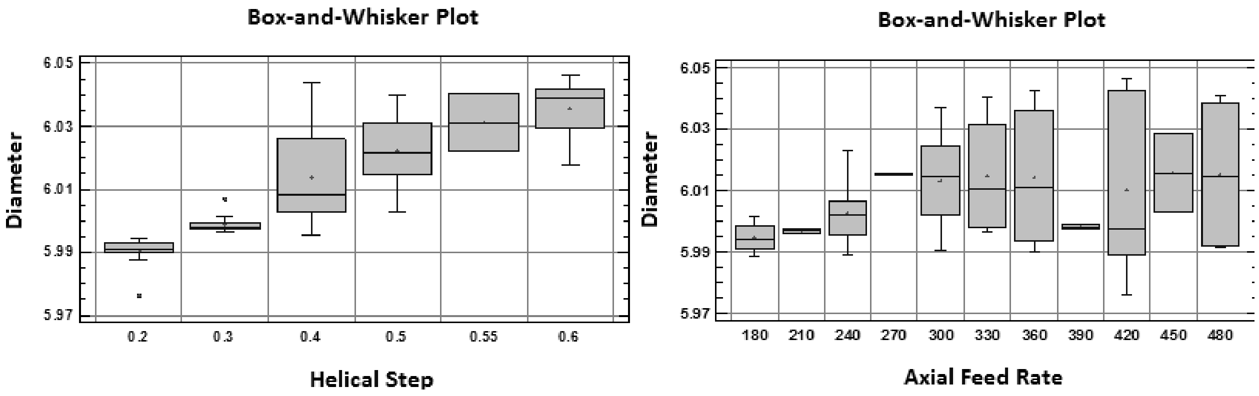


Figure 6. ANOVA and Box-and-Whisker Plot for Helical step and axial feed VS diameter (titanium alloy)

3.3. CFRP Laminates

No significant delamination was present during all tests. The ANOVA for the CFRP laminates did not reveal any influence of the cutting speed, axial feed rate, and helical step on the hole diameter, as the P-Values are much larger than 0.05, as shown in Table 6. The measured values of hole diameter in CFRP are reported in Table 7. As there was no significant delamination, and no significant difference in the results of the diameter value, the maximum cutting speed of 138 m/min was selected as an optimal parameter to improve machining time. However, a helical step of 0.7mm and axial feed rate of 800 mm/min were selected, which are below the maximal values, in order to protect the tool from excessive wear caused by the abrasive CFRP (Table 5).

Table 6 ANOVA for Helical step, cutting speed and axial feed VS diameter (CFRP)

ANOVA Table for Hole Diametrer by Helical Step					
Source	**Sum of Squares**	**Df**	**Mean Square**	**F-Ratio**	**P-Value**
Between groups	0,00004	6	0,000007	0,40	0,8779
Within groups	0,00092	53	0,000020		
Total (Corr.)	0,00096	59			
Groups as Values of helical step in mm (0.25, 0.375, 0.5, 0.625m 0.75, 0.875, 1)					
ANOVA Table for Hole Diameter by Cutting Speed					
Source	**Sum of Squares**	**Df**	**Mean Square**	**F-Ratio**	**P-Value**
Between groups	0,00012	4	0,00003	1,93	0,1179
Within groups	0,00084	55	0,00002		
Total (Corr.)	0,00096	59			
Groups as Values of cutting speed in RPM (6000, 7250, 8500, 9750, 10000)					
ANOVA Table for Hole Diameter by Axial Feed Rate					
Source	**Sum of Squares**	**Df**	**Mean Square**	**F-Ratio**	**P-Value**
Between groups	0,00010	4	0,00003	1,63	0,1801
Within groups	0,00086	55	0,00002		
Total (Corr.)	0,00096	59			
Groups as Values of axial feed rate in mm/min (600, 700, 800, 900, 1000)					

Table 7. CFRP Laminate diameter tests results

Test	Diameter [mm]	Standard Deviation
1	6,015	0,004
2	6,011	0,005
3	6.013	0.004
4	6.011	0.004
5	6.013	0.005
6	6.012	0.005

3.4. Production of burrs

Regarding the quality of the holes in the titanium alloy, it was found that the burr height depended on two factors. First, the geometry of the drill bits seemed to affect the burr height. Burrs were obtained in all tests with ball-nose drill bits in different sets of combinations of cutting speed and feed rate. They were also noted using drills bits with corner radii. The best results were obtained using a drill bit without a corner radius. Secondly, tool wear could increase burr height. This could be explained by the fact that the tool would exert a greater push force as wear increased. When machining CFRP/titanium stacks, burr height also increased with every hole, as the tool wear increased (Table 8). However, the finishing cycle following the orbital motions was capable of eliminating all burrs.

3.5. Delamination

Tests of the CFRP laminates showed no significant delamination, indicating good results for this method. However, delamination at the hole entrance was observed in the CFRP/titanium stacks, probably caused by the evacuation of titanium chips during machining. Delamination values for these tests are shown in Table 8. Figure 7 shows a hole drilled in the CFRP laminate and another drilled in the CFRP/titanium stack. The CFRP hole wall in the stack is gray in color, probably indicating titanium chips adhering to the surface of the hole wall. Delamination is also observed. This delamination was eliminated with the introduction of the finishing cycle when reaching the bottom of the hole, as shown in Figure 8.

3.6. Hole diameter

Hole diameter variations could be caused by the difference in properties of the two materials (Denkena, 2008). With a nominal diameter of 6 mm, the results for the CFRP/titanium stacks tests show that the mean holes diameter for CFRP was 6.0125 mm, and the mean titanium hole diameter was 5.9985 mm. Tests including the finishing cycle show that the diameter was lower than 6 mm for both materials: 5.9665 mm for the titanium and 5.984 for the CFRP. This may be partly due to the tool deflection difference between materials, but there also seem to be a CNC dynamic effect of the cycle, as tests were conducted in an Acrylonitrile Butadiene Styrene material, and similar results were observed in this soft material.

Table 8. Burr height and delamination in stack without finishing cycle

Hole	Burr height [μm]	Delamination [%]
1	40	0.0814
2	95	0.0711
3	165	0.1162
4	135	0.0859
5	245	0.0670

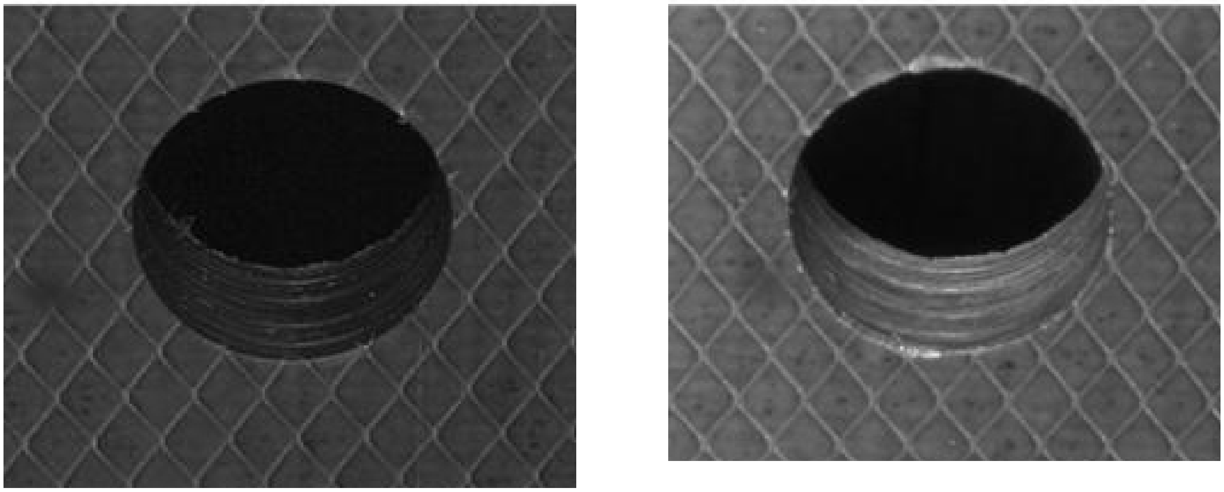


Figure 7. CFRP plate hole wall and CFRP/Titanium stack hole wall comparison

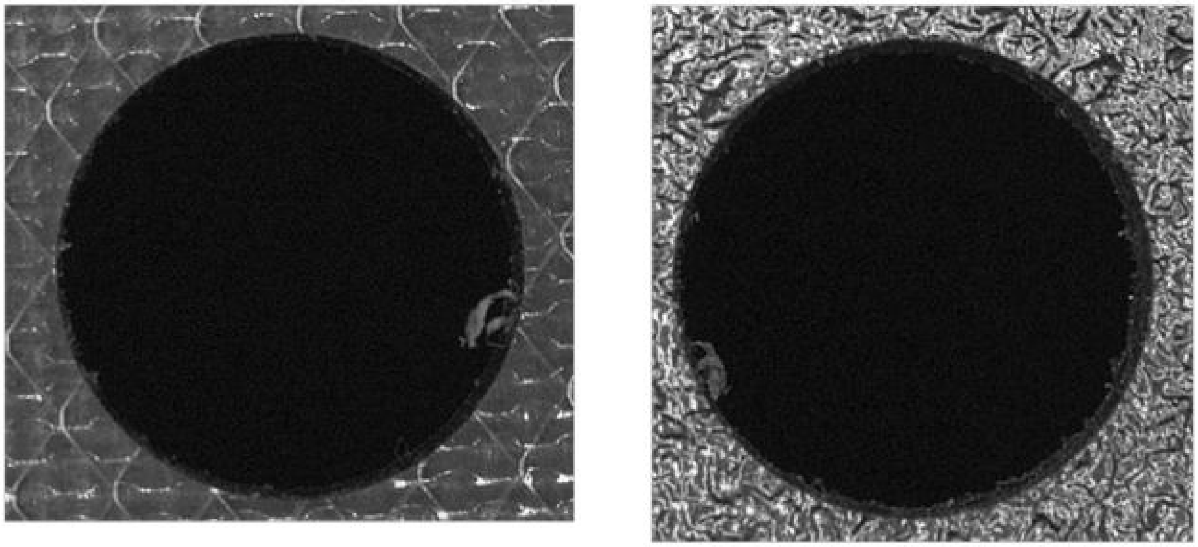


Figure 8. Final Results with optimal parameters and finishing cycle (top surface and bottom surfaces)

4. Conclusions

Hole drilling in stacks of different materials is affected by diverse factors. This paper focuses on how those factors affect delamination, burr formation and hole dimensions. Drill bits of 4mm were used in helical milling machining to produce 6 mm holes in CFRP/titanium stacks. The hole dimension was inspected using a CMM, and the surface integrity, using an electronic microscope.

A relationship was found between the tool geometry and burr size as well as between the tool wear and burr size. A drill bit without a corner radius is preferred for helical milling of titanium thanks largely to the difference in the pushing force related to the tool geometry. A single set of machining parameters for machining both materials successively was difficult to find due to the differences in materials characteristics. When machining CFRP/titanium stacks, the titanium chips evacuation was found to produce delamination at the hole entrance. Also, it was found that the diameter of the CFRP holes was greater than those of the titanium plate, and this could be attributed to the difference in material properties. Finally, the finishing cycle in orbital milling is an effective way to remove burrs and delamination and obtain excellent quality holes with no delamination and burr.

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