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Review Article

Influence of cutting conditions in drilling of CFRP/Al stacked composites

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Composite laminates are gorgeous for several applications such as aerospace and aircraft structural components due to their excellent properties. Typically, mechanical drilling has been important machining operation for components made of composite laminates. Nevertheless, laminated composites are considered as hard-to-machine material which results in low drilling efficiency and drilling-induced delamination which is undesirable. This paper reviews the experiments during drilling of CFRP/Al stacked and sandwich composites. The machinability facets of these material stacks has been generally used in aerospace applications, it has been studied based on impact of drill material, drill geometries, and drilling process parameters such as speed and feed. Composite material requires high spindle speed and low feed rate, whereas drilling aluminum requires stability between speedsto feed rate. The review reports essential results and gap in the collected literature for CFRP/Al stacked and sandwich composites. A compromise between several parameters is required during drilling of multi-material stacks. The problems and solutions allied to drilling of multi-material stacks are deliberated and the directions in which the research on drilling of multi-materials may be carried out are suggested in this paper. It is intended to assist readers to acquire a thorough view on mechanical drilling of laminated composite.

Keywords: CFRP/Al stack, Drilling, Delamination, Thrust force, Drill type, Geometry

1 Introduction

In modern aviation industry, it has been achallenge for manufacturing engineers in developing the hybrid laminated stacks of composites to improve the functionality of advanced structures and to promote the continuous production of energy-saving mechanical assemblies. An example of the hybrid composite structure is a material consisting of multi-layerfibre reinforced polymer and metallic alloy (e.g., titanium alloy, aluminum alloy, magnesium alloy, etc.). They are categorized by improved mechanical properties without substantially rising the weight of the part. The hybrid composite stack thus contains the attractive characteristics of each constituent material and avoids its weaknesses[1].

The preeminent capacities to convey vitality sparing and to progress framework execution made the material a commendable wannabe to replace standard composites and single metal amalgams in different modern applications. As of late, composite stacks and fibre metal laminates (FMLs) have been profoundly requested to utilize itfor airplane industry to endure high thermo-mechanical anxieties. These days, carbon composite contains up to half in weight and 80% in volume of new airplanes[2,3]. This is generally endorsed to the more prominent solidarity to weight proportion of carbon fibre reinforced plastic (CFRP), that is normally around[4] ~750 kN m/kghas been contrasted with metallic materials, for example, titanium and aluminum combinations of ~200–250 kN m/kg, permitting lighter airframes and along these lines that have been improved eco-friendliness. For example, Boeing 787 contains about 35 tons of CFRP and a portion of the CFRP is stacked with titanium or aluminum combinations that have been utilized in different parts such as fuselage and nose barrel[5,6].

Owing to the strongest combination of physical and metallurgical properties comprising great strength-to-weight ratio, fracture and fatigue resistance, superior damage threshold energy, and exceptional corrosion/ erosion resistance, the CFRP/Al (CFRP/Al, Al/CFRP/ Al, CFRP/Al/CFRP) stack, has been recognized as the most prevalent combination among the existing configurations of hybrid composite stacks[7,8,9,10,11]. Figure 1 shows a typical CFRP/Al composite stack and its detailed composition is shown in Table 1. A significant amount of holes need to be drilled during the assembly of composite/metal parts to satisfy the requirement for mechanical riveting or bolting. The precision of the assembly is critically dependent on the accuracy of the machined holes rendering estimates about 60 percent of the dismissals

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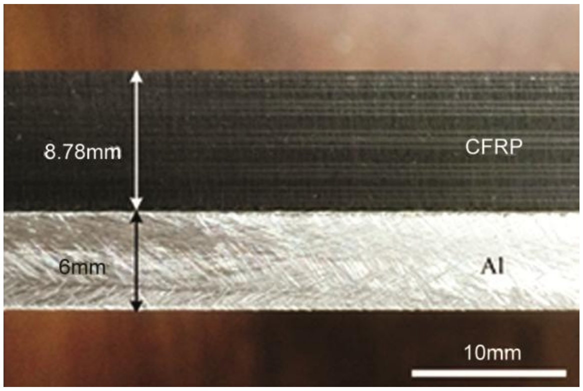

Fig. 1 — Stack materials consisting of T800/ X850 CFRP and 7075-T651 Al[14].

Table 1 — Composition of T800/X850 CFRP composite laminates.

Reinforcing	Epoxy Matrix	Fiber volume content	Fiber bundle	Thickness
T800	X850	65%	5μm ,12K	8.74 mm

are due to holes defects, so that nature of the holes upset the flight efficiency and service life of aircraft directly[12]. Improving single shot drilling process for multi-layer CFRP metallic stacks has been the subject of wide research in advance as a solution to increase efficiency as well as to diminish/evitate misalignment of holes during sandwich configuration assemblage[13].

While the FRP/Al stack assembly has been used in activities for many decades, experimental and theoretical findings regarding its physical/mechanical drilling responses are quiet considerably under-studied. Even though the assortment of study papers existing on understanding the machinability of CFRP[15,16,17,18,19,20,21] and single aluminum alloys[22,23] assessments regarding the multi physical issues with drilling of the two combined components (CFRP/Al) were not described till now. Krishnaraj *et al.*[24] has delivered a comprehensive analysis of multi material stack drilling. In order to analyze the drilling actions of different constituents like composite laminate, aluminum alloy and titanium alloy, more attention must be made in the work rather than the laminated composite drilling action. Recently, Xu *et al.*[25] reviewed the developments in drilling of hybrid FRP/Ti composites. For the sake of continuous development of scientific advances in this area, aiming for a modern research concept will afford a valuable guide for present and future study together. This situation is the primary motivation that encourages the current analysis research to delight the most important accomplishments achieved during bimaterial drilling with accuracy. Based on the literature, the physical aspects tangled in hybrid composite CFRP/Al drilling have been addressed precisely. In addition, a collection of cutting criteria, cutting tool and material for high quality CFRP/Al stack drilling is also updated.

2 Drilling on CFRP/AL stack

Laminated composite (usually an assembly of fibrous composite material to influence on mechanical properties like stiffness, strength, hardness, thermal expansion etc.,) drilling is a difficult activity for manufacturing engineers in light of its particular physical and mechanical properties and handling systems[26]. For illustration, the CFRP laminate displayed anisotropic, abrasive nature, and low thermal conductivity, that stimuli excessive tool wear and poor machined surface quality in machining[27,28]. However, various disruption modes were seen during drilling because of its anisotropy and laminated nature of the carbon fibre reinforced plastics. Such varieties of harm are the peeling of hole entry delamination, thermal modification, tearing along the path of the fibre, shrinking, fibre pulling out and blurring on the hole wall, exit delamination and uncut fibre at the hole exit[29,30,31]. In the meantime, during drilling of aluminum alloy, built up edge, adherent layer and burr will arise due to low elastic modulus and melting point. However, as aluminum is piled at the CFRP base, nonstop and high temperature aluminum chips travelled through CFRP layers break down the consistency of the void. Table 2 summarizes the common drilling induced damages of hybrid CFRP/Al composite. It can be perceived that the drilling-induced delamination occurred via the peel-up, push-out and pull-out mechanisms as shown in Fig. 2 at the boundary of both the hole entry and exit. It is significant to select the right tool and process parameters to ensure consistency and precision of the hole.

3 Drilling factors

The parameters of the input process, such as tool geometries, tool types, cutting parameters, tool materials and coatings showed the influence on delamination, torque, thrust force, tool wear, surface roughness etc. called process output parameters. In order to obtain the best output in the drilling procedure, i.e. the ultimate hole efficiency that represents least damage to the machined components and the machined surface, it is vital to take the proper

Table 2 — Common drilling induced damages of hybrid CFRP/Al composite.

Layer type	Drilling induced damage
CFRP Layer	Matrix cratering, thermal alterations, fibre pullout and fuzzing, de-lamination, Micro-crack, debondingfibre/matrix, spalling, fibre tearing, loss of resin, surface cavities.
CFRP/Al interface	Splintering delamination, damage ring, discoloration ring, etc.
Al layer	Error in hole size, roundness error, error in position, surface drag, cracking, burr, feed marks, lattice surface, microchip debris, deformed grains, surface plucking, surface cavities etc.

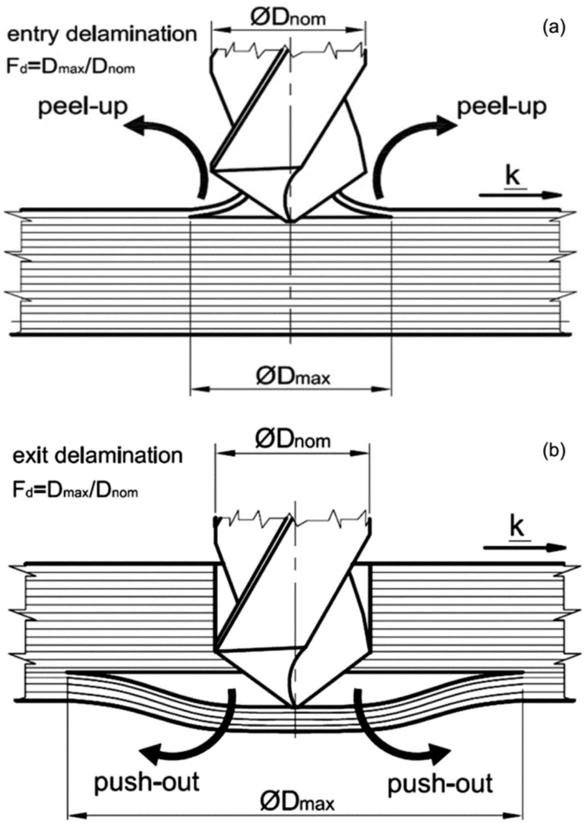

Fig. 2 — Mechanism of drilling-induced delamination in FRPs composite laminates[21] (a) Peel-up delamination, and (b) Push-out delamination.

process parameters. Figure 3 displays the schematic description of drilling of composite laminate for better understanding the drilling studies.

3.1 Requirements of cutting tool

Owing to differential machining properties, the challenging job for manufacturing engineers is to drill multi-materials. Drilling holes by means of low diameter deviations are arduous to machine, due to different material characteristics. The modulus of elasticity of the materials induced disparate elastic distortions leads ultimately fluctuating tolerances around the absolute hole. In addition, chips travelled through the hole besides built-up edges of aluminum (or titanium) on the primary cutting edges and the rised wear of the tool impact the consistency of the hole.[32,33,34,35]. Figure 4 illustrates the chip removal troubles when drilling multi-material stack. For machining multi-material stacks, high-hot hardness and sharp tool materials are needed and should also not react with multi-material stack.

Theoretically machining of multi-material appealed for different cutting tools, one fits the composite attributes and another fits the aluminum attributes. The processing of material is achieved primarily by shearing the material during aluminum machining. The biggest issue with aluminum drilling and its alloys incudes the resistance of aluminum to the main cutting edges, the rake face and the drill flutes. This situation is accountable for the early wear of the tool, the hole diameter deviation and the lower surface finish of the hole.

Several investigations were available on drilling of Al/CFRP stacked composite in the literature using carbide, coated and special type of drills. Some authors proposed to utilize coated drills and some others suggested practice of special type of drill geometries for better performance in machining. But it is preferred to identify the best tool for drilling CFRP/Al stacked composite. In the following sections, discussions on the investigations on drilling of multi material composites by the cutting tool geometry, tool type and the nature of tool materials are made.

3.2 Influence of cutting parameters on Performance measures

The machining parameters such as feed rate and spindle speed are the key parameters while drilling hybrid composite stacks and their precise combination significantly effect on the final result. Research review on the impact of cutting parameters on output in drilling of CFRP/Al stack is discussed in this section. The cutting conditions used by the authors for investigation in drilling CFRP/Al stacked composite is summarized in Table 3.

Zitoune *et al.*[26] analyzed the consistency of the holes, tool wear and chip shape being influenced by the drilling parameters. From the study, drilling with nanocomposite coated tool at a spindle speed of 2020 rev/min and a feed rate of 0.1 mm /rev is found to yield discontinued chips and a better performance

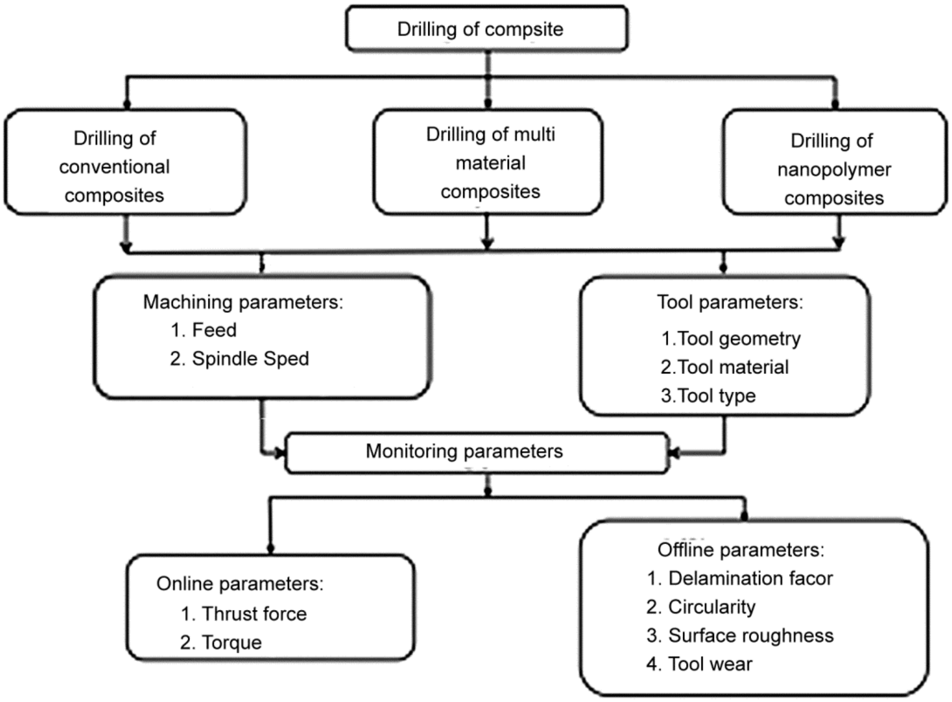

Fig. 3 — The schematic description on drilling of composite materials.

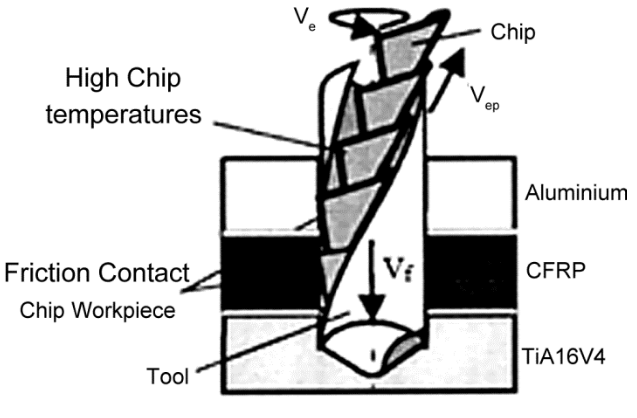

Fig. 4 — Chip removal problems when drilling multi material[33].

compared to uncoated tools. Debnath and Singh[36] found that, during drilling through the mechanisms of push-out and pull-out, peel-up, delamination occurs at the boundary of both entry and exit holes. Delamination tends to be more serious at the edge of the entry hole than at the exit hole because of both the peeling of the initial layer of CFRP by drill flute and the purging of the AA7075 chip across the hole[37]. During CFRP/Al/CFRP composite drilling, the most important damage resulting from greater thrust force at higher feed rate was the delamination on the 1st CFRP entry. Nevertheless, it was found that 2nd CFRP exit delamination was mainly at lower feed and that delamination on 2nd CFRP was significantly observed at lower feed rate of 60mm/min. Rise in feed lead to increase in delamination at entry, greater thrust and torque, rough surface on all surfaces, moreover, lower exit delamination and lowered frayed fibre. Therefore, the recurrence of delamination of a composite material is thoroughly correlated to the applied feed rate[38,39]and to the spindle speed[40], but in a minor way. The low feed, smallest drill point angle and high spindle speed are recommended to check the beginning delamination in composites[41,42,43]. It should be known that improved delamination behavior is exhibited by rising the spindle speed at the composite stack exit surface and keeping the smaller feed rate[44]. But lesser feed rate as suggested for CFRP constituents refers to the producing of lengthy chips in aluminum alloy. This non-fragmentation issue of the chips is particularly notable when drilling CFRP-Al stacks. In fact long chips cause several defects. These chips scratched the reaming, cause the hole to degrade geometrically and dimensionally and even peeled the CFRP[45]. According to Zhang *et al.*[46] the best process parameters intended for machining CFRP/Al stacks are speed of spindle as 4000 rpm, the feed rate as 0.04 mm/rev, using twist drill (point angle 90°) coated with CVD. At the viewpoint of calculated micro and macro geometric deviances, the pair of

Table 3 — Overview of cutting conditions in drilling of composite stacks.

Composite stack	Cutting conditions
CFRP/Al2024[7]	n = 1050, 2020 and 2750 rpm; f = 0.05, 0.1 and 0.15 mm/rev
CFRP/Al2024/ CFRP[8,9]	n = 2000 rpm f = 0.03, 0.1 and 0.25 mm/rev.
Ti6Al4V/CFRP/ Al-7050[13]	v_c = 20 m/min – 120 m/min; f = 0.05, 0.10, 0.15 mm/rev; Cutting environment: wet, spray mist condition.
CFRP/Al7075[14]	n = 1000, 2000 and 3000 rpm; f = 0.02, 0.04, 0.06 and 0.08 mm/rev Dry cutting condition
CFRP/Al; AI/CFRP/TiAI6V4[33]	v_c = 10, 20 m/min; f = 0.15 mm/rev; Cooling: dry/oil mist
CFRP/ UNS A92024 Alloy[47]	v_c = 85/115/145 m/min; f= 200/250/300 mm/min
CFRP/Al2024[48,49]	n = 2020 and 2750 rpm; f = 0.05, 0.1 and 0.15 mm/rev
CFRP/AA 7075/ CFRP[50] CFRP: T700	n = 8000, 6000 rpm; f = 0.2, 0.163 mm/rev
CFRP/Al 6013-T651[51]	v_c =100, 125 and 150 m/min; f = 0.1, 0.2 and 0.3 mm/rev Ø = 90°, 118° and 135°
Ti-6Al-4V/CFRP/ Al-7050[52,81]	v_c = 30, 36 m/min (Ti); v_c = 120, 144 m/min (CFRP/Al); f = 0.05, 0.08, 0.12 and 0.15mm/rev

CFRP/A7075-T6[53]	v_c = 130, 150, 170 m/min (CFRP);
	v_c = 200 m/min (Al);
	f = 0.04, 0.06, 0.08 mm/rev;
	z = 45, 50, 55 Hz;
	A = 0.005, 0.02, 0.05 mm

CFRP/AA2024[54]	n = 6000 rpm; f = 0.02, 0.04, 0.06, 0.08 mm/rev
CFRP/Al7075-T6[55]	n = 1500, 2600 rpm; f = 0.05, 0.1 mm/rev

cutting velocity at 145 m/min and feed at 200 mm/min dealt the best performance for CFRP/ UNS A92024 stack drilling to the average surface roughness value of 2.5 µm for CFRP and 0.5 µm for UNS A92024. Those are the values which remain below 3.2 µm capability for the aeronautical sector[47].

The drill diameter and feed rate parameters hada significant effect on the torque and thrust force during drilling of CFRP/aluminum stack, being spindle speed has a less effect. Zitoune *et al.*[7] used different diameters (4–8mm) of carbide drills with a typical point angle of 118° to determine the consequence of cutting speed (13-69 m/min) and feed rate (0.05–0.15 mm/rev) on the thrust force, hole precision and surface finish during drilling two layers of CFRP/aluminum stacks. The drill diameter and feed rate had a more dominant effect on torque, thrust force and chip breakage than the cutting speed, being the feed rate in the CFRP layer was seen to consequence the surface roughness of the hole. From the investigation of Krishnaraj and Zitoune[56] the diameter of the hole on CFRP is identified to be lesser than the nominal diameter of drill in drilling CFRP/Al stack with plain carbide drill. Circularity with low feed values in CFRP is found to be around 6 µm. The circularity rises to 25 µm, as the feed is increased.

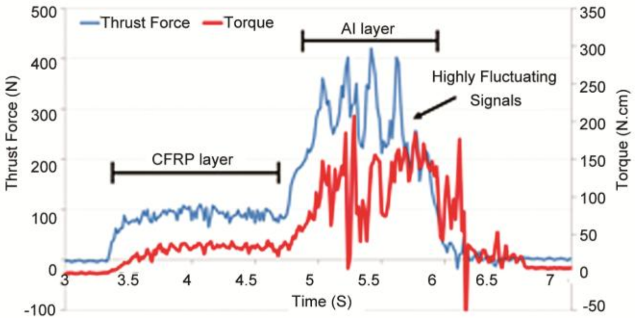

Fig. 5 — Torque signals and thrust force of the first hole in drilling CFRP/Al stack[58].

The thrust force during drilling was one of the crucial indicators too for describing the machinability of laminated composites because it directly upset the quality of the drilled holes, in particular the drilling induced delamination[57]. The analysis of the torque signals and thrust force for first hole when drilling CFRP/Al stack was done by Soo *et al.*[58] which were shown in Fig. 5. The first hole showed substantial fluctuations in both signals exclusively for the Al layer of the stack. The thrust force for both Al and CFRP is almost proportional to the feed rate, whilst it is slightly increased with the rise of the spindle speed. Usually the thrust force raised from 300 N for the first hole to nearly 2200 N for the last hole drilled whilst the torque values for worn tools were usually less than 600 N-cm[59].

3.3 Influence of tool geometry and type on the performance measures

A challenge has been facing in drilling dissimilar materials as the composite metal stacks are on demand in industries. The appropriate drill type with geometries such as the helix angle, point angle, drill diameter, rake angle and chisel edge web thickness have presented considerable effect on the torque, thrust force and delamination during drilling CFRP/Al stacks has to be chosen. Drilling of CFRP/Al stacked composites concerning tool geometries are summarized in Table 4 by the experimental

Table 4 — Experimental researches concerning tool type and geometries in drilling CFRP/Al stacks.

<table>
<tr><th>Stack configuration</th><th>Drill type and Geometry</th><th>Key issues addressed</th></tr>
<tr><td>CFRP/Al2024[7]
CFRP: Unidirectional prepregs, quasi-isotropic laminate
$\Theta=[90^{\circ}/-45^{\circ}/0^{\circ}/45^{\circ}/90^{\circ}/-45^{\circ}/0^{\circ}/45^{\circ}]_s$
t=4.2/3 mm</td><td>(K20) Plain carbide drill
d = 4, 6 and 8 mm.
Ø = 118º</td><td>Torque, Thrust force, surface finish, circularity, hole diameter, chip characteristics</td></tr>
<tr><td>CFRP/Al 2024[10]
CFRP: composed of 16 unidirectional layers
$\Theta = [90^{\circ}/-45^{\circ}/0^{\circ}/45^{\circ}/90^{\circ}/-45^{\circ}/0^{\circ}/45^{\circ}]_s$
t= 4.2/3mm</td><td>Plain WC (K20) drill of diameter 4, 6 and 8 mm.
Ø =118°</td><td>Thrust force, torque</td></tr>
<tr><td>CFRP/Al7075-T7[12]
CFRP: CCF300, Orthogonal woven structure
$\Theta = [0^{\circ}/90^{\circ}]$
t= 3.07/3.1 mm</td><td>CVD diamond-coated WC drills with different geometries designated as A and B
Tool A: d =5mm, Ø = 90º
$\Psi = 25^{\circ}$, $\gamma=23^{\circ}$
Tool B: d =5mm, Ø = 130º
$\Psi = 25^{\circ}$, $\gamma=15^{\circ}$</td><td>Hole accuracy, thrust force, torque, surface roughness, burr height.</td></tr>
<tr><td>CFRP/Al;
AI/CFRP/TiAI6V4[33]
$\Theta = [0^{\circ}/45^{\circ}/90^{\circ}]$</td><td>Conventional twist drill and specially designed step drill coated with TiB_2 and Diamond.
d = 16 mm
Ø = 130°
Ψ = 30°</td><td>Cutting forces,
hole quality,
tool wear,
chip formation</td></tr>
<tr><td>CFRP/Al2024[48]
CFRP: 16 unidirectional layers of 0.26 mm thickness each
$\Theta= [90^{\circ}/45^{\circ}/0^{\circ}/-45^{\circ}/0]_{2s}$.
t=4.2/3 mm</td><td>WC Twist drill (reference drill),
Modified double cone drills with Varying lip length
d = 6.35 mm
Ø = 132º (Reference drill),
90º and 132º (Double cone drills)</td><td>Cutting force,
torque, hole quality, surface roughness, chip flow</td></tr>
<tr><td>CFRP/AL2024[49]
CFRP: 16 unidirectional layers of 0.26 mm thickness each
$\Theta = [90^{\circ}/45^{\circ}/0^{\circ}/-45^{\circ}]_{2s}$ CFRP-4.2 mm thick</td><td>
<table>
<tr><th>Geometry of tools</th><th>WC Twist drill (Reference drill)</th><th>Double cone drill-M1</th><th>Double cone drill-M2</th><th>Double cone drill-M3</th></tr>
<tr><td>d (mm)</td><td>6.35</td><td>6.35</td><td>6.35</td><td>6.35</td></tr>
<tr><td>Web thickness: mm</td><td>0.16</td><td>0.16</td><td>0.16</td><td>0.16</td></tr>
<tr><td>Ø No. 1</td><td>136^0</td><td>136^0</td><td>136^0</td><td>136^0</td></tr>
<tr><td>Ø No. 2</td><td>-</td><td>90^0</td><td>90^0</td><td>90^0</td></tr>
<tr><td>β</td><td>8.58^0</td><td>8.65^0</td><td>8.65^0</td><td>8.65^0</td></tr>
<tr><td>Ψ</td><td>32.5^0</td><td>32.5^0</td><td>32.5^0</td><td>32.5^0</td></tr>
</table>
</td><td>Cutting force
Surface Finish,
delamination models</td></tr>
<tr><td>CFRP/AA2024[54]
CFRP: T800M21
t = 10/10 mm</td><td>Carbide drills with different included angles and rake angles
d = 8mm
Ψ = 30°</td><td>Hole diameter,
chip break up,
wear,
adhesion mechanism,
axial force</td></tr>
<tr><td>CFRP/Al2024[56]
CFRP: composed of 16 unidirectional layers
$\Theta = [90^{\circ}/-45^{\circ}/0^{\circ}/45^{\circ}/90^{\circ}/-45^{\circ}/0^{\circ}/45^{\circ}]_s$
t= 4.2/3mm</td><td>(K20) Plain Carbide drill of diameter 4, 6 and 8 mm.
Ø =118°</td><td>Circularity, thrust force, torque, surface roughness</td></tr>
<tr><td>CFRP/AA7010[59]
CFRP: $[45^{\circ}/135^{\circ}/0^{\circ}/0^{\circ}/45^{\circ}/135^{\circ}/0^{\circ}/0^{\circ}/90^{\circ}/0^{\circ}/45^{\circ}/135^{\circ}/0^{\circ}/0^{\circ}/45^{\circ}/135^{\circ}/0^{\circ}/0^{\circ}/90^{\circ}/0^{\circ}]_s$</td><td>Double cone and
flat point drills
d=6.38 mm</td><td>Delamination factor, burr height, hole diameter, roundness, flank wear</td></tr>
</table>

(*Contd*.)

Table 4 — Experimental researches concerning tool type and geometries in drilling CFRP/Al stacks. (*Contd.*)

Stack configuration	Drill type and Geometry	Key issues addressed
CFRP/Al7010[72] CFRP: T800-DA550 t=7/14 mm	Drills with varying point angles d = 6mm Ø =125º and 60º	Temperature produced on the wall of the drilled hole, heat flux modeling
CFRP/Al 7075-T6[73] CFRP: 26 unidirectional plies of 0.125 mm thick. t=3.25/3.317 mm	WC drill with Ψ =15º, 30º β= 6º, 8º Ø =110º and 130º α = 30º, 45º	Burr height
CFRP/Al-2024[74] Al2024/CFRP t = 16.8/10 mm	Solid carbide standard and stepped drills d = 6.8 mm (standard drill) d = 5 mm (first step), 7.93 mm (second step)-stepped drill	Acoustic emission signal, thrust force signal

researches. Tsao and Hocheng acknowledged the consequence of geometry of drill bit on delamination of CFRP laminated composite. The candle stick and saw drill bits directed to a lesser delamination factor when compared with twist drill tools for the parameters i.e., feed rate and spindle speed. Moreover delamination free drilling under precise drilling conditions is achieved by several researchers by designing the particular drill bits. Examples incorporate the particular drill bit intended by Piquet *et al.*[60], and a step drill offered by Marques *et al.*[61], Brinksmeier and Janssen considered the Al/CFRP/Ti lamination drill and introduced a new process for drilling multiple layers by step drill. Hocheng and Tsao[62,63,64] developed a mathematical model viewing the impact of five special drill bit geometries (a twist drill, a core drill, a candle stick drill, a saw drill and a step drill) on delamination and also examined them experimentally. They reported that the minimum delamination can be attained with core drill whereas the maximum delamination occurred with the "twist drill". Grilo *et al.*[65], analyzed the cutting prospective of three different cutting tools such as brad & spur drill, twist drill and a four-flute drill relating to CFRPs, and declared that the brad & spur drill produces best results in terms of delamination.

Drilling of CFRP/Al stack, under dry drilling conditions, plain carbide drills from 4 to 8 mm in diameter showed that the aluminum portion had enhanced circularity and surface integrity compared to CFRP portion. It was similarly suggested that drill tools with a diameter of 6 mm or less be chosen to avoid major variations in the drilling influence of composites and metals.[7] Drill geometry design incorporating multiple cutting edges or margins has been developed to enhance tool strength/rigidity. Ema *et al.*[66] showed that even though hole accuracy improved when utilizing a drill with 3 cutting edges, associated torque and thrust force levels were up to 50% and 100% higher respectively compared to a conventional two-fluted twist drill. By decreasing the web thickness at the chisel edge and tool inclination angle, it is found that cutting forces are reduced and hole surface quality was enhanced. Zitoune *et al.*[67], Karpat *et al.*[68, 69,70] researched the effects of geometry of the drill bits thru drilling of CFRP / metal sheets. The findings showed that the drill bit with double point angle performed excellently in terms of tool wear, thrust force and surface quality of the hole than the regular twist drill bit. Zitoune *et al.*studied drilling of CFRP/Al laminate by means of double cone drills with varying lip length on holes quality and cutting forces. The different geometry of double cone drills designated with M1, M2 and M3 were used for the study, which are shown in the Table 4. They accomplished that, double cone drill tools produces less thrust force in CFRP compared with typical twist drill. Soo *et al.*[58] used different structured drills shown in Fig. 6 and reported that the double cone geometry drill is inadequate for single-shot drilling of CFRP/Al stack configurations, which failed catastrophically even after working at the least parameter combination after machining only four holes. This was due to extreme stuffing/adhesion of chips in the drill flutes that stuck the subsequent evacuation of swarf through the hole. Ashrafi *et al.*[9] assessed presentation of the drills in terms of hole quality, tool wear, torque and thrust force. The twist drills of different geometries, both coated and uncoated, were used for testing the consequence of the process parameters on the hole efficiency. They concluded that the lower thrust force and higher torque were recorded for the uncoated

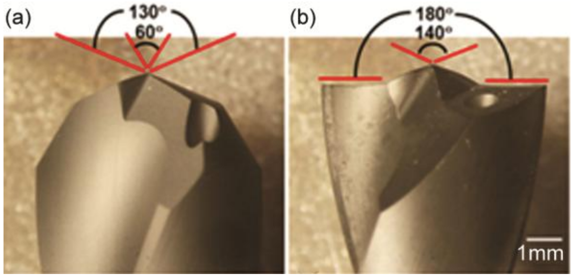

Fig. 6 — Micrographs of (a) double cone geometry and (b) flat point geometry drills [71]

four-facet tool with lower chisel edge, helix and point angles. The four uncoated facets with modified geometry were the best tool for delamination, hole size and fibre fraying. Zhang *et al.*[71] performed drilling experiments on stacked materials of CFRP and Aluminum alloy with special structure drills to evaluate how the effect of roughness, hole precision and burr height and cutting force by process parameters and tools. The drills employed are CVD diamond coated WC of special geometries. The tool A with shorter chisel edge and two major cutting edges and the tool B is conventional twist drill and its specifications are shown in Fig. 6. Their results shown that the cutting capacity of Tool A is significantly greater than the Tool B i.e., the conventional twist drill. They reported that the reason for smaller diameter tolerance was because of the drill geometry compared to the process parameters. Shorter chisel-edge length and capability of fine self-centering of drill holds good for reducing the diameter tolerance. Benezech *et al.*[54] explained the significance of the included angle and axial rake angle showing the performance during the drilling operation which has more scope in industrial application. Concerning value for surface, geometrical and dimensional specifications, these angles had less influence. The study pertained that employing a persistent axial rake angle all over the cutting edge length is helpful for excellence of drilling but the angle has to be selected rendering to the function. In a case study, the rake angle of 30° and a fair included angle of 135° was optimal. Drills with point angle 125º and 60º were used by Montoya *et al.*[72], to analyze the temperature exposed on the drilled hole and heat flux modeling. It has revealed that the heat created in aluminum alloy does not create temperature rise in the stacking composite component. The heat generated due to high thermal conductivity in the aluminum alloy disperses inside it rapidly, this avoids influencing the CFRP slice of the multi-material stack.

Burr height is considered as one of the important eminence metrics used for evaluation of quality of the hole and needs to be reduced for better hole quality when drilling metallic sections. This is very essential, as the height of the prompted exit burr generally forms serious problems during riveting and fasteners installation for further assembly of the stack up. In this view, Hassan *et al.*[73] analyzed the burr height with specific point angle, helix angle, primary clearance angle and chisel edge angle during drilling using tungsten carbide drill. The results showed that the formation of burr height for stacking materials can be reduced by using helix angle 15°,primary clearance angle 8°, point angle 130°, chisel edge angle 30°, spindle speed 2600 rpm and feed 0.05 mm/rev.

3.4 Effect of coated tools on performance measures

In this section, the effect of coatings on the tool during drilling of CFRP/Al composite is discussed. Owing to the abrasive nature of the carbon fibres, the tool wear mechanism during CFRP drilling was largely abrasive wear[74,75,76]. Although, the tool wear mechanism in CFRP/metal stack drilling was usually adhesion wear and abrasive wear due to metal built up edge[77, 78, 79]. The research work concerning to coated tools during drilling of CFRP/Al stacked composite are accessed in Table 5.

Kuo *et al.*[52] performed investigational work to assess the impact of feed rate and cutting speed on work piece surface quality subsequent to single shot drilling of multimaterial stacks (Ti-6Al-4V/CFRP/Al7050) by means of CVD diamond-coated tool. From the work they observed that the tool life across the series of machining parameters employed did not exceed 30 holes. This is majorly due to drastic delamination/flaking of the CVD diamond-coating suggesting that the drill tool was not appropriate to use in single shot drilling of the composite stack. The same author concentrated on the performance of tool coatings (DLC and CVD diamond) on hole quality and tool wear modes in drilling Ti-6Al-4V/CFRP/Al-7050 stacks in a single shot operation. The wear examination revealed that DLC coated drills working at feed rate of 0.08mm/rev in general revealed workpiece adhesion, progressive abrasion and chipping resulting to fracture of the tool corner, while as a consequence of fatigue, fracture was common in tests conducted at the level of high feed rate. On the contrary, adhesion of the carbide substrate coating with chemical vapour–deposited diamond caused to severe chipping, premature flaking and rupture of the

Table 5 — Experimental researches concerning coated drills in drilling CFRP/Al stacked composites.

Stack configuration	Drill tool type and coating	Key issues addressed
CFRP/Al2024/CFRP[8] t=3.5/6.5/3.5 mm	Uncoated, PVD-AlTiN coated four facet carbide drills d = 6mm Ø=133.4º, Ψ = 25º, α = 135º	Thrust force, delamination, fibre fraying
CFRP/AL2024/CFRP[9] t=3.5/6.5/3.5 mm	Four types of K20 carbide drills designated as T1, T2, T3 and T4. Specification: T1- four facet, uncoated, Ø=113.4º, Ψ = 25º, α = 135º T2- four facet, AlTiN coated, Ø=113.4º, Ψ = 25º, α = 135º T3- two facet, uncoated, Ø=113.4º, Ψ = 25º, α = 135º T4- four facet, uncoated, Ø=120º, Ψ = 30º, α = 120º d = 6 mm3	Thrust force, torque, holes size, delamination, fibre fraying, hole edge quality and surface roughness.
Ti6Al4V/CFRP/Al-7050-T651[13] ϴ = [45º/0º/135º/90º/45º/0º]S t= 10/10/10 mm	CVD diamond-coated, uncoated, C7-coated WC drills d= 6.35 mm Ø = 130º Ψ = 30º	Hole size, cylindricity, burr height, hole edge quality, Surface roughness, micro hardness of metal, chip formation.
CFRP/Al7075-T651[14] CFRP: T800/X850 CFRP ϴ=[45º/0º/-45º/0º/+45º/0º/+45º/90º /-45º/0º/-45º/0º/+45º/0º/+45º/90º/-45º/90º/-45º/0º/+45º/0º]s t=8.74/6 mm	Diamond-coated cemented carbide drills with double point angle. d = 9.53 mm, Ø =130ºand 60º Ψ = 30º	Thrust force, drilling temperature, hole surface quality, hole diameter.
CFRP/Al2024[26] CFRP: Unidirectional prepregs, quasi-isotropic laminate t=4.25/3 mm	Uncoated, nc-CrAlN/a-Si3N4 coated WC drills d = 6 mm Ø = 132º	Thrust force, surface roughness, chip shape analysis, tool wear
CFRP/Al 7010-T7451[37] CFRP-T800 t=7/14 mm	Uncoated, Diamond coated, TiAlCrN coated, AlTiSiN-G coated WC twist drills D = 6 mm Ø =124º Ψ = 30º	Tool wear (Abrasive and Adhesive wear), thrust force, hole diameter, hole wall roughness
CFRP/AA 7075/CFRP[50] CFRP: T700 Al: AA7075- T651 Bonded by using an epoxy adhesive at a thickness of about 0.25 mm. t=2.8/20 /2.8 mm	DLC coated, nanocompositeTiAlN coated WC twist drills d = 6.8 mm Ø =118º (DLC coated), 140º (TiAlN coated)	Thrust force, tool wear, flank wear, delamination and hole diameter.
CFRP/Al6013-T651[51]	Uncoated, TiAlN and TiN coated HSS drills d = 8mm Ψ = 30º	Entry and exit delamination
Ti-6Al-4V/CFRP/Al-7050[52] CFRP: composed of 36 unidirectional layers each 0.18mm thick ϴ = [45º/0º/135º/90º/45º/0º]3S t = 27 mm (Overall thickness)	CVD diamond coated WC drills d = 6.38 mm Ø = 120º, 180º (Two stage point angle) Ψ = 30º γ= 14º	Surface roughness, surface defects, wear, microhardness
CFRP/A7075T6[53] ϴ = [0º/90º] t=3.5/3 mm	CVD diamond-coated drills d = 6.375 mm	Torque, Thrust force, tool flank wear, burr height, hole diameter, hole surface roughness, microhardness

(*Contd*.)

Table 5 — Experimental researches concerning coated drills in drilling CFRP/Al stacked composites. (*Contd.*)

Stack configuration	Drill tool type and coating	Key issues addressed
Ti6Al4V/CFRP/Al-7050[59] CFRP: unidirectional carbon fibreprepregs each 0.125 mm thick. $\Theta = [45^0/0^0/135^0/90^0/45^0/0^0]S$ t= 10/10/10 mm	CVD diamond-coated, uncoated, C7-coated WC drills d= 6.35 mm Ø = 130º Ψ = 30º	Flank wear, tool life, thrust force, torque
CFRP/Al7075-T7[71] CFRP: CCF300, Orthogonal woven structure Ɵ = [0º/90º] t= 3.07/3.1	CVD diamond-coated WC drills with different geometries designated as A and B Tool A: d=5mm, Ø = 90º Ψ = 25º, γ=23º Tool B: D=5mm, Ø = 130º Ψ = 25º, γ=15º	Hole accuracy, thrust force, torque, surface roughness, burr height.
Ti-6Al-4V/CFRP/Al-7050[81] CFRP: comprised of 30 unidirectional prepregs each 0.3 mm thick. Ɵ = [45º/0º/135º/90º/45º/0º]3s. t = 30 mm (Overall thickness)	DLC, CVD diamond coated WC drills d = 6.38 mm Ø = 120º, 180º (Two stage point angle) Ψ = 30º	Torque, Thrust force, tool wear, hole accuracy, burr formation, burr height.
Ti-6Al–4 V/CFRP/AA7050[82] CFRP: composed of 36 unidirectional prepregs Ɵ = [45º/0º/135º/90º /45º /0º]3s t=30 mm (overall thickness)	Uncoated, TiAlN/TiN coated solid WC twist drills d = 6.35 mm Ø = 140º Ψ = 30º γ= 14º	Torque, Thrust force, flank wear, hole cylindricity, hole diameter, hole surface roughness, drill life, microhardness, burr formation and burr height on metallic layers, chip morphology

drill cutting and chisel edge. Although severe chipping /flaking, the CVD diamond coated drill formed superior hole quality in addition to lesser burring with respect to the DLC-coated tools because of the lower geometrical damage and two-stage point design at the peripheral corner.

For drilling CFRP/Al laminated stack, Kuo *et al.*[52] employed double point geometry CVD diamond coated tool. The goal is to establish a strategy of universal drilling focused on ideal cutting factors for piled composite materials consisting of CFRP and aluminum alloy. Using the CVD diamond coating on the WC tools, the vibration effect caused due to severe flank could be suppressed. The average diameter was lesser than the actual diameter of the CVD diamond coated drill for the holes on CFRP and Al layers. The irregular protrusions on the hole surface under the erratic cutting actions were because of the elastic features and also the influence of carbon fibres pulled out of the CFRP layers. Subsequently, as the drill approached into the Al layer, the formation of chip perhaps affected thru the wear of tool and the essential ductile nature of the aluminium alloy influenced the chip formation. Wang *et al.*[14] employed diamond coated with double point angle drill tools to examine drilling temperature, drilling force, diameter and surface quality of hole in machining of CFRP/Al stack materials. According to Montoya *et al.*[37] the thrust force (by limiting wear) through a diamond coating can be shrunk by 65% for CFRP and by 35% for Al. The outcomes have revealed that, as the drilled holes number rises, the thrust force created with the pair of coated and uncoated drills gradually proliferate due to the tool wear in both composite and metal parts. The review has also pointed the significance of the advancement of the drill micro geometry on the thrust force. Good hole quality attaineddue to lesser flank wear and thrust forces when using the diamond coating. Zhang *et al.*[80] used CVD diamond WC drills to study the cutting ability during machining. They displayed that the cutting potential of coated tool A is appreciably greater than conventional twist drill (tool B). Kuo *et al*[81,82], studied the execution of PVD coated and uncoated WC twist drills, for single shot drilling of layered metallic composite stacks. The holes formed utilizing of TiAlN/TiN coated drills showed excellent feature perfection in terms of cylindricity, diameter and roundness. Further, it wasreported that there is no variation between TiAlN and TiN coated tools in terms of reducing entrance and exit delamination. Ashrafi *et al.*[9] analyzed the behaviour of coated and uncoated four facet carbide drills during machining of CFRP and aluminum stack. It showed that the thrust force on behalf of coated tools was relatively greater than the uncoated tools, owing to the consequence of

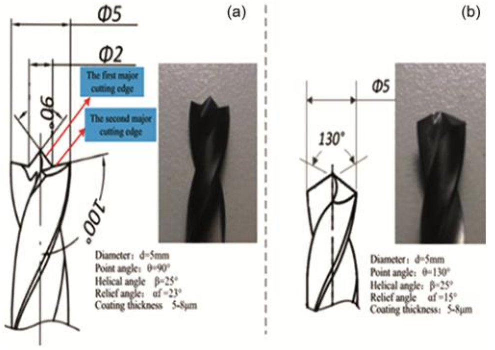

Fig. 7 — The geometry of twist drill a) Tool A, and b) Tool B[71].

coating on edge of cutting lips. Irrespective of greater thrust force of the coated drills, their achievement was superior than uncoated drills regarding delamination damage on CFRP layers.

The study of nano coated drill tools on multi material made of CFRP and aluminum alloy was prepared by Zitoune *et al.*[26] Two variants of tungsten carbide drills, one with nano-coating (nano crystalline-CrAlN/amorphous-Si3N4) and the other, without nano coating were used for the study. The thrust force created with coated drills during drilling of the composite stack was 10–15% lower when compared to uncoated drill tools, similarly the thrust force in the aluminum alloy was 50% lower with coated drills compared to uncoated drill tools. It can be attributed to the fact that, the coating tools largely reduced the friction between the body of the drill and the machined surface as well as the friction between the chips and the flutes of the cutting tool (rake face). Hence, employing nano coated drills considerably decreased the surface roughness and thrust force as long as compared to uncoated drills. This was basically using enhancing of tools particularly before coating (PVD) for better bonding of nano crystalline layer. Thus, the drilling with coated drill tools advanced the surface quality of aluminum and composite. Shyha *et al.*[13] performed investigational trials to investigate the impact of coatings (uncoated, nano-grained AlTiN coated WC and CVD diamond) during machining Ti-6Al-4V/CFRP/Al-7050 stacks. They reported as the tool coatings had merely a marginal effect and also the significance of high pressure cutting fluid (70 bar) in keeping tolerable hole values (diametrical accuracy, cylindricity and out of roundness) and work piece integrity. Similar studies on the accomplishment of the CVD diamond coating and hard metal AlTiN coating (SiC amorphous matrix embedded with nano-crystalline grains) revealed that there was no benefit from these coatings regarding tool life over uncoated WC drills. D'Orazio *et al.*[50] evaluated the influence of two twist drills one coated with DLC and other with nano composite TiAlN when drilling of multi layered CFRP/AA7075 stacks. They stated that the drill tool coated with DLC undergoes lower wear than the TiAlN coated drill and as the number of drilled holes increases, the delamination factor rises and is far less evident using the drill coated with DLC.

4 Conclusion

Owing physical and mechanical properties like excellent tensile strength, superior chemical and corrosion resistance, modulus, dynamic stability and adhesion have inspired the usage of composites in a wide variety of industrial applications. This paper presents analysis of many studies in the available literature regarding force generation, cutting mechanisms, delamination damage, etc when drilling of CFRP/Al stacked composite laminates. Based on the accessible literature study, few important decisions on present and future work has been concluded as follows.

1) The analysis of cutting force in drilling of hybrid CFRP/Al stacked composites by changing machining parameters; a spindle speed of 1000–3000 rpm, feed of 0.02–0.15 mm/rev and varying drill bit sizes (4–8 mm diameter) has been considered in the studies for the enhanced deliberation of force generation, drilling induced delamination and cutting mechanisms.
2) Executes distinctive requirements on the structure of the tool and the drill wear mechanism during drilling of hybrid composites. The double point angle drill bit has been exhibited better performance than the conventional twist drill bit regarding thrust force, hole surface quality and tool wear by considering tool geometry. It is also experiential from the literature that lesser thrust force is achieved when employing double cone drills.
3) Besides plain carbide twist drill, special coated drills such as diamond coated cemented carbide drills, DLC coated WC drills, PVD-AlTiN coated carbide drills, nano composite TiAlN coated WC twist drills and special coated drills aimed at drilling of hybrid composites have been employed to diminish the delamination feature and thrust force.
4) The use of a diamond coated tool can reduce the thrust force by 65% for CFRP and 35% for Al and

enhance the quality of the hole. From the literature review, it has beenproposed to use special geometry drill with diamond coating can significantly diminish the thrust force and progress the machined hole quality during drilling.

5 Future scope

In the present state, through the meticulous literature survey, major scientific progresses have been achieved considering the work studies of hybrid CFRP/Al composite drilling. Nevertheless, quite inadequate publications were found in the literature dealing with the statistical studies of hybrid CFRP/Al drilling. Really to optimize the mechanism investigations when drilling this multi-phase material, the numerical approach should be a promising tool that can significantly help for this work. In the forthcoming, the collective numerical and experimental studies have been straightaway claimed to address specifically the physical concerns that have been involved in hybrid CFRP/Al composite drilling.

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