Comparative Study of Hole Quality Performance in Drilling of CFRP/Al7075-T6 Stack Using Tetrahedral Amorphous Carbon Coated Drill

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Abstract. Stack up materials which consists of fiber composite panel and aluminium / titanium alloys keep on replacing conventional materials in the aircraft industry. Though stack up materials have enhanced mechanical properties, machining of it is still being as a challenge. This paper compares the hole quality of the holes drilled by uncoated and tetrahedral amorphous carbon (Ta-C) coated tungsten carbide twist drills in terms of hole diameter error, circularity error and hole surface roughness. Drilling experiments were performed at a constant speed of 2600 rev/min and feed rate of 0.05 mm/rev. The stack material of Al7075-T6/CFRP which has a composite laminate thickness of 3.387 mm and Al7075-T6 thickness of 3.317 mm was used as workpiece and drilled under single shot process in dry condition. The results show that, uncoated drill produces better stack up diameter tolerance, circularity and Al7075-T6 surface finish, while Ta-C coated drill bits produce better CFRP surface finish.

INTRODUCTION

Composite materials have gained prominence during the past few years as a means of reducing the weight of aircraft structures. In actuality, 52% of the Airbus A350's total structural materials and 57% of the Boeing 787's major structure are composites [1]. Fibrous composites and metallic alloys are widely employed in stack form in the current aerospace sector to gain enhanced mechanical properties and functions for components requiring the energy-saving features [2,3]. Though there are many fibers and metals available, the superior qualities of CFRP, Ti and Al attracted the industries to select them for this application. Carbon fibres are integrated with very high stiffness, high fatigue strength, light weight, low impact resistance and low density [4]. Titanium alloys are relatively light metallic materials with excellent biocompatibility, high specific strength, and exceptional characteristics that are retained at high temperatures [5,6]. While having excellent features including high thermal conductivity, high fatigue strength, light weight, and ease of workability, aluminium also has poor surface properties, low tensile strength, less stiffness, and low resistance to abrasion [7,8]. When the composite part and the metal part stack up together, it gives superior thermo mechanical properties of composite and metal phase.

To provide various geometrical qualities and ensure secure assembly with other components for increased product integrity, dependability, and life cycle, hole drilling has long been a typical practice employed in the manufacturing sector [9,10]. Hole drilling has proved to be crucial in the automotive and aerospace industries when it comes to the machining of lightweight metals and composites [11,12]. Due to the anisotropic nature of fibres compared to the isotropic nature of metals, single shot stack drilling incorporating these two components is quite challenging and can

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cause a variety of tool and hole damages. Drilling of multi material stack has problems like chip disposal, change in dynamic cutting forces, hole damage, increase in tool temperature and tool wear [13,14] and these problems account for approximately 60% of part rejections [12].

The mechanical characteristics of the workpiece and tool, such as hardness, coefficient of thermal expansion, thermal conductivity, the rigidity and actual size of the cutting tool, the cutting parameters, the environment, etc., can all have an impact on the ability to produce holes with tight tolerances. If the hole in one material of the stack is undersized (hole diameter < tool diameter) or oversized (hole diameter > tool diameter) or highly rough (1.6 µm ≤ roughness of Al and 3.2 µm ≤ roughness of CFRP) [15], it is necessary to implement a repair procedure, and that process typically increases the assembly process's time and expense. Additionally, using a screw or rivet to fasten materials into an undersized hole may concentrate stresses at the hole walls, leading to fracture initiation and propagation until the component fails, whereas doing the same with the oversized hole may cause a loose assembly and potential bearing failure [16].

The degree to which coated drill bits exhibit concurrent tribological behavior in their interactions with both tool-composite and tool-metallic interface determines how desirable they are for stack up drilling [17,18]. As a result of these interactions, surface quality and the frequency of hole damage can be predicted when drilling stack up materials [19]. Manufacturing industries principally uses inorganic compounds to coat cutting tools either through chemical vapor deposition (CVD) [20] or physical vapor deposition (PVD) [21,22]. Though many researchers have tried with different coatings like TiAlN, TiN, AlTiSiN-G, TiAlCrN, TiAlCr / TiSi, TiSiN etc. they couldn’t find the best coating for this purpose. Current research is introducing tetrahedral amorphous carbon (Ta-C) as the coating to the drill bit and comparing its performance with the uncoated tool. This paper aims to compare the drilled hole quality of Ta-C coated and uncoated tungsten carbide (WC) drills in terms of stack up diameter difference, hole circularity and hole surface roughness when performing single shot drilling of CFRP/Al7075-T6 stacks.

METHODOLOGY

Materials

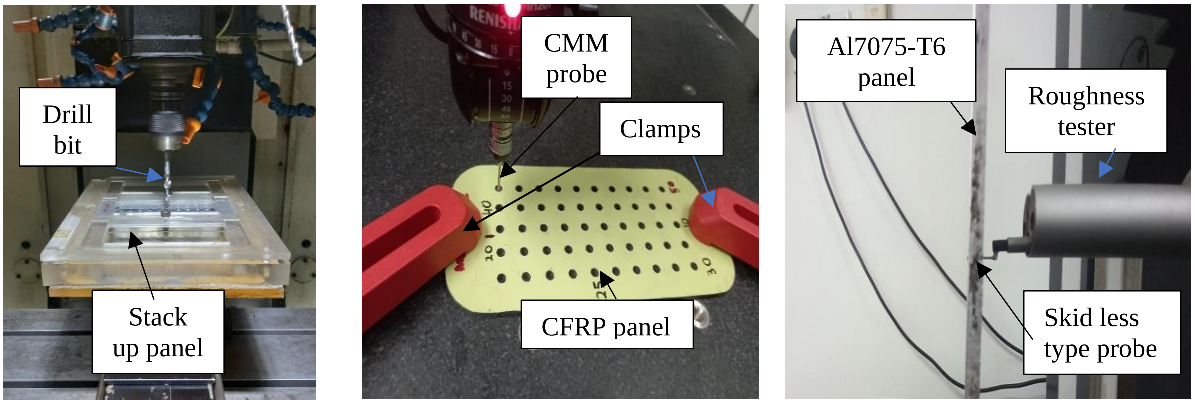
CFRP and aluminium alloy (Al7075-T6), which have densities of 1.601g/cm^3 and 2.597g/cm^3, were the stack materials used in this research work. The CFRP composite specimen has a total laminate thickness of 3.387 mm and the thickness of Al7075-T6 is 3.317 mm. The dimensions of the stack were 185 mm x 85 mm. The drill's diameter is 4.85 mm and sintered rod of tungsten carbide (WC) was chosen as the drill bit material due to its remarkable resistance to wear while drilling abrasive materials like CFRP. Drilling was done in a single shot, starting from the CFRP side, and moving towards the Al7075-T6 panel. During drilling, the stack panels were slotted into the fixture and clamped. In this work, the substantial impact of Ta-C coating was observed using a spindle speed of 2600 rev/min and a feed rate of 0.05 mm/rev for all runs. The PVD coating method is used for coating process and the thickness of the coating was 2 microns. In this experiment, dry drilling conditions are employed to imitate the drilling process that occurs during industrial manufacturing. The drilling set up is shown in Fig. 1 (a).

Hole Damage Measurements

Hole integrity assessment was carried out for stack up diameter error, hole circularity and hole surface roughness. Making sure the diameter difference between two holes and roughness of the hole walls are as little as possible while drilling a stack material with various material qualities is the key issue in this research work to address.

The discrepancy between the measured hole diameter and nominal value of the hole diameter is known as the hole diameter error. The difference between the measured holes in CFRP and Al7075-T6 is used to define the diameter difference between stack up panels and is termed as stack up diameter error. A model Crysta-Plus M443 Coordinate Measuring Machine (CMM) with the accuracy of 3.0+4L/1000 µm and probe size of 2 mm was used to measure the hole diameter for both CFRP and Al7075-T6 as shown in Fig. 1 (b). To ensure uniformity is attained during the measurement, four reference points are acquired at positions 0°, 90°, 180°, and 270° for each point and the readings obtained are shown in Fig. 2. Hole circularity was also measured by the same machine and 40 contact points for each hole were considered in order to finalize the circularity of holes. Figure. 3 shows the circularity diagram of a hole and relevant readings obtained from the software. The hole surface roughness was measured using SURFTEST SV-3100 contact roughness tester with the help of skidless type of probe as shown in Fig. 1 (c) and the software used here is FORMTRACEPAK. For each hole, the roughness was measured four times at positions of 0°, 90°, 180°, and 270°

with the average value being calculated. The surface roughness measurement is taken for Al7075-T6 and CFRP separately due to the two different requirment values according to OEM standards. The surface roughness expected to be below 1.6 µm for Al7075-T6 and 3.2 µm for CFRP panel in the aircraft industry [15].



(a) (b) (c)

FIGURE 1. The experimental set up for (a) drilling stack up (b) hole diameter error & hole roundness error measurement and (c) hole surface roughness measurement.

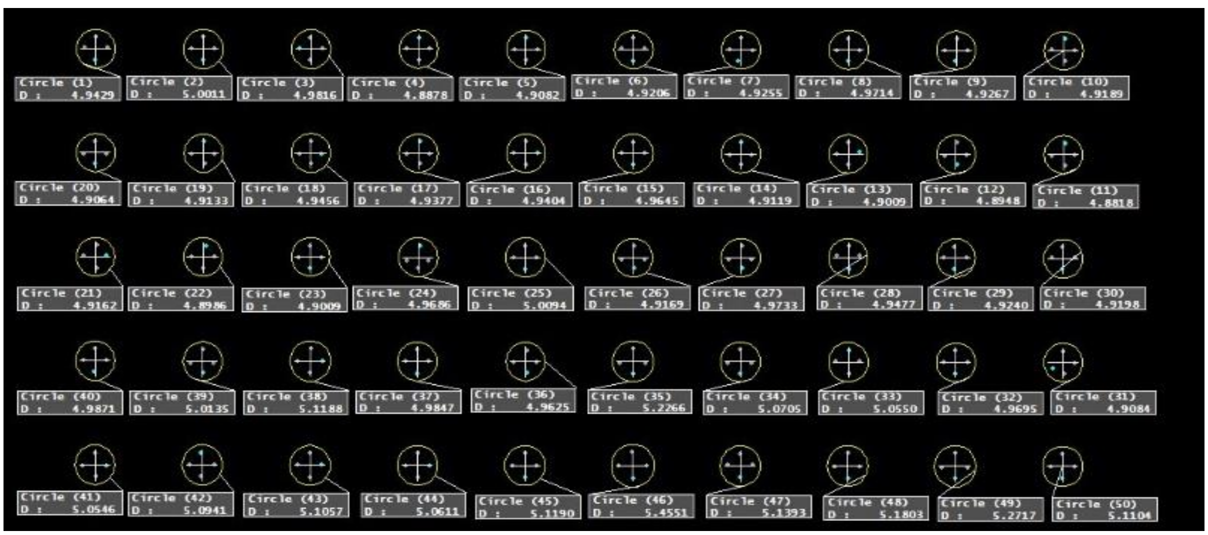


FIGURE 2. The sample of readings obtained for hole diameter error

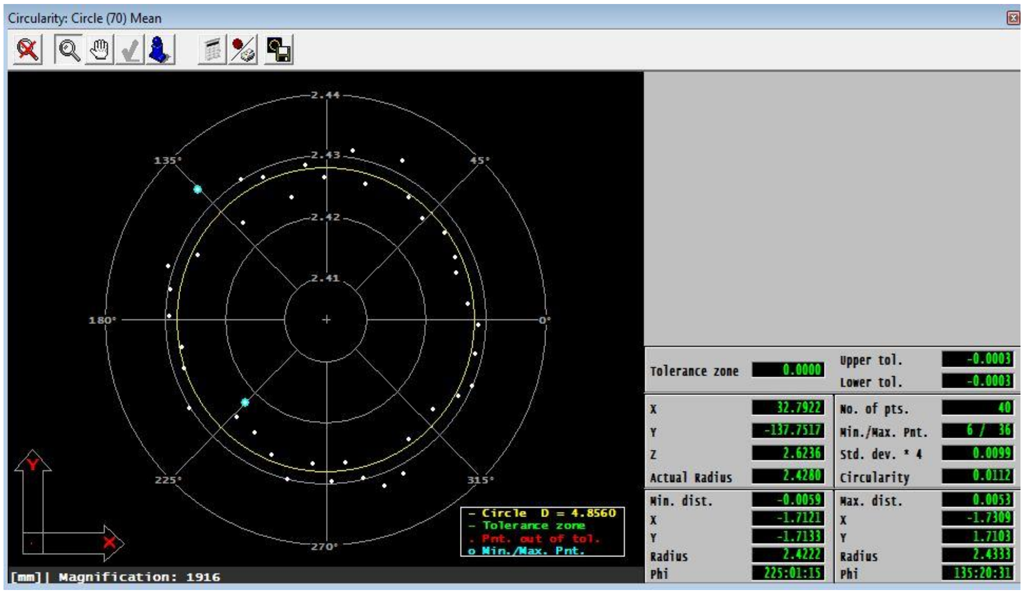


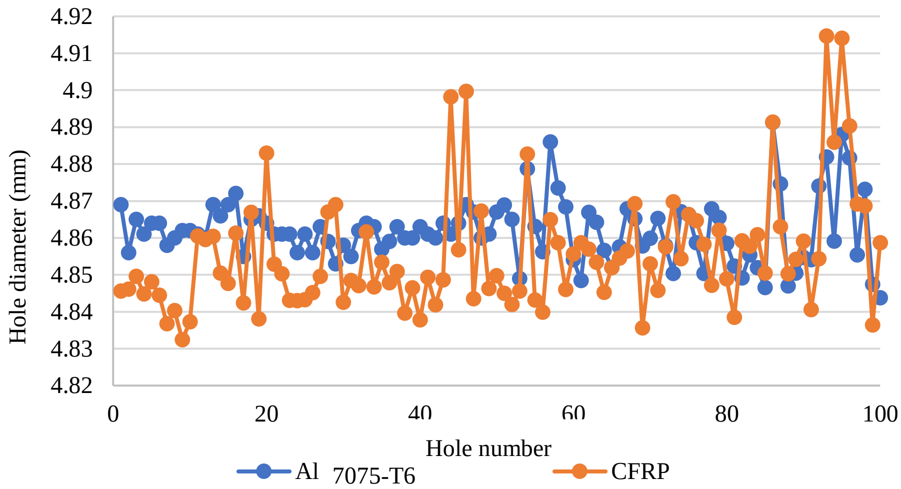
FIGURE 3. Sample of a reading obtained for hole roundness error

RESULTS AND DISCUSSION

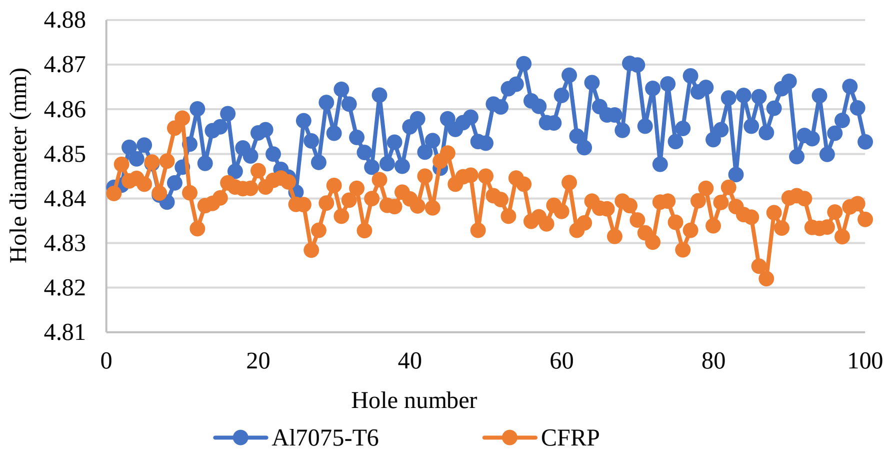
Hole Diameter Error

As a common pattern, the diameters of the holes drilled in Al7075-T6 are larger than the same in CFRP when using either coated tool or uncoated tool. When closely observing the holes produced by each tool, the uncoated drill bit produced almost similar sized holes in Al7075-T6 throughout the operation while increasing hole size pattern was obtained for CFRP as shown in Fig. 4 (a). The average diameter of the holes drilled by uncoated tool in Al7075-T6 is 4.8619 mm and in CFRP is 4.8553 mm. The range of the size of the holes lie between 4.83 mm to 4.89 mm, neglecting the five oversized holes out of two hundred holes. When considering Ta-C coated drill bit, it produced holes which tend to decrease in size in CFRP and increase in size in Al7075-T6. The slope of this trend is very small, as around 10 µm change for hundred holes as shown in Fig. 4 (b). The average diameter of the holes drilled by Ta-C coated drill bit in Al7075-T6 and in CFRP are 4.85564 µm and 4.83919 µm respectively. The range of the hole diameters lie between 4.83 µm to 4.87 µm, neglecting the four undersized holes in CFRP. Due to the thermal expansion that took place during the drilling operation, the Al7075-T6 panel hole is enlarged as compared to the nominal value of the diameter. When drilling the Al7075-T6, the produced aluminium chip clogs at the flute and raises the drilling temperature and this rise in temperature causes thermal expansion. Under the sizing of CFRP material than nominal hole diameter could be due to the shrinking effect that happens during cutting process.

The evaluation of hole diameter error in both CFRP and Al7075-T6 plate is shown in Fig. 5. The difference between the absolute error of the measured value and the nominal value, for both CFRP and Al7075-T6, is called the diameter error of each material. The diameter error between CFRP panel and Al7075-T6 panel is called stack up error. The average stack up error in the holes drilled by uncoated tool is 13.28 µm and by Ta-C coated tool is 17.24 µm. While 50% of the holes drilled by uncoated tool stays within H7 hole diameter error tolerance range, only 30% of the holes drilled by Ta-C coated drill stays within that limit. Furthermore, an uncoated tool produces a greater number of H7 tolerance holes near to the end of drilling phase, but Ta-C coated drill produce more H7 tolerance holes at the start of the drilling phase. This is because, when drilling with Ta-C coated tool, the diameter of Al7075-T6 panel keep on increasing while the diameter of the CFRP panel is keep on decreasing with number of holes. The hole diameter is not intended to vary more than ± 12 microns. However, due to the difficulties in maintaining ± 12 micron (H7) standards, more liberal tolerances, such as ± 18 microns (H8) or ± 30 microns (H9), were permitted to be utilized when drilling composites [23,24]. For instance, SANDVIK tool manufacturers advises that the tolerance for drilled holes in a composite metal stack be between ± 20 and ± 40 microns [25]. According to this, both the Ta-C coated, and uncoated drills produce 90% of the holes within H9 tolerance range and comparatively uncoated drill produces 22.96 % better stack up diameter tolerance than Ta-C coated tool.

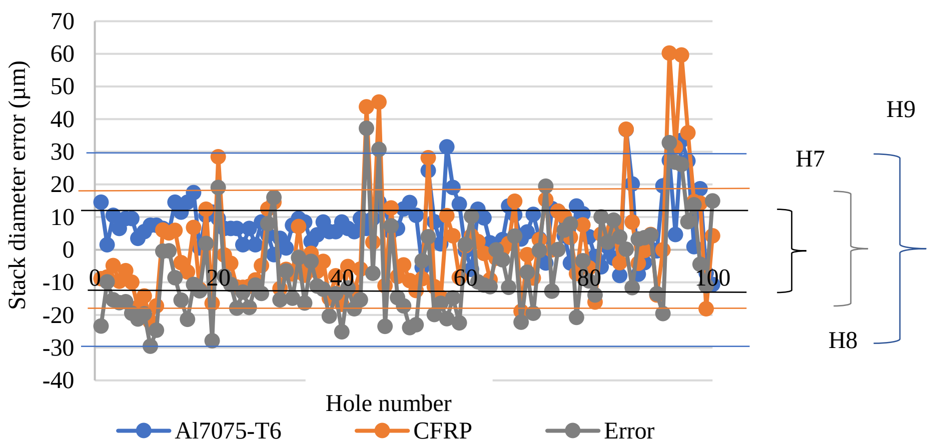


(a)

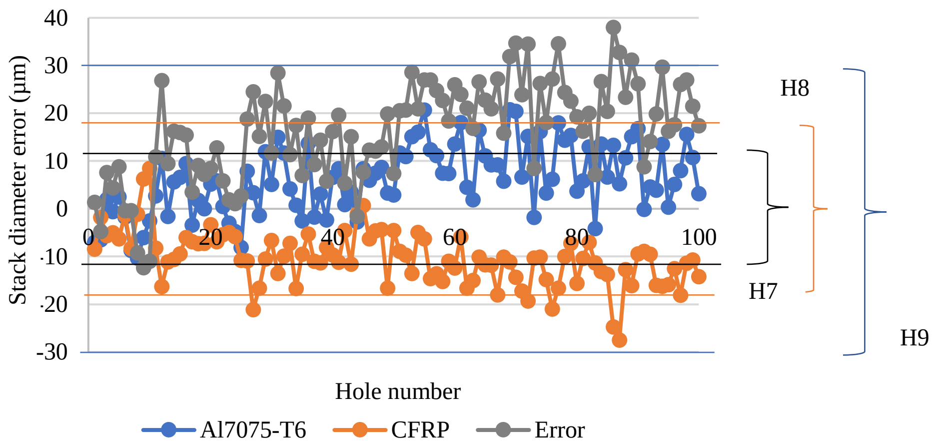


(b)

FIGURE 4. Hole diameter variation for the holes drilled by (a) Uncoated tool and (b) Ta-C coated tool



(a)

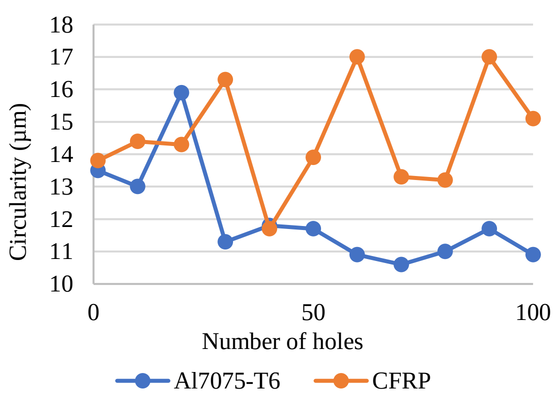


(b)

FIGURE 5. Hole diameter error for the holes drilled by (a) Uncoated tool and (b) Ta-C coated tool

Hole Circularity

Figure. 6 shows the average hole circularity in drilling of CFRP/Al7075-T6 stacks material with and without tool coating. Overall, the average hole circularity of the CFRP and Al7075-T6 laminates were below 20 µm. In CFRP, the circularity ranged between 9.3 µm and 18.4 µm, and for Al7075-T6, it was between 10.6 µm and 17.9 µm. The circularity of Al7075-T6 is better than its counterpart CFRP in the holes drilled with uncoated drill bit while for the holes drilled with Ta-C coated drill bit, there isn't much difference in circularity between Al7075-T6 and CFRP panels. When analyzing the circularity of holes drilled in Al7075-T6, uncoated drill gave better results than coated drill and this pattern is sharpened when the number of holes keep on increasing. This pattern could be because of the wear and tear of coating on coated drill bit, as the circularity readings obtained in both Ta-C coated and uncoated drill bits started in the same range, but uncoated bits show slightly decreasing pattern with increase in number of holes. The average hole circularity obtained in Al7075-T6 with uncoated drill is 12.027 µm and with Ta-C coated drill is 15.264 µm. There wasn't any significant pattern in the case of CFRP, as both the bits gave almost comparable circularity below 19 µm. The average hole circularity obtained in CFRP with uncoated drill is 14.545 µm and with Ta-C coated drill is 15.082 µm. Ta-C coated drill produced more circularity error of 21.206 % in Al7075-T6 and 3.56 % in CFRP when compared to uncoated drill.



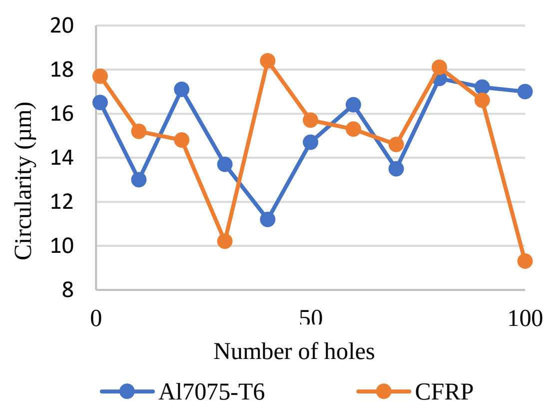
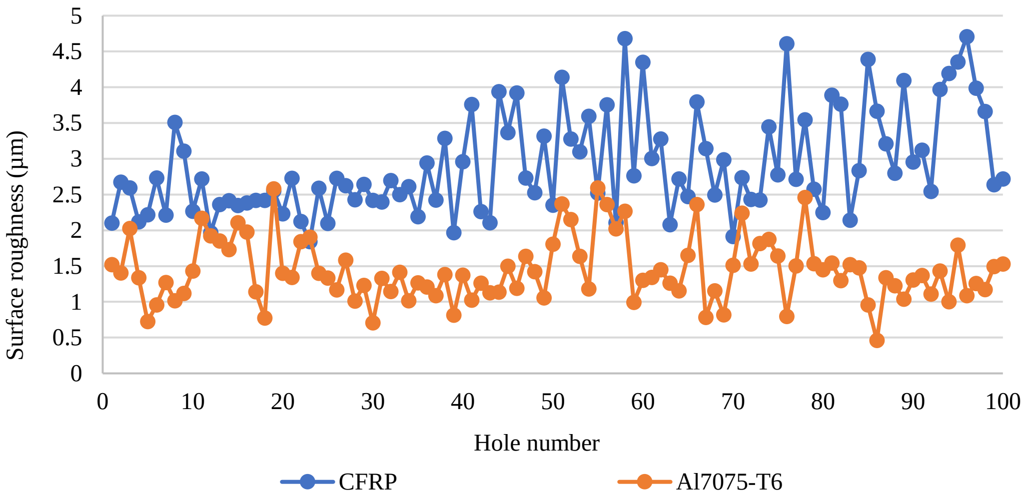


FIGURE 6. Comparison of hole roundness of holes drilled by (a) Uncoated and (b) Ta-C coated tool

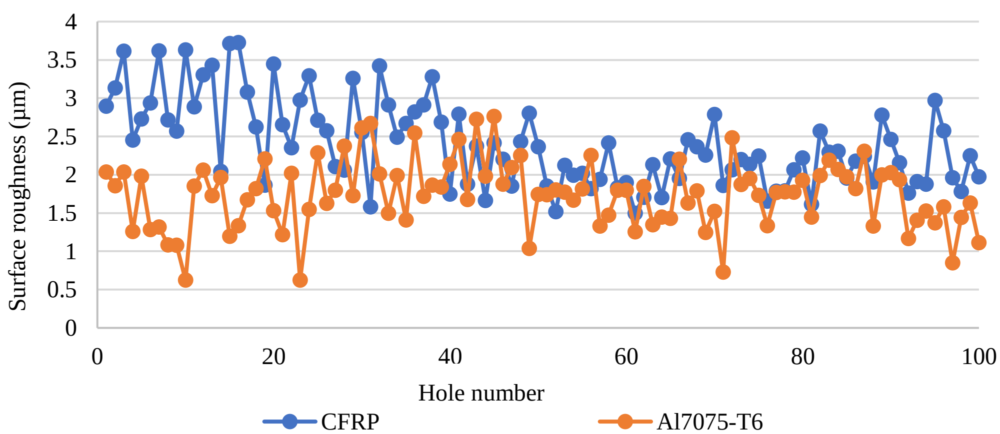
Hole Surface Roughness

With the increase in drilled hole number, the roughness of holes drilled by uncoated drill bit in Al7075-T6 shows slightly decreasing pattern while in CFRP it shows a highly increasing pattern as shown in Fig. 7 (a). In the case of Ta-C coated drill bit, the roughness of holes drilled in Al7075-T6 stays stable within a range while that in CFRP shows a decreasing pattern as shown in Fig. 7 (b). The difference in hole surface roughness between CFRP and Al7075-T6 at the start was larger and which was minimized when it reaches the end. In the CFRP panel, the hole surface roughness value for all trials is in the range of 0.9284 µm – 3.99 µm as shown in Fig 8 (a), and for the Al7075-T6 panel, it is in the range of 0.4133 µm – 2.9842 µm as shown in Fig. 8 (b). Because the laminates adhere together ply by ply with variable stacking sequences and the material behavior of CFRP is inhomogeneous, the standard deviation of hole surface roughness is higher for CFRP panels than it is for Al7075-T6 panels as also stated by [26]. This high standard deviation is also due to the substantial variance in roughness values caused by fracture, projecting fibres, and epoxy debris during drilling [27]

When comparing the hole surface roughness of the holes drilled in Al7075-T6; uncoated drill produces less roughness than Ta-C coated drill and when it comes to CFRP; Ta-C coated drill bit gave the minimum roughness. With the increasing number of holes in CFRP, the roughness of the holes produced by Ta-C coated drill bits decreases slightly while the roughness of holes produced by uncoated drill bit is increasing.

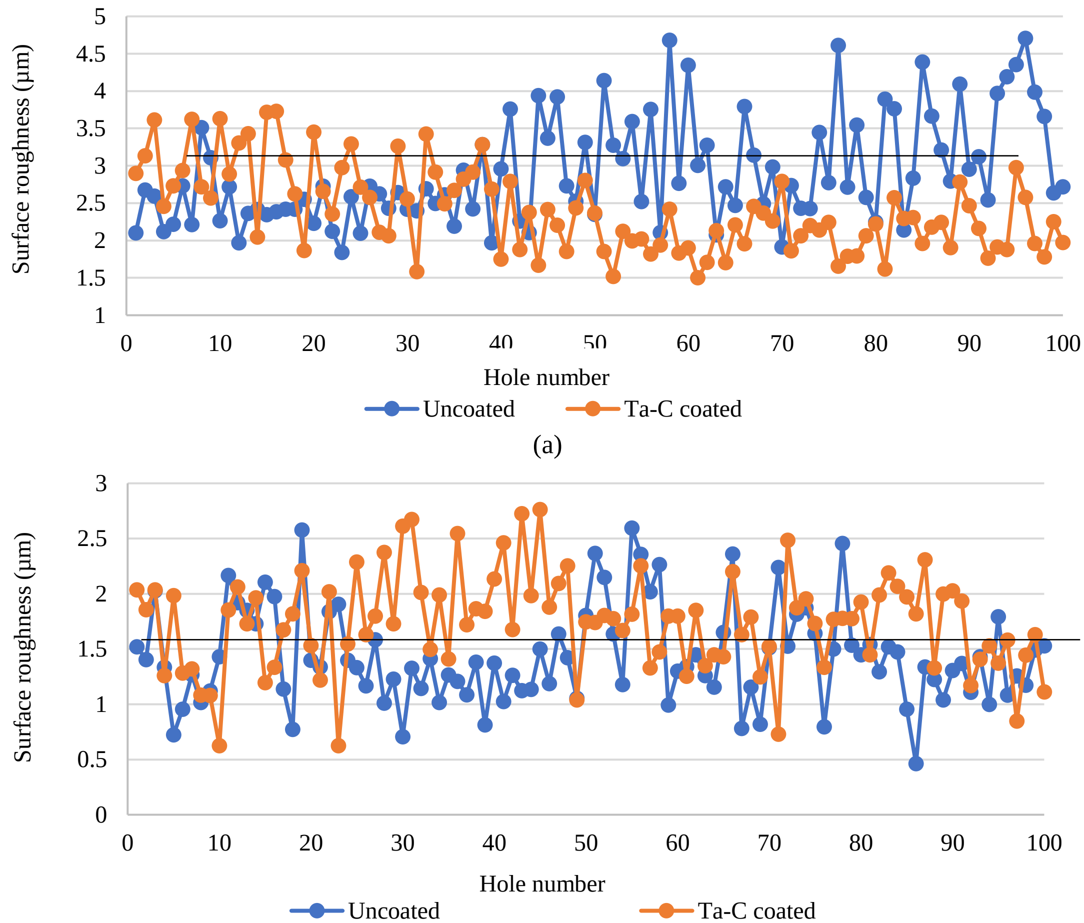


(a)



(b)

FIGURE 7. Hole surface roughness for the holes drilled by (a) Uncoated tool and (b) Ta-C coated tool



(a) (b)

FIGURE 8. Comparison of hole surface roughness of (a) CFRP panel and (b) Al7075-T6 panel

Hole surface roughness of 75% of the holes drilled in Al7075-T6 is lesser than 1.6µm and in CFRP is lesser than 3.2µm by the uncoated drill. The average roughness of holes drilled by uncoated drill in Al7075-T6 and CFRP are 1.451µm and 2.91µm respectively. Nevertheless, hole surface roughness of only 35% of the holes drilled in Al7075-T6 by Ta-C coated drills are lesser than 1.6 µm while 98% of the holes drilled by the same in CFRP are lesser than 3.2µm. The average roughness of holes drilled by Ta-C coated tool in Al7075-T6 and CFRP are 1.765µm and 2.539µm respectively. As the overall observation, Ta-C coated drill bits produce 12.74% better hole surface finish in CFRP than uncoated drill bits and uncoated drill bits produce 17.79% better surface finish in Al7075-T6 than Ta-C coated drill bits.

CONCLUSION

This research work compares the hole quality of single shot stack up drilling between uncoated and Ta-C coated tools. The hole diameter, circularity and surface roughness are the parameters tested. The diameters of the holes drilled in Al7075-T6 panel are larger than in CFRP panel when using either Ta-C coated or uncoated tools. The diameter variation for most of the holes drilled using uncoated drill falls within H7 and H8 tolerance range and almost 95% of the holes drilled using either tool was within H9 tolerance. The circularity of the holes drilled in CFRP and Al7075-T6 using either uncoated or Ta-C coated drills were below 20 µm. The uncoated drill produced comparatively better hole circularity in Al7075-T6 panel, but in CFRP panel there is not much difference. The uncoated drill produced less hole surface roughness than Ta-C coated drill in Al7075-T6 panel and in CFRP panel, Ta-C coated drill bits gave the minimum roughness. Based on the calculations, uncoated drill produces 22.96 % better stack up diameter tolerance, 21.206 % better circularity in Al7075-T6, 3.56 % better circularity in CFRP and 17.79 % better surface finish in Al7075-T6. At the same time, Ta-C coated drill bits produce 12.74 % better hole surface finish in CFRP. Further analysis of hole quality in terms of delamination, burr formation and tool wear will lead to fix a better coating.

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